Human Exploration of Mars:

The Reference Mission of the NASA Mars Exploration Study Team

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Foreword

Mars has long beckoned to humankind from its travels high in the night sky. The ancients assumed this rust-red wanderer was the god of war and christened it with the name we still use today.

Early explorers armed with newly invented telescopes discovered that this planet exhibited seasonal changes in color, was subjected to dust storms that encircled the globe, and may have even had channels that crisscrossed its surface.

Recent explorers, using robotic surrogates to extend their reach, have discovered that Mars is even more complex and fascinating—a planet peppered with craters, cut by canyons deep enough to swallow the Earth's Grand Canyon, and shouldering the largest known volcano in the solar system. They found intriguing evidence that water played an important role on Mars with channels that bear a striking resemblance to stream beds and clouds of crystalline ice that still traverse its red sky. But they also found that Mars was cold and dry, and believed to be devoid of life.

Now present day explorers have announced that pieces of Mars have arrived on Earth as meteorites, and that these bits of the red planet contain evidence pointing to the possible existence of life early in Mars history. This has resulted in renewed public interest in this fellow traveler of the solar system, adding impetus for exploration.

Over the past several years studies have been conducted on various approaches to exploring Earth's sister planet Mars. Much has been learned, and each study brings us closer to realizing the goal of sending humans to conduct science on the Red Planet and explore its mysteries. The approach described in this publication represents a culmination of these efforts but should not be considered the final solution. It is our intent that this document serve as a reference from which we can continuously compare and contrast other new innovative approaches to achieve our long-term goal. A key element of future improvements to this document will be the incorporation of an integrated robotic/human exploration strategy currently under development.
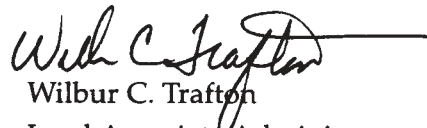
We will continue to develop alternative approaches, technologies, precursor missions, and flight demonstrations that collectively move us forward. Inputs have been, and will always be, encouraged from all sources—NASA centers, industry, research organizations, entrepreneurs, government agencies, international partners, and the public at large—which will improve our understanding and current planning. We plan to use the results of these assessments to shape our investments in technology, and to

look for high leverage, innovative, breakthrough approaches to the most cost effective exploration. These data will also help us understand the required infrastructure, as well as provide important insights into how we can use the International Space Station to validate key assumptions and technologies.

To achieve our goal, we must fundamentally change the way in which we explore with both humans and robots. We must search for alternatives to substantially reduce the cost of exploration, while increasing the inherent value to humankind. This Reference Mission provides a viable starting point for NASA's continuing efforts to develop the technologies and systems, as well as the international partnerships, needed for the grand adventure of sending humans to explore another planet in our solar system— one that may have once, and may yet again, harbor life.

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Acknowledgments

Sending people to Mars has been a long-held dream of humankind, and many have approached the task of turning the dream into reality. This document is another chapter in the ongoing process of melding new and existing technologies, practical operations, fiscal reality, and common sense into a feasible and viable human mission to Mars. However, this is not the last chapter in the process, but marks a snapshot in time that will be added to and improved upon by others in the future. This report has benefited from the contributions and advice of many individuals from the government and private sectors. The individuals listed on the following page assisted in preparing the concepts described in this report and in compiling the words, images, and data used for that description.

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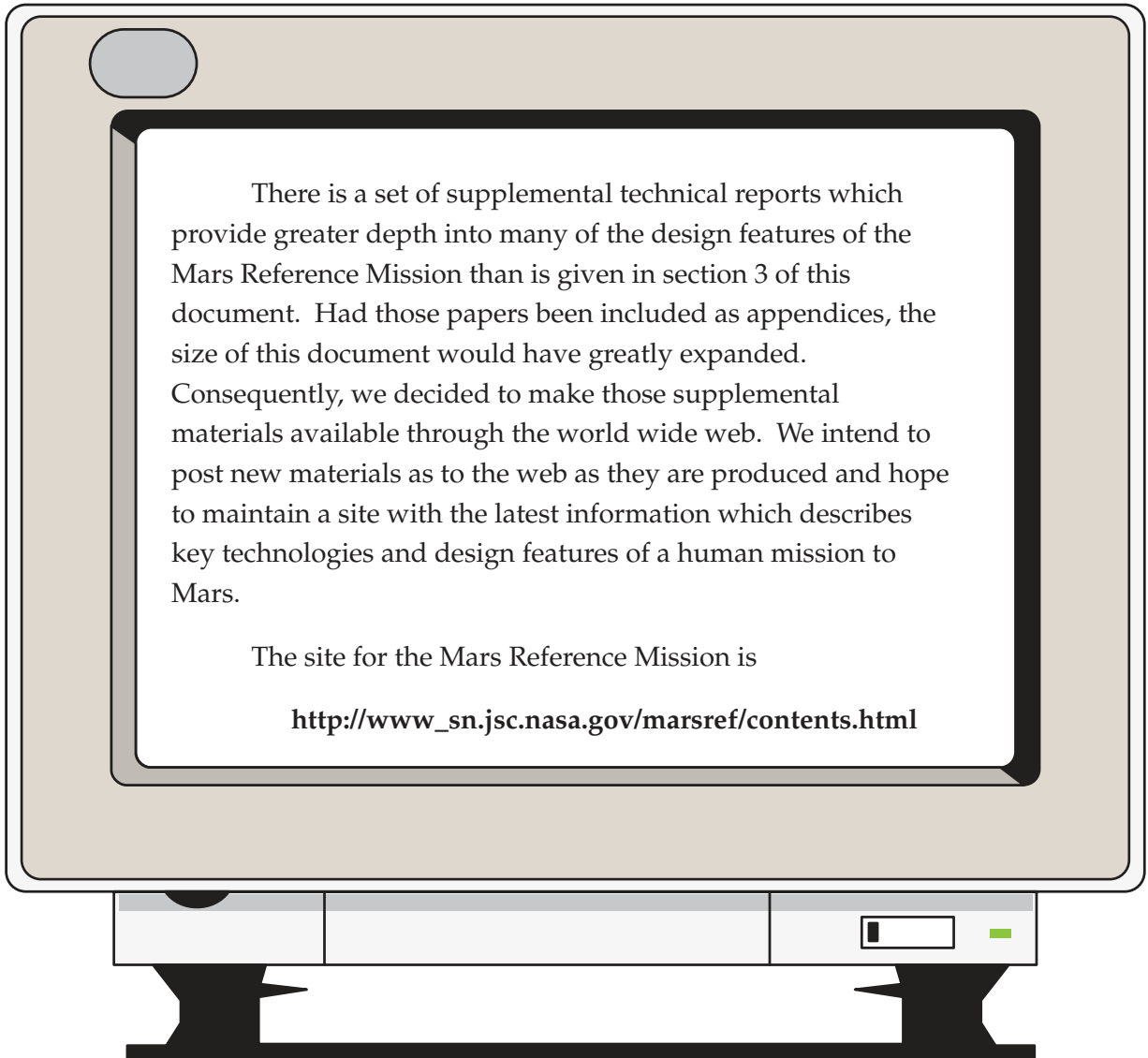 Anthony Gross

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There is a set of supplemental technical reports which provide greater depth into many of the design features of the Mars Reference Mission than is given in section 3 of this document. Had those papers been included as appendices, the size of this document would have greatly expanded. Consequently, we decided to make those supplemental materials available through the world wide web. We intend to post new materials as to the web as they are produced and hope to maintain a site with the latest information which describes key technologies and design features of a human mission to Mars.

The site for the Mars Reference Mission is

http://www_sn.jsc.nasa.gov/marsref/contents.html

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Acronyms

AMCM	Advanced Missions Cost Model
COSPAR	Committee on Space Research
CPAF	cost plus award fee
CPFF	cost plus fixed fee
DIPS	Dynamic Isotope Power System
ECCV	Earth crew capture vehicle
ERV	Earth return vehicle
ETO	Earth-to-orbit
EVA	extravehicular activity
GCR	galactic cosmic radiation
HMF	health maintenance facility
HLLV	heavy-lift launch vehicle
IAA	International Academy of Astronautics
IMLEO	intial mass to low Earth orbit
ISRU	in-situ resource utilization
LEO	low Earth orbit
LMO	low Mars orbit
LOX	liquid oxygen
LSS	life support system
MAV	Mars-ascent vehicle
MGS	Mars Global Surveyor
MOI	Mars Orbit Insertion

MTV	Mars transfer vehicle
NASA	National Aeronautics and Space Administration
ND	NERVA derived
NDR	NERVA derivative reactor
NERVA	nuclear engine for rocket vehicle application
NTR	nuclear thermal rocket
PI	principal investigator
PVA	photovoltaic array
RFC	regenerative fuel cell
RTG	radioisotope thermoelectric generator
SPE	solar proton event
SSME	Space Shuttle Main Engine
STS	Space Transportation System
TEI	trans-Earth injection
TCS	Thermal Contract System
TMI	trans-Mars injection
TROVs	telerobotic rovers

1. Overview

1.1 Introduction

The human exploration of Mars will be a complex undertaking. It is an enterprise that will confirm the potential for humans to leave our home planet and make our way outward into the cosmos. Though just a small step on a cosmic scale, it will be a significant one for humans, because it will require leaving Earth with very limited return capability. The commitment to launch is a commitment to several years away from Earth, and there is a very narrow window within which return is possible. This is the most radical difference between Mars exploration and previous lunar explorations.

Personnel representing several NASA field centers have formulated a "Reference Mission" addressing human exploration of Mars. This report summarizes their work and describes a plan for the first human missions to Mars, using approaches that are technically feasible, have reasonable risks, and have relatively low costs. The architecture for the Mars Reference Mission builds on previous work, principally on the work of the Synthesis Group (1991) and Zubrin's (1991) concepts for the use of propellants derived from the martian atmosphere. In defining the Reference Mission, choices have been made. In this report, the rationale for each choice is documented; however, unanticipated technology advances or political decisions might change the choices in the future.

One principal use of the Reference Mission is to lay the basis for comparing different approaches and criteria in order to select better ones. Even though the Reference Mission appears to have better technical feasibility, less risk, and lower cost than previous approaches, improvement is still needed in these areas to make the first piloted Mars mission a feasible undertaking for the spacefaring nations of Earth. The Reference Mission is not implementable in its present form. It involves assumptions and projections, and it cannot be accomplished without further research, development, and technology demonstrations. It is also not developed in the detail necessary for implementation, which would require a systematic development of requirements through the system engineering process. With this in mind, the Reference Mission may be used to:

- Derive technology research and development plans.

- Define and prioritize requirements for precursor robotic missions.

- Define and prioritize flight experiments for precursor human missions, such as those involving the Space Shuttle, Mir, or the International Space Station.

- Understand requirements for human exploration of Mars in the context of other space missions and research and development programs, as they are defined.

- Open discussion with international partners in a manner that allows identification of potential interests of the participants in specialized aspects of the missions.

- Provide educational materials at all levels that can be used to explain various aspects of human interplanetary exploration.

- Describe to the public, media, and political system the feasible, long-term visions for space exploration.

- Establish an end-to-end mission baseline against which other proposals can be compared.

However, the primary purpose of the Reference Mission is to stimulate further thought and development of alternative approaches which can improve effectiveness, reduce risks, and reduce cost. Improvements can be made at several levels; for example, in the **architectural**, **mission**, and **system** levels.

- The **architectural** level involves assembly of all elements into an integrated whole. The principal features to be addressed in a new architecture that will improve on the Reference Mission appear to be simplification (particularly the number of separate elements that must be developed) and integration with other programs. Simplification by reduction of system elements can lower life-cycle costs and diminish both programmatic and technical risk. For example, the development of higher performance space propulsion systems can lead to simplification, particularly if one vehicle can be used for transit to and from Mars. Integration opportunities to link the Mars program with other development programs could reduce total cost through sharing of developmental costs. The Reference Mission did not assume integration with a lunar exploration program. The development of a major Earth-orbiting operations center in another program could lead to major changes in the Reference Mission architectural approach.

- At the **mission** level, it may be possible to reduce the number of separate launches from Earth. Reducing the total number of launches required to implement the Reference Mission objectives could potentially reduce program and technical risk as well as cost. Focusing and streamlining mission

objectives and improving technology that will lower mass and power requirements can improve the mission level.

- At the **system** level, the performance of individual systems and subsystems can be improved through research and development programs. The programmatic and technical risks can be reduced by demonstrations of ground, Earth-orbit, or planet surface (including the Moon) technology. Criteria for improved systems are principally technical—reduced mass, reduced power, increased reliability.

The current section of this report provides a brief overview of the origins of the study and the Reference Mission design, specifically discussing key issues, findings, and recommendations. Section 2 of this report addresses what can be learned by undertaking the Reference Mission and describes the scientific and technical objectives of Mars exploration. Section 3 provides a detailed discussion of the mission life cycle, the systems needed to carry it out, and the management challenges and opportunities that are inherent in a program to explore Mars with humans.

1.2 Background

The Mars Exploration Study Project was undertaken to establish a vision for the human exploration of Mars that would serve as a mechanism for understanding the programmatic and technical requirements that would be placed on existing and planned Agency programs.

In August 1992, the first workshop of the Mars Study Team held at the Lunar and Planetary Institute in Houston, Texas, addressed the "whys" of Mars exploration to provide the top-level requirements from which the Mars exploration program could be built (Duke and Budden 1992). The workshop attendees identified the major elements of a potential rationale for a Mars exploration program as:

- Human Evolution – Mars is the most accessible planet beyond the Earth-Moon system where sustained human presence is believed to be possible. The technical objectives of Mars exploration should be to understand what would be required to sustain a permanent human presence beyond Earth.

- Comparative Planetology – The scientific objectives of Mars exploration should be to understand the planet and its history, and therefore to better understand Earth.

- International Cooperation – The political environment at the end of the Cold War may be conducive to a concerted international effort that is appropriate to, and may be required for, a sustained Mars program.

- Technology Advancement – The human exploration of Mars currently lies at the ragged edge of achievability. The

necessary technical capabilities are either just available or on the horizon. Commitment to the program will both effectively exploit previous investments and contribute to advances in technology.

- Inspiration – The goals of Mars exploration are grand; they will motivate our youth, benefit technical education goals, and excite the people and nations of the world.

The study team of personnel from NASA field centers used these inputs to construct the Reference Mission, and then translated the inputs into a set of goals and objectives. Ground rules and assumptions were agreed upon and reflect the lessons learned from previous study efforts. From this work, a mission and a set of systems were developed.

1.3 Reference Mission Summary

1.3.1 Objectives

Reflecting the conclusions of the August 1992 workshop, three objectives were adopted for the analysis of a Mars exploration program and the first piloted missions in that program. They are to conduct:

- Human missions to Mars and verify a way that people can ultimately inhabit Mars.

- Applied science research to use Mars resources to augment life-sustaining systems.

- Basic science research to gain new knowledge about the solar system's origin and history.

The human missions to Mars, which are required to accomplish the exploration and research activities, also contain requirements for safe transportation, maintenance on the surface of Mars, and return of a healthy crew to Earth. The surface exploration mission envisions approximately equal priority for applied science research (that is, learning about the environment, resources, and operational constraints that would allow humans eventually to inhabit the planet) and basic science research (that is, exploring the planet for insights into the nature of planets, the nature of Mars' atmosphere and its evolution, and the possible past existence of life). These more detailed objectives form the basis for defining the required elements and operations for the Reference Mission.

In addition, past mission studies have yielded results that have characterized piloted Mars missions as being inherently difficult and exorbitantly expensive. To confront these commonly accepted beliefs that are unfortunately tied to Mars missions, this study added objectives to:

- Challenge the notion that the human exploration of Mars is a 30-year program that will cost hundreds of billions of dollars. Although the nations of the world could afford such expenditures in comparison to, for example, military budgets, the smaller the total cost, the

more likely it is that the program will be implemented.

- Challenge the traditional technical obstacles associated with sending humans to Mars.

- Identify relevant technology development and investment opportunities that benefit both Mars exploration and Earth-bound endeavors.

From these basic objectives, a Reference Mission was crafted by drawing on lessons learned from many past studies and by adding new insights to various aspects of the mission. This approach substantially improved the yield from piloted missions while also reducing risk and cost.

1.3.2 Ground Rules and Assumptions

Translating these objectives into specific missions and systems for the Reference Mission required adopting a number of ground rules and assumptions. These were to:

- Balance technical, programmatic, mission, and safety risks.

- Provide an operationally simple mission approach emphasizing the judicious use of common systems.

- Provide a flexible implementation strategy.

- Limit the length of time that the crew is continuously exposed to the interplanetary space environment.

- Define a robust planetary surface exploration capacity capable of safely and productively supporting crews on the surface of Mars for 500 to 600 days each mission.

- Define a capability to be able to live off the land.

- Rely on advances in automation to perform a significant amount of the routine activities throughout the mission.

- Ensure that management techniques are available and can be designed into a program implementation that can substantially reduce costs.

- Use the Earth-Mars launch opportunities occurring from 2007 through 2014. A 2009 launch represents the most difficult opportunity in the 15-year Earth-Mars cycle. By designing the space transportation systems for this opportunity, particularly those systems associated with human flights, they can be flown in any opportunity with either faster transit times for the crew or increased payload delivery capacity.

- Examine three human missions to Mars. The initial investment to send a human crew to Mars is sufficient to warrant more than one or two missions. Each mission will return to the site of the initial mission thus permitting an evolutionary establishment of capabilities on the Mars surface.

Although it is arguable that scientific data return could be enhanced by a strategy where each human mission went to a different surface site, the goal of understanding how humans can inhabit Mars seems more logically directed toward a single outpost approach.

1.3.3 Mission and Systems

Previous studies of human exploration of Mars have tended to focus on spacecraft and flight, rather than on what the crew would do on the surface. The Reference Mission takes the point of view that surface exploration is the key to the mission, both for science and for evaluation of the potential for settlement. As a consequence, the Reference Mission architecture allows for a robust surface capability with significant performance margins: Crews will explore in the vicinity of the outpost out to a few hundred kilometers, will be able to study materials in situ and in a surface laboratory, and will be allowed to update and modify the exploration plan to take advantage of their discoveries.

In addition, key technologies will be developed and demonstrated to test settlement issues, potentially imposing a substantial workload on the Mars exploration crew. To improve the effectiveness of surface operations, supporting systems must be highly reliable, highly autonomous, and highly responsive to the needs of the crew. Some needs may not be anticipated during crew preparation and training, which will

significantly challenge the management and operations systems to support the crew in the new situations.

1.3.3.1 Mission Design

The crew will travel to and from Mars on relatively fast transits (4 to 6 months) and will spend long periods of time (18 to 20 months; 600 days nominal) on the surface, rather than alternative approaches which require longer times in space and reduce time on the surface. Figure 1-1 illustrates a typical trajectory. Designed to the worst-case mission opportunity (2007-2009) of the next two decades, the transit legs are less than 180 days in both directions. For easier Mars mission opportunities (for example, 2016-2018), the transit legs are on the order of 130 days. Shorter transit times reduce the time spent by the crew in zero g to the length of typical tours of duty for the International Space Station. (Thus, the Mars Study Team chose not to use artificial gravity spacecraft designs for the Reference Mission.) In addition, relatively fast transits will reduce the exposure to galactic cosmic radiation and the probability of encountering solar particle events. Reducing the exposure to zero g and radiation events helps reduce the risk to the crew.

The strategy chosen for the Reference Mission, generally known as a "split mission" strategy, breaks mission elements into pieces that can be launched directly from Earth with launch vehicles of the Saturn V or Energia class, without rendezvous or assembly in low

Earth orbit (LEO). The strategy has these pieces rendezvous on the surface of Mars, which will require both accurate landing and mobility of major elements on the surface to allow them to be connected or to be moved into close proximity. Another attribute of the split mission strategy is that it allows cargo to be sent to Mars without a crew during the same launch opportunity or even one or more opportunities prior to crew departure. This allows cargo to be transferred on low energy, longer transit time trajectories and the crew to be sent on a required higher energy, shorter transit time trajectory. Breaking the mission into two launch windows allows much of the infrastructure to be emplaced and checked out before committing a crew to the mission, and also allows for a robust capability, with duplicate launches on subsequent missions providing either backup for the earlier launches or growth of initial capability.

Figure 1-2 illustrates the mission sequence analyzed for the Reference Mission. In this sequence, three vehicles will be launched from Earth to Mars in each of four launch opportunities which, for reasons presented earlier, start in 2007. The first three launches will not involve a crew but will send infrastructure elements to low Mars orbit and to the surface for later use. Each of the remaining opportunities analyzed for the Reference Mission will send one crew and two cargo missions to Mars. These cargo missions will consist of an Earth-return vehicle (ERV) on one flight and a lander carrying a Mars-ascent vehicle (MAV) and additional supplies on the second. This
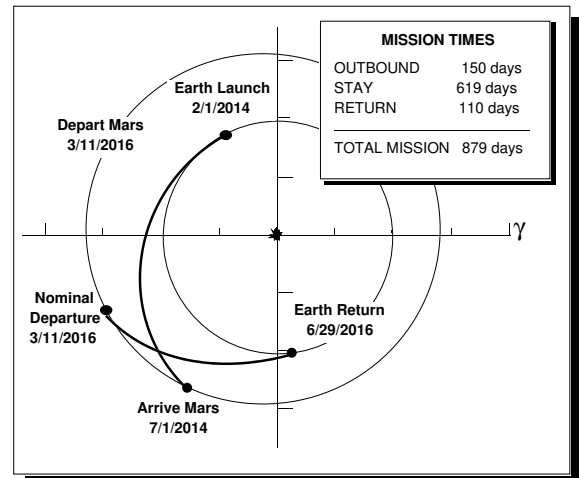
Figure 1-1 Typical fast-transit trajectory.

sequence gradually builds up assets on the martian surface so that at the end of the third crew's tour of duty, the basic infrastructure could be in place to support a permanent presence on Mars.

The six launches used to support the activities of the first crew will be discussed in more detail here to illustrate what will typically occur for all three crews. (Note: For the nominal mission, launches 1 through 4 are required to support the first crew; launches 5 and 6 provide backup systems for the first crew and, if not used, are available for the second crew.) Figure 1-3 illustrates the general sequence of events associated with the first crew's mission to Mars as discussed in the following paragraphs.

In the first launch opportunity, three cargo missions are sent on minimum energy trajectories direct to Mars (that is, without assembly or fueling in LEO). Launch 1

delivers a fully fueled ERV to Mars orbit. (The crew will rendezvous with this stage and use it to return to Earth after completion of their surface exploration mission.) Launch 2 delivers an unfueled MAV, a propellant production module, a nuclear power plant, liquid hydrogen (to be used as a reactant to produce the ascent vehicle propellant), and approximately 40 tonnes of additional payload to the surface. After the descent stage lands on the surface, the nuclear reactor autonomously deploys itself several hundred meters from the ascent vehicle. Using the Mars atmosphere as feedstock, the propellant production module begins to manufacture the nearly 30 tonnes of oxygen and methane that
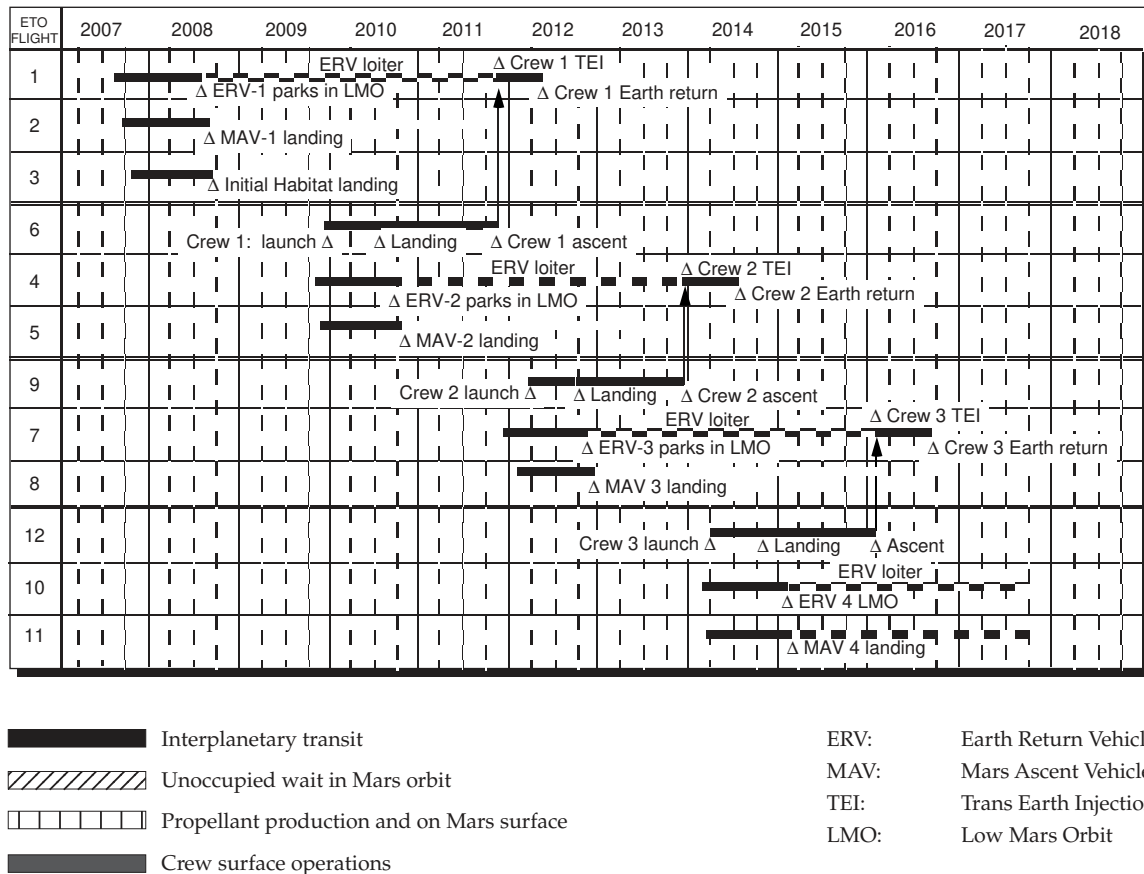
Figure 1-2 Mars Reference Mission sequence.

Near Term Mars Precursor Strategy

1. Robotic Sample Return Mission Demonstrates Mars Resource Utilization

2. Energia Launches Mars Habitat Prototype

3. Mars Habitat Prototype Demonstrated on Space Station

Human Exploration of Mars

An Exploration Mission Concept

4. Ascent Vehicle and Outpost Cargo Arrives at Mars

5. Power Systems Deployed and Propellant Production Begins

6. Arrival of Initial Surface Habitat

Figure 1-3 General sequence of events associated with first mission to Mars.

7 Backup Ascent Vehicle and Exploration Systems

8 Crew Positions Habitation System

9 Pressurized Rover Docked with Habitation System

Human Exploration of Mars
An Exploration Mission Concept Continued

10 Crew Departs Mars After 500 Days on the Surface

11 Rendezvous with Earth Return Vehicle

12 Crew Returns to Earth

Figure 1-3 General sequence of events continued.

will be required to eventually deliver the crew to Mars orbit. This production is completed within approximately one year—several months prior to the first crew's scheduled departure from Earth. Launch 3 lands in the vicinity of the first descent vehicle and delivers a surface habitat/laboratory, nonperishable consumables for a safe-haven, and a second nuclear power plant to the planetary surface. The second nuclear power plant autonomously deploys itself near the first power plant. Each power plant can provide sufficient power (160 kWe) for the entire mature surface outpost, thereby providing complete redundancy within the power production function.

During the second launch opportunity, two additional cargo missions and the first crew are launched. All assets previously delivered to Mars have been checked out and the MAV, already on the martian surface, is verified to be fully fueled before either the crew or the additional cargo missions are launched from Earth. (Should any element of the surface system required for crew safety or critical for mission success not check out adequately, the surface systems will be placed in standby mode and the crew mission delayed until the systems can be replaced or their functions restored. Some systems can be replaced using hardware originally intended for subsequent missions; others may be functionally replaced by other systems.) The first cargo launch of this second opportunity is a duplicate of Launch 1 from the first opportunity, delivering a second fully fueled ERV to Mars orbit. The second cargo launch

similarly mirrors Launch 2 of the previous opportunity, delivering a second unfueled ascent vehicle and propellant production module. These systems provide backup or extensions of the previously deployed capabilities. For example, the second MAV and second ERV provide the first crew with two redundant means for each leg of the return trip. If, for some reason, either the first ascent vehicle or the first return vehicle becomes inoperable after the first crew departs Earth, this crew can use either of the systems launched in the second opportunity instead. If the first ascent and return vehicles operate as expected, then the systems delivered in the second opportunity will support the second crew that will launch to Mars in the third opportunity.

The first crew of six departs for Mars in the second opportunity. They leave Earth after the two cargo missions have been launched, but because they are sent on a fast transfer trajectory of only 180 days, they will arrive in Mars orbit approximately 2 months before the cargo missions. The crew lands on Mars in a surface habitat substantially identical to the habitat/laboratory previously deployed on the martian surface. After capturing into a highly elliptic Mars orbit, the crew descends in the transit habitat to rendezvous on the surface with the other elements of the surface outpost. (The crew carries sufficient provisions for the entire surface stay in the unlikely event that they are unable to rendezvous on the surface with the assets previously deployed.)

Surface exploration by robotic vehicles and human explorers will include a wide range of activities.

- Observing and analyzing the surface and subsurface geology.

- Observing and analyzing the composition and structure of the atmosphere.

- Collecting samples and examining them in the outpost laboratory.

- Performing experiments designed to gauge the ability of humans to inhabit Mars.

Prior to the arrival of the first human crew, telerobotic rovers (TROVs) may be delivered to the surface. (These rovers are assumed to be intelligent enough to perform broadly stated objectives without human assistance. But humans will continue to monitor progress and be available to "supervise" the TROV if it cannot solve a particular problem.) When the crew arrives, the rovers will be available for teleoperation by the crew. The TROVs may be designed to provide global access and may be able to return samples to the outpost from hundreds of kilometers distance from the site if they are deployed 2 years before the crew arrives.

The outpost laboratory will be outfitted to provide mineralogical and chemical analyses of rocks, soils, and atmospheric samples; and depending on technical development, it may be possible to undertake simple kinds of geochronologic analysis on

Mars. The purpose of these studies would be to support the field investigations, answer "sharper" questions, and allow the human explorers to narrow their focus to the sites of optimum sample collection. As hypotheses evolve, crews will be able to return to sample sites and gather specific samples to test the hypotheses. Ultimately, selected samples will be returned to Earth for more detailed analysis.

As experience grows, the range of human exploration will grow from the local to the regional. Regional expeditions, lasting perhaps 2 weeks and using mobile facilities, may be conducted at intervals of a few months. Between these explorations, analysis in the laboratory will continue. The crew will also spend a significant portion of its time performing maintenance and housekeeping tasks (system design requirements addressing enhanced reliability and maintainability will help keep these activities to a minimum). Figure 1-4 provides a possible time line for the first surface mission.

The deployment of a bioregenerative life support capability will be an early activity after crew landing. Although this system is not required to maintain the health and vitality of the crew, it will improve the robustness of the life support system and is important to the early objectives of the outpost.

Crew activities related to living on another planet should be viewed as experiments. With minor modifications in

Mars Surface Mission Time Allocation

(Total Time = 8 crew X 24 hr/day X 600 days = 115,200 hr)

8 crew X 24 hr day = 200)

Personal
14 hr
(total 67,200 hr)

Hr/Over
head

3 hr
(14,400 hr)

Production
7 hr
(33,600 hr total)

600 day (or 20 months, or 86 weeks)

Sleep, Sleep Prep, Dress, Undress: 8 hr

Hygiene, Cleaning, Personal Communication: 1 hr

Recreation, Exercise, Relaxation: 1 hr

Eating, Meal Prep, Clean-up: 1 hr

One Day Off Per Week: 3 hr (per day)

General Planning, Reporting, Documentation, Earth Communication: 1 hr

Group Socialization, Meetings, Life Sciences Subject, Health Monitoring, Health Care: 1 hr

System Monitoring, Inspection, Calibration, Maintenance, Repair: 1 hr

Production Activity	Days
Site Prep, Construction	90 days
Verification	
Week Off	7 days
Local Excursions	
Analysis	100 days
Distant Excursion	10 days
Analysis	40 days
Week Off	7 days
Distant Excursion	
Analysis	
Distant Excursion	
Analysis	
Week Off	
Distant Excursion	100 days
Analysis	
Distant Excursion	
Analysis	
Flare Retreat	15 days
Week Off	7 days
Distant Excursion	
Analysis	100 days
Distant Excursion	
Analysis	
Week Off	7 days
Sys Shutdown Departure Prep	60 days

Charge Fuel Cells
Check Vehicle
Load Vehicle
Plan Excursion
Drive Vehicle
Navigate
Don Suits (X 20)
Pre-breathe (X 20)
Egress (X 20)
Unload Equip
Set up Drill (X 10)
Operate Drill
Collect Samples
In Situ Analysis
Take Photos
Communicate
Disassemble Equip
Load Vehicle
Ingress (X 20)
Clean Suit (X 20)
Stow Suit, Equip
Inspect Vehicle
Secure for night
(Sleep, eat, cleanup
hygiene, etc.
covered)

3 Crew X 7 hr X 10 Day =
210 hrs total

Figure 1-4 Possible time line for first Mars surface mission.

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hardware and software, ordinary experiences can be used to provide objective databases for understanding the requirements for human settlement.

The first crew will stay at the outpost for 18 to 20 months. Part of their duties will be to prepare the outpost site for the receipt of additional elements launched on subsequent mission opportunities. Since the first crew will have to depart before the second crew arrives, some systems will have to be placed in standby mode.

After their stay on Mars, each crew will use the previously landed and in situ-resource-utilization fueled ascent vehicle to return to orbit where they will rendezvous with the waiting ERV. The crew will return to Earth in a habitat similar to the one used for the outbound transit leg. This habitat, which is part of the ERV deployed in a previous opportunity by one of the cargo flights, typically will have been in an untended mode for nearly 4 years prior to the crew arrival.

1.3.3.2 In Situ Resource Production

The highly automated production of propellant from martian resources is another defining attribute of the Reference Mission. The technology for producing methane and liquid oxygen from the martian atmosphere and some nominal hydrogen feedstock from Earth is an effective performance enhancement and appears to be technologically feasible within the next few years. The split mission strategy allows the propellant production capability to be

emplaced, checked out, and operated to produce the required propellant prior to launching the crew from Earth.

In addition to spacecraft propulsion, the production capability on Mars can provide fuel for surface transportation, reactants for fuel cells, and backup caches of consumables (water, oxygen, nitrogen, and argon) for the life support system.

1.3.3.3 Flight Crew

Humans are the most valuable mission asset for Mars exploration and must not become the weak link. The objective for humans to spend up to 600 days on the martian surface places unprecedented requirements on the people and their supporting systems. Once committed to the mission on launch from LEO, the crew must be prepared to complete the full mission without further resupply from Earth. Unlimited resources cannot be provided within the constraints of budgets and mission performance. Their resources will either be with them or will have already been delivered to or produced on Mars. So trade-offs must be made between cost and comfort, as well as performance and risk. Crew self-sufficiency is required because of the long duration of their mission and the fact that their distance from Earth impedes or makes impossible the traditional level of communications and support by controllers on Earth. The crews will need their own skills and training and specialized support systems to meet the new challenges of the missions.

The nominal crew size for this mission is six. This number is believed to be reasonable from the point of view of past studies and experience and is a starting point for study. Considerable effort will be required to determine absolute requirements for crew size and composition. This determination will have to consider the tasks required of the crew, safety and risk considerations, and the dynamics of an international crew. Crew members should be selected in part based on their ability to relate their experiences back to Earth in an articulate and interesting manner, and they should be given enough free time to appreciate the experience and the opportunity to be the first explorers of another planet. Significant crew training will be required to ensure that the crew remains productive throughout the mission.

1.3.3.4 Robotic Precursors

Robotic precursor missions will play a significant role in three important areas of the Reference Mission. The first area is to gather information about Mars that will be used to determine what specific crew activities will be performed and where they will be performed. The second area is to demonstrate the operation of key techonologies required for the Reference Mission. The third is to land, deploy, operate, and maintain a significant portion of the surface systems prior to the arrival of the crew.

For optimum mission performance, it will be necessary to pick a landing site based primarily on its ability to achieve Reference Mission objectives. The site must be consistent with operational considerations, such as landing and surface operational safety. Detailed maps of candidate landing sites built from data gathered by precursor robotic missions will define the safety and operational hazards of the sites, as well as confirm whether access to scientifically interesting locations is possible by humans or robotic vehicles. Robotic surface missions, including missions to return samples, may be required to confirm remotely sensed data from orbit and to satisfy planetary protection issues. To satisfy the human habitation objectives in particular, it would be highly desirable to locate the outpost site where water can be readily extracted from minerals or from subsurface ice deposits. Such a determination may only be possible from data collected by a robotic surface mission.

To accomplish the Reference Mission, key advances in certain critical technologies will need to occur. The robotic precursor missions offer an opportunity to demonstrate the operation of many of those technologies, such as in situ resource utilization, aerocapture, precision landing, etc. The information and experience gained from the demonstration of these technologies will add immeasurable confidence for their use in the human mission.

The first phase of human exploration is the automated landing of surface infrastructure elements, including a system to produce propellant and life support consumables, the first of two habitats, power

systems, and surface transportation elements. All of these systems will be delivered, set up, and checked out using robotic systems operated or supervised from Earth. The propellant required for the MAV will be produced and stored as will oxygen and water caches for the habitat. The overall site will be prepared for receipt of the second habitat.

1.3.3.5 Launch Systems

The scale of the required Earth-to-orbit (ETO) launch capability is determined by the mass of the largest payload intended for the martian surface. The nominal design mass for individual packages to be landed on Mars in the Reference Mission is 50 tonnes for a crew habitat sized for six people that is transferred on a high-energy orbit. This requires the capability for a single launch vehicle to be from about 200 to 225 tonnes to LEO.

Because 200-ton-class launch vehicles raise development cost issues, consideration was given to the option of launching pieces to LEO using smaller vehicles and assembling (attaching) them in space prior to launching them to Mars. This smaller launch vehicle (110 to 120 tonnes) would have the advantage of more modest development costs and is within the capability of the Russian Energia program. However, the smaller launch vehicle introduces several potential difficulties to the Reference Mission scenario. The simplest, most desirable implementation using this smaller launch vehicle is to simply dock the two elements in Earth orbit and immediately

depart for Mars. To avoid the boiloff loss of cryogenic propellants in the departure stages, all elements must be launched from Earth in quick succession. This places a strain on a single launch facility and its ground operations crews or requires the close coordination of two or more launch facilities. Assembling the Mars vehicles in orbit and loading them with propellants from an orbiting depot just prior to departure may alleviate the strain on the launch facilities, but the best Earth orbit for a Mars mission is different for each launch opportunity. Therefore, a permanent construction or propellant storage facility in a single Earth orbit is not an optimal solution.

The choice of a launch vehicle remains a significant issue for any Mars mission. For the Reference Mission, however, the larger, 200-ton-class launch vehicle has been assumed without specifying a particular configuration.

1.3.3.6 Interplanetary Transportation System

The interplanetary transportation system consists of a trans-Mars injection (TMI) stage, a biconic aeroshell for Mars orbit capture and Mars entry, a descent stage for surface delivery, an ascent stage for crew return to Mars orbit, an Earth-return stage for departure from the Mars system, and a crew capsule (similar to an Apollo Command Module) for Earth entry and landing. As mentioned earlier, the Reference Mission splits the delivery of elements to Mars into cargo missions and human missions, all of which are targeted to the same locale on the

surface and must be landed in close proximity to one another. The transportation strategy adopted in the Reference Mission eliminates the need for assembly or rendezvous of vehicle elements in LEO, but it does require a rendezvous in Mars orbit for the crew leaving Mars. The transportation strategy also emphasizes the use of common elements to avoid excessive development costs and to provide operational simplicity.

The TMI stage (used to propel the spacecraft from LEO onto a trans-Mars trajectory) employs nuclear thermal propulsion. Nuclear thermal propulsion was adopted for the TMI burn because of its performance advantages; its advanced, previously demonstrated state of technology development; its operational flexibility; and its inherent mission enhancements. A single TMI stage was developed for both piloted and cargo missions. The stage is designed for the more energetically demanding 2009 fast transit trajectory and then used in the minimum energy cargo missions to carry the maximum payload possible to Mars. In the human missions, the TMI stage uses four 15,000 lb. thrust NERVA (Nuclear Engine for Rocket Vehicle Application)-derivative reactor (NDR) engines (Isp = 900 seconds) to deliver the crew and the surface habitat/descent stage onto the trans-Mars trajectory (Borowski, et al., 1993). After completion of the two-perigee-burn Earth departure, the TMI stage is inserted into a trajectory that will not reencounter Earth or Mars over the course of one million years. The TMI stage used with the crew incorporates a shadow shield

between the NDR engine assembly and the LH$_2$ tank to protect the crew from radiation that builds up in the engines during the TMI burns. Although it may seem wasteful to discard the nuclear stage after one use, the complexity of Mars orbit insertion and rendezvous operations for the return flight are avoided.

As shown in Figure 1-5, the same TMI stage is used in all cargo missions, which allows the transportation system to deliver approximately 65 tonnes of useful cargo to the surface of Mars or nearly 100 tonnes to Mars orbit (250 × 33,793 km) on a single launch from Earth. The TMI stage for cargo delivery requires the use of only three NDR engines, so one NDR engine and the shadow shield are removed from the TMI stage, which reduces cost and improves performance.

Mars orbit capture and the majority of the Mars descent maneuver is performed using a single biconic aeroshell. The decision to perform the Mars orbit capture maneuver was based on the facts that (1) an aeroshell will be required to perform the Mars descent maneuver no matter what method is used to capture into Mars orbit, (2) the additional demands on a descent aeroshell to meet the Mars capture requirements were determined to be modest, and (3) a single aeroshell eliminated one staging event, and thus one more potential failure mode, prior to landing on the surface.

The crew is transported to Mars in a habitat that is fundamentally identical to the

2007 Cargo Mission 1
"Dry" Ascent Stage & Lander

2007 Cargo Mission 2
Hab Module & Lander

2007 Cargo Mission 3
LOX/CH$_4$ TEIS & Hab

2009 Piloted Mission 1
Surface Hab with Crew and Lander

15.0 m

16.3 m

19.0 m

7.6 m

16.3 m

20.6 m*

86.0 t LH$_2$
(@ 100%)

86.0 t LH$_2$
(@ 100%)

86.0 t LH$_2$
(@ 192.9%)

86.0 t LH$_2$
(@ 100%)

10 m

10 m

10 m

10 m

4.7 m

LOX | CH$_4$ | LOX

IMEO =   **216.6T**   **216.6T**   **204.7T**   **212.1T**
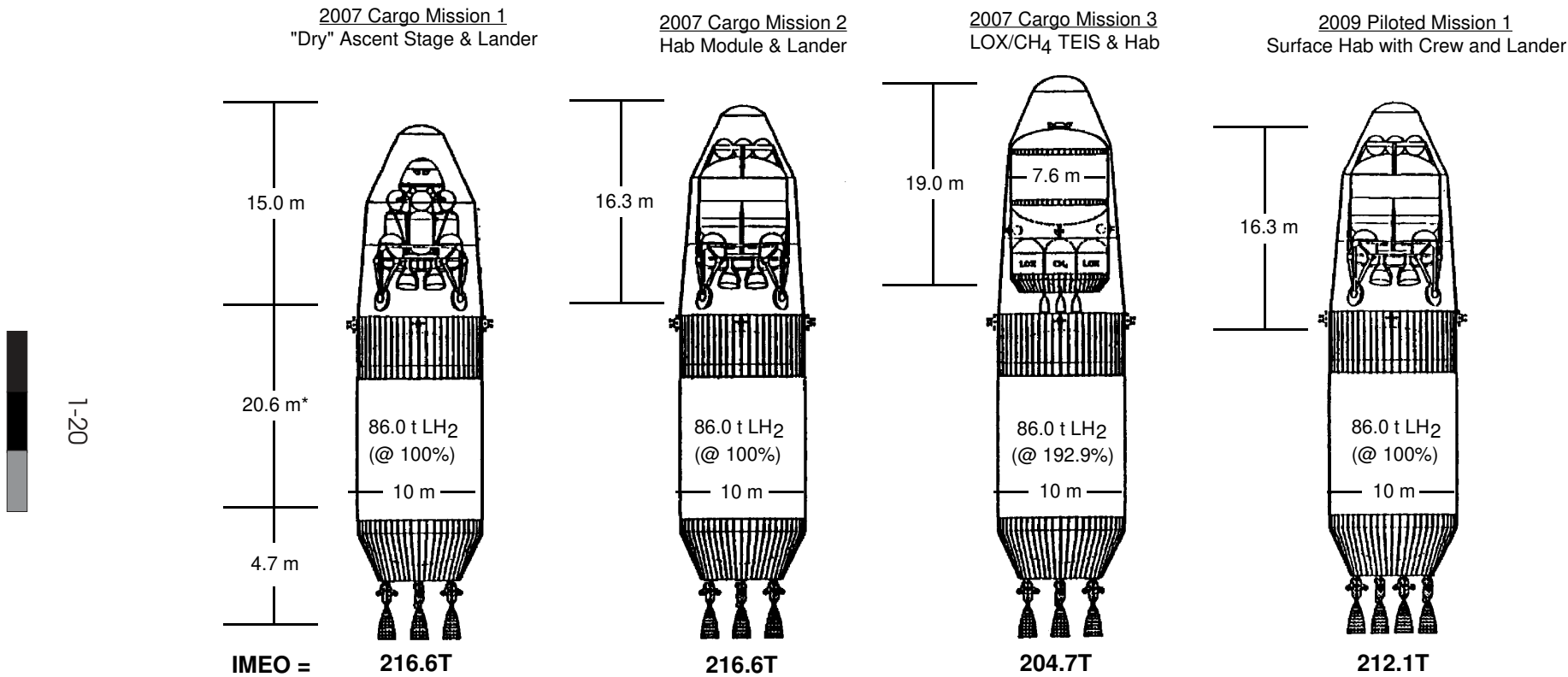
"Expandabe TMI Stage LH$_2$ (@ 18.2 m length) sized
by 2009 Mars Piloted Mission

Figure 1-5 Reference Mars cargo and piloted vehicles.

surface habitat deployed robotically on a previous cargo mission. By designing the habitat so that it can be used during transit and on the surface, a number of advantages to the overall mission are obtained.

- Two habitats provide redundancy on the surface during the longest phase of the mission.

- By landing in a fully functional habitat, the crew does not need to transfer from a "space-only" habitat to the surface habitat immediately after landing, which allows the crew to readapt to a gravity environment at their own pace.

- The program is required to develop only one habitat system. The habitat design is based on its requirement for surface utilization. Modifications needed to adapt it to a zero-g environment must be minimized.

A common descent stage has been assumed for the delivery of the transit/ surface habitats, the ascent vehicle, and other surface cargo. The descent vehicle is capable of landing approximately 65 tonnes of cargo on the Mars surface. The landing vehicle is somewhat oversized to deliver crew; however, design of a scaled-down lander and the additional associated costs are avoided To perform the postaerocapture circularization burn and the final approximately 500 meters per second of descent prior to landing on the Mars surface, the common descent stage employs four RL10-class engines modified to burn LOX/CH_4. The use of parachutes has

been assumed to reduce the descent vehicle's speed after the aeroshell has ceased to be effective and prior to the final propulsive maneuver. The selection of LOX/CH_4 allows a common engine to be developed for use by both the descent stage and the ascent stage, the latter of which is constrained by the propellant that is manufactured on the surface using indigenous materials.

The ascent vehicle is delivered to the Mars surface atop a cargo descent stage. It is composed of an ascent stage and an ascent crew capsule. The ascent stage is delivered to Mars with its propellant tanks empty. However, the descent stage delivering the ascent vehicle includes several tanks of seed hydrogen for use in producing the approximately 30 tonnes of LOX/CH_4 propellant for the nearly 5,600 meters per second delta-V required for ascent to orbit and rendezvous with the ERV. The ascent vehicle uses two RL10-class engines modified to burn LOX/CH_4.

The ERV is composed of the trans-Earth injection (TEI) stage, the Earth-return transit habitat, and a capsule the crew will use to reenter the Earth's atmosphere. The TEI stage is delivered to Mars orbit fully fueled, where it waits for nearly 4 years before the crew uses it to return to Earth. It uses two RL10-class engines modified to burn LOX/CH_4. These are the same engines developed for the ascent and descent stages, thereby reducing engine development costs and improving maintainability. The return habitat is a duplicate of the outbound transit/surface

habitat used by the crew to go to Mars, but contains consumables for the return trip only and minimizes crew accommodations required for the surface mission.

1.3.3.7 Surface Systems

The provision of adequate amounts of electrical power is fundamental to a successful exploration program. For the transit phase, the need for power is less severe than on the martian surface. Solar energy is available for crew needs throughout the cruise phase (the transit phase both to and from Mars).

The selection of a power systems strategy for surface operations is guided by risk considerations, which require two-level redundancy for mission-critical functions and three-level redundancy for life-critical functions. The surface power systems should have 15+ year lifetimes to allow them to serve the three mission opportunities with good safety margins. Surface transportation power systems should have 6+ year lifetimes to minimize the need for replacement over the program lifetime.

The strategy adopted for the Reference Mission includes a primary and backup nuclear reactor with dynamic energy conversion. Each system is capable of producing 160 kWe. Additionally, each habitat retains the solar arrays used during transit, and they can also be operated on the martian surface. Due to several factors (for example, the presence of an atmosphere, a day-night cycle, etc.) each power system can produce

approximately 30 percent of the power generated in space. For emergency situations, the pressurized rover's Dynamic Isotope Power System can supply 10 kWe of continuous power.

From a series of volume, mass, and mission analyses, a common habitat structural cylinder, 7.5 meters in diameter, bilevel, and vertically oriented, was derived for the Reference Mission. The three habitation element types identified for the Reference Mission (the surface laboratory, the transit/surface habitation element, and the Earth-return habitation element) will contain substantially identical primary and secondary structures, windows, hatches, docking mechanisms, power distribution systems, life support, environmental control, safety features, stowage, waste management, communications, airlock function, and crew egress routes. The following are brief descriptions of the unique aspects of the three primary habitation elements developed for the Reference Mission analysis.

- The Mars surface laboratory, sent out, landed, and verified prior to the launch of any crew members, will operate only in 3/8 gravity. It contains a large, nonsensitive (that is, no special environmental control required) stowage area with crew support elements on one level and the primary science and research lab on the second level. Future development of this element includes possible retrofitting of the stowage level into a greenhouse as consumables and

resources are consumed and free volume is created.

- The Mars transit/surface habitats contain the required consumables for the Mars transit and surface duration of approximately 800 days (180 days in transit and 600 days on the surface) as well as all the required equipment for the crew during the 180-day transfer trip. This is the critical element that must effectively operate in both zero and partial gravity. Once on the surface of Mars, this element will be physically connected with the previously landed surface lab thereby doubling the pressurized volume for the crew. Eventually, all four habitation elements (the surface laboratory and three transit/surface habitats) will be interconnected.

- The Earth-return habitat, functioning only in zero g and requiring the least amount of volume for consumables, will be volume rich but must be mass constrained to meet the limitations of the TEI stage. Since little activity (other than conditioning for the one-g environment on Earth and training for the Earth-return maneuvers) is projected for the crew during this phase of the mission, mass and radiation protection were the key concerns in the internal architecture concepts created.

Extravehicular activity (EVA) tasks consist of maintaining the habitats and surface facilities and conducting a scientific exploration program encompassing geologic field work, sample collection, and deployment, operation, and maintenance of instruments.

Mobility on several scales is required by people operating from the Mars outpost. Crew members outside the habitat will be in pressure suits and will be able to operate at some distance from the habitat, determined by their capability to walk back to the outpost. They may be served by a variety of tools, including rovers, carts, and wagons. On a local scale, perhaps 1 to 10 kilometers from the outpost, exploration will be implemented by unpressurized wheeled vehicles. Beyond the safe range for exploration on foot, exploration will be in pressurized rovers, allowing explorers to operate for the most part in a shirtsleeve environment.

The requirements for long-range surface rovers include having a radius of operation of up to 500 km in exploration sorties that allow 10 workdays to be spent at a particular remote site, and having sufficient speed to ensure that less than half of the excursion time is used for travel. Each day, up to 16 person-hours would be available for EVAs. The rover is assumed to have a nominal crew of two people, but be capable of carrying four in an emergency. Normally, the rover would be operated (maneuvering from site to site, transmitting high data rate communications, supporting EVA activities, etc.) only in the daytime, but could conduct selected investigations at night.

1.3.3.8 Operations

Previous space missions have generally cost more to operate than to design and construct. This phenomenon was caused partly by the fact that systems were designed first and operations were developed to fit the designs. The Reference Mission attempts to bring operational considerations into the process early to better balance the cost of design and development with the cost of operations.

1.3.3.8.1 Crew Operations

The principal difference between Mars exploration and previous space ventures is the requirement for crew operations in an environment where on-call communications, assistance, and advice from ground controllers is not available in emergencies due to the communications delay. This leads to a set of operations requirements that:

- The crew be able to perform autonomously for time-critical portions of the mission.

- Highly reliable, autonomous system operations be possible without intensive crew participation.

- A balance be struck between ground control and the crew on Mars which optimizes the crew's time and effectiveness yet maintains their independence and motivation to attain mission objectives.

Thus, the Reference Mission will be successful to the degree that ground and flight crews can execute all activities which lead to the accomplishment of mission objectives. All crew activities throughout each mission, from prelaunch through postlanding, constitute crew operations and as such are essential to the overall program. To enhance program success, they must be factored into all aspects of program planning. The majority of crew activities fall into one of four categories: training, science and exploration, systems operations and maintenance, and programmatics.

- Training includes activities such as development of training programs, development of training facilities and hardware, prelaunch survival training for all critical life support systems, operational and maintenance training on mission-critical hardware, prelaunch and in-flight proficiency training for critical mission phases, and science and research training for accomplishing primary science and exploration objectives.

- The majority of science and exploration activities will be accomplished on the surface of Mars and will include, but not be limited to, operating TROVs, habitability exercises, local and regional sorties, and planetary science investigations. Supplemental science objectives may be accomplished during other phases of the mission as well but will be limited by the mass available for onboard science equipment. Those activities required for crew health and safety (such as medical checks during

transit phases, monitoring solar activities for flares, etc.) will be performed.

- During the first mission, a substantial amount of crew time will be devoted to the operation and maintenance of vehicle systems. This time is expected to decrease during subsequent missions as both the systems and operational experience bases mature. However, maximizing the crew's useful science and exploration time will increase overall mission effectiveness, and the systems or procedures which contribute to increasing this time and decreasing routine operations and maintenance will be incorporated wherever possible.

- Lastly, programmatic activities for flight crews will include public relations, documentation, reporting, and real-time activity planning. Public relations activities have been and always will be an integral part of crew activities. While these activities absorb resources, the most significant of which is time, they also bring public and political support to the program and provide some of the return on investment of the program. Throughout all mission phases, documentation of activities and feedback on training effectiveness will be required of all crews. This will be essential to make effective use of the follow-on crew's training time and the program's training hardware and facilities. Many of the mission-critical activities will be planned and rehearsed in great detail

before each crew leaves Earth. However, once on the surface of Mars, the very nature of the work done by the crews will require real-time activity planning to take advantage of discoveries made as the mission progresses.

No specific conclusions regarding hardware requirements, facilities requirements, training programs, and the like were derived for this study. But a number of recommendations and guidelines regarding these areas have been developed and tailored to the various mission phases that will be experienced by each crew sent to Mars. While these and other crew activities may not be seen as directly affecting program success, all areas contribute to the successful execution of each mission and, therefore, are essential to the overall success of the Reference Mission.

1.3.3.8.2 Earth-Based Support

The overall goal of Earth-based support operations is to provide a framework for planning, managing, and conducting activities which achieve mission objectives. Achieving this operational goal requires successful accomplishment of the following functions.

- Safe and efficient operation of all resources. This includes, but is not limited to, vehicles, support facilities, training facilities, scientific and systems data, and personnel knowledge and experience bases.

- Provision of the facilities and an environment which allow users (such as scientists, payload specialists, and to an extent crew members) to conduct activities that will enhance the mission objectives.

- Successful management and operation of the overall program and supporting organizations. This requires defining roles and responsibilities and establishing a path of authority. Program and mission goals and objectives must be outlined so that management responsibilities are clear and direct. Confusing or conflicting objectives can result in loss of resources, the most important of which are time and money. In addition, minimizing the number of layers of authority will help to prevent operational decision-making activities from being prolonged.

The Reference Mission, while large and complex, has the added complication of being a program with mission phases which cannot be supported with near real-time operations. Planetary surface operations pose unique operational considerations on the organization of ground support and facilities. A move toward autonomy in vehicle operations, failure recognition and resolution, and mission planning is needed. And ground support must be structured to support these needs.

In general, due to the uniqueness of planetary surface operations, Earth-based support should be assigned the role of managing and monitoring operations planning and execution while crew members will be assigned the actual responsibility for operations planning and execution. Crew members will be told what tasks to do or what objectives to accomplish, but not how to do it. This has the benefit of involving system and payloads experts in the overall planning, yet giving crews the flexibility to execute the tasks. The proposed method for the Reference Mission would take advantage of the unique perspective of crew members in a new environment but would not restrict their activities because of the mission's remote nature. Additionally, it places the responsibility of mission success with the crew, while the overall responsibility for prioritizing activities in support of mission objectives resides with Earth-based support.

After dividing functional responsibilities between Earth-based support and crew, the support may be structured to manage the appropriate functions. To accomplish mission objectives while maintaining the first operational objective of safe and efficient operation of all resources, Earth-based support can be organizationally separated into systems operations and science operations provided a well-defined interface exists between the two. The systems operations team would be responsible for conducting the safe and efficient operation of all resources, while the science operations team would be responsible for conducting activities which support scientific research. Such an organizational structure would

dictate two separate operations teams with distinct priorities and responsibilities yet the same operational goal.

Systems operations are those tasks which keep elements of the program in operational condition and support productive utilization of program resources. Thus, the systems operations team has responsibility for conducting the safe and efficient operation of all such resources. The systems operations team consists of representatives from each of the primary systems (power, propulsion, environmental, electrical, etc.) which are used throughout the various mission phases.

The science operations team's sole function is to recommend, organize, and aid in conducting all activities which support scientific research within the guidelines of the mission objectives. The team will consist of representatives from the various science disciplines (biology, medicine, astronomy, geology, atmospherics, etc.) which support the science and mission objectives. Each scientific discipline will have an appropriate support team of personnel from government, industry, and academia who have expertise in that field. The science operations team will act as the decision-making body for all science activities—from determining which activities have highest priority to handling and disseminating scientific data.

Crew and vehicle safety are always of primary concern. When those are ensured, science activities become the highest priority. To accommodate this hierarchy of priorities within the operations management structure,

the overall operations manager should reside within systems operations. A science operations manager, who heads the science operations team, should organizationally be in support of the operations manager. Various levels of interfaces between systems engineers and science team members must exist to maximize the amount of science and mission objectives that can be accomplished.

1.3.3.9 Mission and Systems Summary

To summarize, the major distinguishing characteristics of the Reference Mission include:

- No extended LEO operations, assembly, or fueling.

- No rendezvous in Mars orbit prior to landing.

- Short crew transit times to and from Mars (180 days or less) and long surface stay-times (500 to 600 days) for the first and all subsequent crews exploring Mars.

- A heavy lift launch vehicle capable of transporting either crew or cargo direct to Mars, and capable of delivering in four launches all needed payload for the first human mission and in three launches for each subsequent opportunity.

- Exploitation of indigenous resources from the beginning of the program, with important performance benefits and reduction of mission risk.

- Availability of abort-to-Mars surface strategies, based on the robustness of the Mars surface capabilities and the cost of trajectory aborts.

- Common transit/surface habitat design.

- Maintenance of a robust, safe environment for crews throughout their exploration.

- Substantial autonomy of crew and system operations from ground control.

1.4 Testing Principal Assumptions and Choices

A number of assumptions and choices were made in constructing this Reference Mission. For each assumption, this section provides a top-level trade analysis, the rationale for the choice, and guidance to further research and development which could strengthen, improve, or change the choice.

1.4.1 Robust Surface Infrastructure

The principal payoff from Mars exploration lies in surface capability—stay-time, crew safety, exploration range, and other factors that characterize the crew's performance environment. All dictate a robust infrastructure. The choice to land all of the payloads and crews at the same site on four different opportunities was based on the assumption that the marginal cost of additional surface capability would be a cost-effective way to substantially increase the accomplishment of the program.

Two different approaches have been proposed in the past. The first is comparable to the Reference Mission by the long stay-time on the martian surface. The second involves a short stay-time (<30 days on the martian surface) mission. Table 1-1 characterizes principal discriminators of the two scenarios.

In most studies, the short stay-time missions have only been invoked for the first mission; to develop long stay-time capability would require close to total mission redesign and much higher cost for a continued program.

The second alternative is to land each crew at a different location. This scenario would be permitted by the capability defined in the Reference Mission. The principal trade-off is between the additional exploration that might be accomplished by exploring three distant sites versus the benefits of building up the capability to test settlement technologies (such as closed life support systems) and the reduced risk provided by accumulating surface assets at one site. As the range of exploration provided in the single location Mars outpost is high (hundreds of kilometers), the advantages of exploring several landing sites were considered of lower priority for the Reference Mission.

1.4.2 Split Mission Strategy

The split mission strategy takes advantage of the currently available capability to successfully fly and land automated spacecraft on another planet. Such capability can be used to deliver supplies and

Table 1-1 Principal Discriminators of Short and Long Stay-Time Mission Scenarios

	Long Stay-Times	Short Stay-Times	Key Discriminating Factor
Surface Accomplishment	High	Low	Difference in time on surface
Surface risk/day	Low	High	Robust vs. limited surface capability
Surface risk/cumulative	Low	Low	Difference of time vs. robustness
Interplanetary risk	Low	High	
Available to direct launch	Yes	No	
Available to split mission	Yes	Difficult	
Abort to Mars surface	Yes	No	
Availability of Mars at every opportunity	Yes	No	

equipment to support human missions without a crew being present. By using this capability to deliver cargo not absolutely necessary for transporting crews between Earth and Mars, the size of the transportation system (both launch vehicles and upper stages) for any one mission becomes smaller and thus less expensive to develop and manufacture. In addition, these cargo missions can be sent on the absolute minimum energy trajectories between Earth and Mars because there is no time-critical or life support critical element on board. However, the total number of launches increases under this strategy which offsets at least part of the cost savings due to the increased number of transportation elements that must be used.

The split mission strategy is contrasted with the "all-up" approach in which a single vehicle, assembled in LEO, is capable of landing the required assets in a single mission to the surface. The principal trade-off is between rendezvous and assembly in LEO and rendezvous on the Mars surface. For the all-up approach, significant capability is required in LEO to assemble and fuel the spacecraft. Previous designs (the 90-Day Study; see NASA, 1989) projected very high LEO infrastructure costs, which would have to be expended in the early phases of the program. For chemically propelled spacecraft,

the logistics of transporting, storing, and loading propellants was excessive and inevitably high in cost. Because the best departure orbit at Earth is different for each Mars opportunity, the space-based infrastructure would have to be moved or reproduced, or additional propulsion penalties be taken to modify the vehicle's departure orbit for every launch to Mars. The elimination of this element in the architecture provides a significant cost reduction. It has been assumed here that the capability of very precise landing on Mars can be developed technically, and that all assets for each flight can be integrated on Earth and simply joined on Mars. These capabilities can be demonstrated on precursor robotic missions.

While the savings resulting from a smaller transportation system may not alone be sufficient to invoke the use of the split mission strategy, the strategy does enhance another assumed element of the Reference Mission—the use of in situ resource utilization. By splitting the missions into cargo and crew flights, infrastructure can be set up and operated before committing a crew to a flight to Mars. Operating this infrastructure for an extended period prior to launching a crew also improves the confidence of using the Mars surface as a safe haven for the crew.

1.4.3 Nuclear Thermal Propulsion

High-performance propulsion is found to be an enabling technology for a human exploration program. Nuclear thermal

propulsion was selected because of its higher propellant utilization efficiency and because nuclear rockets were developed almost to flight status in the 1960s. For any given velocity change needed to depart from or be captured at a planet, a nuclear thermal rocket uses approximately 50 percent less propellant than the theoretical best chemical engine. (The Space Shuttle main engine is approaching this theoretical upper limit.) The vast majority of mass needed for a Mars mission is propellant, and any option that reduces the need for propellant can lower the program life cycle cost by reducing the size and number of launch vehicles. Although such rockets might be expensive to test on Earth (the magnitude of which has not been determined) with current environmental concerns, their use in space should not present an environmental issue for they are dangerous only after firing the engines for a significant period of time. Higher performance engines would be better, but typically require a large source of electrical power (from either a nuclear source or very large solar arrays) which calls for additional development to reach the same level of maturity as nuclear thermal rockets.

1.4.4 In Situ Resource Utilization

This technology (assumed to be currently available) has been developed at breadboard level and can be demonstrated on robotic missions. It provides significant benefits to the mission by reducing launch mass from Earth and increasing robustness of surface systems where caches of consumables and

surface vehicle fuels can be maintained. As discussed in the previous section, any technology that can reduce the amount of mass (and propellant is the largest single item on such a list) can do much to reduce life cycle cost. This is accomplished primarily by reducing the size and number of launches from Earth and by providing a dual purpose infrastructure that not only provides propellants for a return trip but also supports crew activities and helps reduce risk.

1.4.5 Common Habitat Design

A common habitat was chosen for the Reference Mission primarily to save on cost over the life of the program. Because seven separate habitats will be required to support the three crews sent to Mars, this item becomes a likely candidate for a common approach rather than designing, testing, and building separate systems for the interplanetary leg, the surface leg, and the transition between the two. It may not be feasible to use a common design for all of the components that make up a habitat. However, some of the significant elements—such as the pressure vessel (both primary and secondary structure), electrical distribution, hatches, and docking mechanisms—lend themselves to a common approach. Inasmuch as these major elements of the habitat can be defined and their cost estimated, a common design for the habitats has been adopted for the Reference Mission. A significant amount of work still remains on definition and design of interior details of the habitats which will become part of future efforts associated with Mars mission

planning. Study team members were not unanimous in the choice of a common habitat for space transit, for landing on the surface, and for surface habitation. Some argued that, due to the different requirements, a common design was not in the best interest of the mission. This is an area for further research.

1.4.6 Nuclear Surface Power

With no known natural resources on Mars that can be used to generate power, a crew exploring Mars must rely on either converting solar radiation or using a power source they have brought with them. With Mars lying, on average, 50 percent farther from the Sun as Earth, only 44 percent as much solar radiation reaches that planet. This means a crew must bring 2.25 times as much solar energy collecting and converting systems to generate the same amount of power as could be generated on Earth. Add to this a day-night cycle (which requires the addition of an energy charging and storage system) as well as martian dust storms (which significantly diminish the amount of light reaching the surface over extended periods of time) and the size of a solar power station on Mars becomes both large in area and mass and subject to interruption or diminished effectiveness due to the dust storms. Of those sources of energy that can be brought with the crews, only a nuclear power source can concentrate sufficient energy in a reasonable mass and volume. However, other concerns— environmental on Earth, operational on Mars, to name a few—are added to any mission that considers the use of a nuclear power source.

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Given these kinds of considerations, a choice was made to rely primarily on nuclear power for systems operating on the martian surface. Power provided by the solar arrays used during the transit to Mars will be available for backup and emergency situations. However, the solar arrays will not be sufficient to power the propellant manufacturing plants that are also a key feature of this mission architecture.

1.4.7 Abort to the Surface

Mars missions differ from Space Shuttle and lunar missions in that once the crew is committed to launch, orbit mechanics force the crew to remain away from Earth for approximately 2 to 3 years. This imposes on all of the systems the need for a higher degree of reliability and maintainability or for multiple independent means of providing life-critical functions (collectively referred to as robustness).

There has been a tendency to view the martian surface as the most hostile location for a crew during a Mars mission. However, of the three environments that a crew will encounter—Earth, interplanetary space, and the martian surface—interplanetary space offers the highest potential for debilitating effects on the crew. Practicality dictates a relatively small habitable space for the crew during transit. To do otherwise causes a corresponding increase in the size and cost of the systems, primarily launch vehicles and transfer stages, associated with the transportation system. But to confine the crew

to a small habitable space for an extended duration can lead to cabin fever. Zero g has known debilitating effects on the human body that must be addressed. Radiation from a constant background and the threat of solar flares require that protection be adequate for background sources and that a safe haven be provided for extreme events. All of these threats have engineering solutions that can make the extended stay in interplanetary space a viable prospect for the crew. But the solutions typically require increases in size, mass, and complexity of the vehicle and the transportation elements that are used to move it from planet to planet.

An alternate strategy, and one that was selected for this Reference Mission, is to take advantage of the martian surface as a safe haven where open space, gravity, and radiation protection are naturally available. This strategy, referred to as "abort to the surface," builds on these naturally available resources and breaks from the previous viewpoint of Mars as the most hostile environment encountered on the mission. The reliability and maintainability of the systems needed to keep the crew alive on the surface is no greater than that imposed on space-based systems. In fact, the buildup of an infrastructure at a single site on the surface enhances the safe haven character of the martian surface. This approach places a greater burden on the entry, landing, and martian-based launch systems. However, the trade-off of making these systems a viable part of the abort strategy through increased

redundancy and reliability versus the enhancements needed to sustain a crew through a 2- to 3-year interplanetary abort have tended to favor the abort to the surface strategy. The enhancements that will be made to various systems to allow an abort to the surface also work to the advantage of the overall mission by improving the chances of the crews to successfully reach the surface and perform their exploration activities.

1.4.8 *Design for the Most Difficult Opportunity*

The design of the Reference Mission was based on the premise that a series of closely spaced missions would result in costs significantly lower than the sum of an equivalent number of single missions. To achieve this cost savings requires that a single set of systems be designed which can accomplish the mission under the most difficult circumstances of any single opportunity. The most significant of these variations results from trajectory differences that occur during sequential mission opportunities. As a result, some systems may have excess capability during some years. However, this allows the advantage of either launching more payload mass in those years with more favorable trajectories or reducing mission durations by flying shorter trajectory legs, but at the expense of greater fuel consumption. For example, in the 2009 opportunity, transit times for piloted missions are approximately 6 months; using the same systems in the 2018 opportunity reduces transit times to just 4 months.

1.5 Conclusions and Recommendations

Based on both mission and programmatic points of view, a number of conclusions and recommendations are made in the following areas: mission and systems, technology development, environmental protection, program cost, international participation, and program management and organization.

1.5.1 *Mission and Systems*

Conclusions

A feasible mission scenario and suite of vehicles and other systems have been integrated to meet the objectives initially set out for this study. In addition, the Reference Mission addresses a long-standing issue regarding extended-duration flights and crew safety by adopting a view that the surface of Mars is a safe haven and that equipment and procedures should be developed with this in mind.

The Reference Mission includes technology assumptions which require further development and which contribute to an estimated development cost that is higher than can currently be supported. Both technology and cost must be addressed and the alternative missions and systems could result in a better program for human exploration of Mars. However, the mission and systems described here substantially reduce the program cost and at the same time present a more robust approach than in previous studies of this subject.

Recommendations

- Use this study as an informal baseline against which future alternatives should be compared.

- Continue investigating alternative mission scenarios and systems to improve this Reference Mission, or suggest a better alternative.

1.5.2 Technology Development

Conclusions

The Reference Mission was developed assuming advances in certain technology areas thought to be necessary to send people to Mars for a reasonable investment in time and resources. The Reference Mission is not intended to lock in these assumed technologies. The purpose of identifying technologies at this time is to characterize those areas that can either significantly reduce the required mass or cost of the program or significantly reduce its risks (for example, in the area of fire safety). Alternative means of satisfying these requirements may be identified and, if promising, should be supported. The alternatives could be the result of a dual use development, spin off from other programs, or a fortunate "spill over" from some unexpected area.

At this particular stage in developing human exploration missions to Mars, it is difficult to do more than speculate about spin off and spill over technologies that could result from or be useful to this endeavor. However, identifying dual uses for some of the assumed technologies can be started now and, to a certain degree, may be required for such a program to progress. In the current political environment, investment in technology is seen as a means of improving the general quality of life for people on Earth, and multiple use of technologies is emphasized to obtain the best return on the resources invested in their development. The following is a list of twelve technologies which are important to space transportation, humans living in space or on a planetary surface, or the utilization of extraterrestrial resources.

Resource Utilization

- Extraterrestrial mining techniques

- Resource extraction process and chemistry

- Material preparation and handling in reduced gravity

- Extraterrestrial manufacturing

Transportation and Propulsion

- Advanced chemical systems that provide high performance and are compatible with the resources available on the Moon and Mars

- Nuclear propulsion to enable short trip times to Mars

- Aerocapture/aerobraking at the Earth and at Mars for propulsive efficiency and reusable systems

- Lightweight/advanced structures

- Reduced-g combustors

Cryogenic Fluid Management

- Long-term (years) storage in space
- Lightweight and high efficiency cryogenic liquefaction
- Zero g and microgravity acquisition, transfer, and gauging

EVA Systems

- Lightweight, reserviceable, and maintainable suit and PLSS
- Durable, lightweight, high mobility suits and gloves

Regenerative Life Support Systems

- Contamination and particle control
- Loop closure
- Introduction of locally produced consumables
- Food production
- Trash and waste collection and processing
- High efficiency and lighter weight active thermal control systems

Surface Habitation and Construction

- Lightweight structures
- Seal materials and mechanisms
- Construction techniques using local materials

Human Health and Performance

- Zero-g adaptation and countermeasures
- Human factors
- Health care at remote locations
- Radiation protection in transit and on surface

Power Generation and Storage

- Long life, lighter weight, and less costly regenerative fuel cells
- Surface nuclear power of the order of 100kw
- High efficiency solar arrays

Teleoperations/Telerobotics

- Remote operations with long time delays
- Fine control manipulators to support wide range of surface activities
- Telepresence sensors and displays

Planetary Rovers

- Long range (hundreds of km) rovers
- Motor lubricants (long-term use)
- Dust control
- High efficiency lightweight power generation and storage

Advanced Operations

- Automated systems control
- Systems management and scheduling
- Simulations and training at remote locations

Fire Safety

- Fire prevention
- Fire detection
- Fire suppression

Some of these technologies (such as nuclear thermal propulsion, Mars surface space suits, and in situ resource extraction), at the system level, are unique to the Reference Mission or to human space exploration in general. It is likely that NASA or cooperating international partners will have to bear the burden for support of this research and development. The Reference Mission, as it is described here, will fail if these systems are not advanced to a usable state. Other areas, such as medical countermeasures, closed-loop life support systems, autonomous operations systems, surface power systems, and surface mobility, may be of more general interest and may provide opportunities for government and industry to develop shared programs. In still other areas, such as long-lived electronics and materials research, where the underlying research will probably be done by industry to address general problems of technology development, NASA or the international partners should focus on infusing that technology. The exchange of information should be continuous between NASA and the commercial sector particularly concerning the needs of future missions, so that industry can incorporate research into its privately funded programs where it is justified. In all areas, subsystem or component technologies may be developed by industry to meet commercial requirements, and the Mars Program will need to have processes that allow the element designers to use the most advanced capabilities available.

Recommendations

• Establish a Mars Program Office (discussed further under International Participation and Management and Organization) early in the process (now, probably) at a low level to lay the foundation for technology requirements to be undertaken by NASA or other government agencies with similar requirements. Formal organizational agreements should exist between these offices if the technology development is not formally assigned to the Program Office.

• Rank technology investments according to their return to the Program, as either cost or risk reductions.

• Prior to initiation of the Reference Mission, take critical technologies to a demonstration stage. NASA should ensure that experimental work in support of the Reference Mission is incorporated into the International Space Station program at the earliest reasonable time.

• Create a database (in the Program Office) of available technologies that can be used in design studies, and track the progress of these technologies. The database should include domestic and international capabilities.

1.5.3 *Environmental Protection*

Conclusions

Fundamental principles of planetary environmental protection have been developed since the first planetary exploration missions began in the 1960s. With respect to Mars, the principles adopted by the international scientific community are straightforward: Mars should be protected from biological contamination from Earth that would interfere with or confound the search for natural martian organisms, and Earth must be protected from contamination by martian organisms harmful to the terrestrial biosphere. The United States is signatory to a treaty under the auspices of the Committee on Space Research (COSPAR) which provides the basic framework for its Planetary Protection policy and program (COSPAR 1964 and United Nations 1967).

Planetary protection will be an ongoing discussion at an international level. The policy principles stated here and those that evolve in the future must be carried along as significant requirements for mission planning and system design.

A further political concern is unfortunately tied to the planet Mars. A significant portion of the popular press and the entertainment industry is devoted to speculation about life, intelligent and otherwise, that may exist beyond the planet Earth. Percival Lowell, H. G. Wells, Orsen Wells, and others have placed Mars in the forefront of possible locations for extraterrestrial life. NASA itself has contributed to this perception by supporting legitimate scientific research in this area. Because it is not possible to prove that Mars is completely devoid of life, there is the potential for misinterpretation or misunderstanding when martian materials and human crews are brought back to Earth. For example, an ailment (regardless of the source) among a returning human crew could give rise to speculation that the crew has some unknown Mars "bug" and is about to expose the rest of the human population to its effects.

Recommendations

- Develop adequate and acceptable human quarantine and sample handling protocols early in a Mars exploration program. The protocols must address not only the purely scientific concerns to maintain the pristine nature of samples but also the societal concerns, real or imagined, that are likely to arise.

- Include the protocols as program-level requirements for mission and system development.

- Publicly release for review (by independent authoritative bodies) the principles and practices of contamination control in effect for Mars missions.

1.5.4 Program Cost

Conclusions

The cost of the Reference Mission was estimated using standard models. Input for these models was derived from previous experience and information provided by members of the Study Team. Included in the estimate were the development and production costs for all of the systems needed to support three human crews as they explore Mars. In addition, ground rules and assumptions were adopted that incorporated some new management paradigms, as discussed later in the Program Management and Organization section. The management costs captured program level management, integration, and a Level II function. Typical pre-production costs, such as Phase A and B studies, were also included.

Not included in the cost estimate were selected hardware elements, operations, and management reserve. Hardware costs not estimated include science equipment and EVA systems, for which data were not available at the time estimates were prepared; however, these are not expected to add significantly to the total. No robotic precursor missions are included in the cost estimate although their need is acknowledged as part of the overall approach to the Reference Mission. Operations costs have historically been as high as 20 percent of the development cost. However, due to the extended operational period of the Reference Mission and the recognized need for new approaches to

managing and running this type of program, estimating the cost for this phase of the program was deferred until an approach is better defined. Similarly, the issue of management reserve was not addressed until a better understanding of the management approach and controls has been developed.

When compared to earlier estimates of a similar scale (NASA, 1989), the cost for the Reference Mission is approximately an order of magnitude lower. A distribution of these costs is shown in Figure 1-6. It can be seen from this figure that the major cost drivers are those associated with the transportation elements: the ETO launch vehicles, the TMI stages, and the Earth-return systems.

The Mars Study Team recognizes that, even with the significant reduction in the program cost achieved by this Team, the Reference Mission is probably still too expensive in today's fiscal environment. More work to further reduce these costs is needed.

Recommendation

- Seek alternative solutions or effective approaches to cost reduction in each of the areas cited above. The efforts may require revolutionary changes throughout NASA, the aerospace industry, the United States, and the world.

1.5.5 International Participation

Conclusions

The human exploration of Mars should be inherently an international, indeed a global, undertaking. Just as the U. S. landing on the Moon excited and amazed the world at U. S. technological skills and organizational accomplishment, the human exploration of Mars can excite and amaze the people of the world with a commonly sought level of technological prowess and organizational capability. The International Academy of Astronautics' International Mars Exploration Study (IAA 1993) describes in more detail the rationale and possible organizational approaches to an international Mars exploration program.

The Reference Mission is rich in possibilities for multinational or even global participation. Many major elements, systems, and subsystems will have to be developed and produced, precursor missions must be developed and flown, and operations capabilities must be developed; and the mission operations can be designed to be undertaken on an international basis. Three types of international participants may
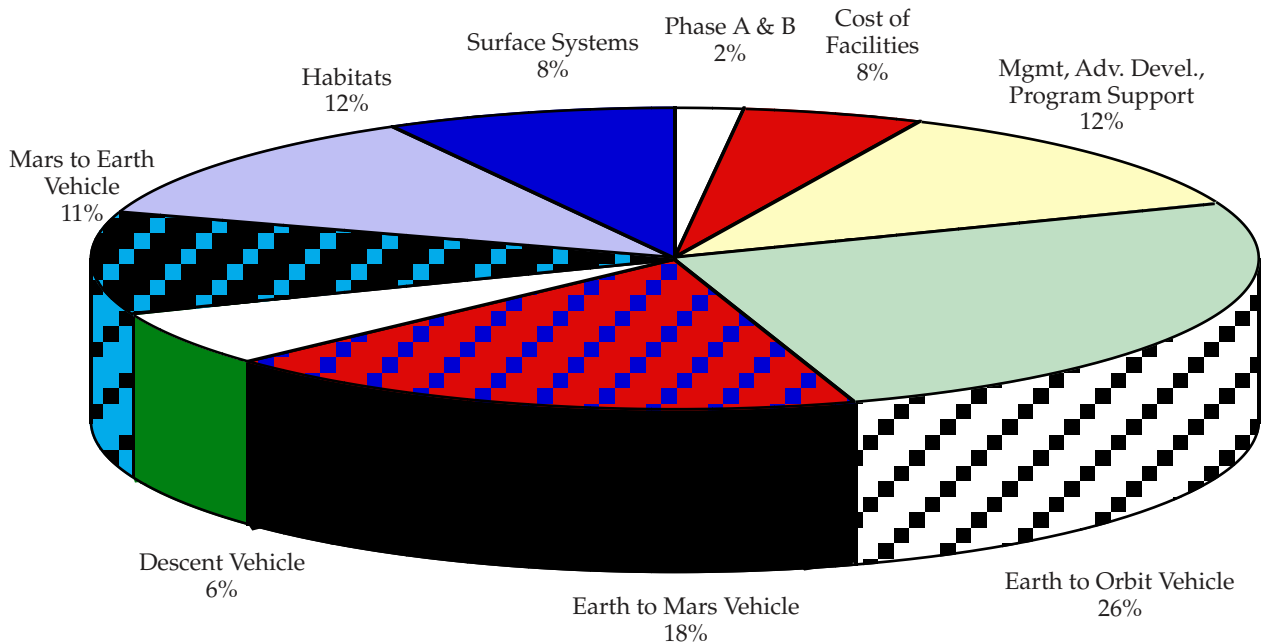
Figure 1-6 Distribution of Reference Mission costs.

contribute based on the ability to provide resources and participate technically in the program.

- Countries with limited resources and technical base. Their participation could be linked to technology transfer to their countries, which could improve the level of technical education and take advantage of technical internship in the endeavor. These relationships might be similar to the participation of Cuba or Viet Nam in the Russian space program.

- Countries with greater amounts of resources and technical base. Their participation would reflect technical interest in limited areas targeted for technical or industrial growth in their economies. The participation of Canada in the International Space Station program is an example.

- Countries with substantial resources and technical base. Their participation would reflect a desire to demonstrate world leadership, retain broad technological skills, and promote aerospace industry. The major contributors to the International Space Station program fall into this category.

All participating countries should expect to gain in proportion to their investment in the enterprise; richer countries might view the program as an opportunity to help poorer countries improve their standards of living through stimulation and transfer of modern technology and technological training.

The ranges of opportunities and interests are large and must be well understood before an international program is constructed. The discussions may be iterative with respect to initial design in order to optimize the collective returns to all nations in the program, and it is not unlikely that 10 years would be needed to formulate the principles and agreements needed to undertake the program. It is important that these discussions lead to a set of basic principles under which the program will be designed and implemented.

Recommendations

- Make the human exploration of Mars program international from its inception, and take as a basic principle that all partners will have a voice in all phases of the program in proportion to the resources contributed to the program.

- Do not exclude any nation even though their participation might be small in economic terms.

- Create a forum in the near future for discussion of the elements of an international program to lay the basis for international participation.

- Create an International Program Office (sensitive to political and technical issues) to lead the design effort. Just as it is important to have all of the design requirements understood prior to development, all of the political requirements must also be understood early in the process.

1.5.6 Program Management and Organization

Conclusions

Organization and management is one of the principal determinants of program cost. This is a rather wide-ranging topic, which is not entirely divisible from the technical content of the program, because it includes program level decision-making that is intimately tied to the system engineering decision-making process. The relationship between program cost and program culture (Figure 1-7) is an indication of that relationship.

The relationship between cost and management style and organizational culture is rather well-known in a general manner, through a large number of "lessons learned" analyses made postprogram. The list of key elements of lower-cost programs (shown in Table 1-2) have been pointed out in a series of analyses, but have not commonly been applied at the critical stage of developing program organization and management approaches. The organizational and management style has been determined rather late in the program, generally because the program content and final design was typically delayed through redesign, changing requirements, and funding irregularities. For example, the International Space Station program went through several redesigns, and some of the hardware was actually in production when the program architecture was modified to integrate the Russian and Space Station Freedom programs. To manage a Mars exploration program to a lowest possible cost, several recommendations are proposed.

Recommendations

• In subsequent studies of the Reference Mission, investigate the design of the organization and management system.

• Reach a formal philosophical and budgetary agreement (between all parties) as to the objectives and requirements imposed on the mission before development is initiated, and agree to fund the project to its completion. In the U. S., this would include multiyear budgetary authority. This should be accompanied by a management process that would protect against program overruns through appropriate incentives.

• Prepare a risk management plan. The human exploration of Mars will have risks that are quite different from any space mission previously undertaken. Two general types of
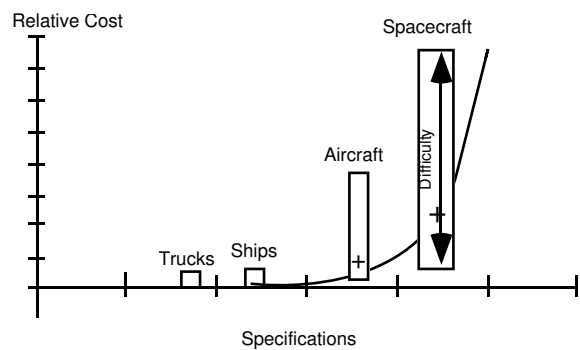
Figure 1-7 Relationship between program cost and program culture.

risk seem to be most critical: risks to the safety of the crew and accomplishment of the mission (primarily technical risks) and risks of not meeting cost and schedule objectives. Maintaining launch schedule is important due to the dependency on several successful launches for mission success and the high cost of missed launch windows. Failure to maintain the launch schedule implies a 2-year program delay at a potentially high program cost.

- •Establish a clear demarcation between the design phase and the development and production phase of the project, and do not allow development to begin before the design phase is ended. Prove all technologies prior to initiating production of program elements. Do not change requirements after they are established unless they can be relaxed. Ensure that a system to document the relationship and interaction of all requirements exists and is available for

Table 1-2 Key Elements of Lower-Cost Programs

- •Use government only to define requirements.
- •Keep requirements fixed: once requirements are stated, only relax them; never add new ones.
- •Place product responsibility in a competitive private sector.
- •Specify end results (performance) of products, not how to achieve the results.
- •Minimize government involvement (small program offices).
- •Ensure that all technologies are proven prior to the end of competition.
- •Use the private sector reporting system: reduce or eliminate specific government reports.
- •Don't start a program until cost estimates and budget availability match.
- •Minimize or eliminate government-imposed changes.
- •Reduce development time: any program development can be accomplished in 3 to 4 years once uncertainties are resolved.
- •Force people off of development programs when development is complete.
- •Incentivize the contractor to keep costs low (as opposed to CPAF, CPFF of NASA).
- •Use geographic proximity of contractor organizations when possible.
- •Use the major prime contractor as the integrating contrator.

use prior to the beginning of production. The Reference Mission requires a number of elements, many of which are technically alike but serve somewhat different functions over the duration of the program. For example, the surface habitat may be the basis for the transit habitat; each of the habitats delivered to the surface will have a different complement of equipment and supplies, according to its position in the delivery sequence. The elements will be developed over a period of several years, and there will be a temptation to improve the equipment and supply manifest. To maintain cost control for the program, requirements must be fixed at the time of initial development.

• Provide clear requirements for the design phase, describing the performance expected and a clear set of criteria for completeness of design as a function of resources expended in design. Use a significant design cost margin to manage the design resources. Terminate the project if a satisfactory design cannot be accomplished within the available resources. Further, select the successful prime contractor as integration contractor for the development phase, and exclude the prime contractor as a development contractor. The design phase of the program is critical to successful cost control, and should be based on a set of functional requirements established by the Program Office (which may well be a multinational activity). The Program Office will be in place to manage technical requirements, provide decisions that require consultation and trade-offs (both technical and political), and manage development contracts. The Program Office should establish functional requirements for the design phase and conduct a competitive procurement for the design phase, with the selection of a prime contractor.

• Prepare a specific construction sequence and plan to accompany each production element of the program. Once committed to development, the development time should be strictly limited if costs are to be contained. This will be difficult in the Mars program, where it probably will be effective to produce common elements sequentially rather than all at one time, although there may be a high enough production rate that costs will drop as experience is gained. A new approach will be needed to ensure that the development time for each individual element is strictly limited.

• Make the two levels of integration, program and launch package, the responsibility of a single organization—a prime contractor to the Program Office. The program will require two levels of integration, similar to that of the International Space Station program: a program level which ensures that overall mission requirements are met at each

stage of the mission, that is, for the packages assembled for each launch opportunity; and a launch package level integration, in which all required elements of each launch to Mars are packaged and their performance ensured.

- Include operational considerations in the design and development phases of the program, and use life cycle costs for program design and development decisions. The operational phase of the Mars program must be represented in the design and development phase. This will require a concurrent engineering approach which considers the operational costs as well as the development costs in a life cycle cost approach to the program. If the approaches identified above to separate design and development and to obtain prior commitments for funding for the entire program are successful, there should be less of a problem maintaining the life cycle cost approach to minimizing program costs.

- Put into place positive incentives to maintain program costs within approved levels at all stages of design, development, production, and operations, and to reduce costs of each phase of the program.

1.6 References

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2. Science and Exploration Rationale

2.1 Introduction

Mars is an intriguing and exciting planet with many adventures and discoveries awaiting planetary explorers. But before we go, we must provide the tools the explorers will use, anticipate as much as possible the situations they will encounter, and prepare them for the unexpected. For the first time in a space exploration mission, it will be up to the crew and supporting personnel on Earth to create specific activities as the mission progresses and discoveries are made. The length of time spent on the martian surface, as presented in the Reference Mission, will preclude development of the detailed, highly choreographed mission plans typical of today's space missions. The crew will have general goals and objectives to meet within their other time constraints (for example, exercise for health maintenance, regular medical checks, routine systems maintenance, etc.). Based on knowledge gained from precursor robotic missions, the crew will land in an area that has a high probability of satisfying the pre-set mission objectives. However, due to the extended communications time lag between Earth and Mars, the crews and their systems must be able to accomplish objectives in a highly autonomous manner with only general support from Earth. From the rationale generated by the Mars Study Team for sending human crews to Mars, goals and objectives are derived to provide guidance for the exploration crews during their extended stay on the martian surface. This section will discuss that Study Team rationale.

2.2 The "Why Mars" Workshop

In August 1992, a workshop was held at the Lunar and Planetary Institute in Houston, Texas, to address the "whys" of Mars exploration. This workshop brought together a group of experts (listed in Table 2-1) familiar with the key issues and past efforts associated with piloted Mars missions in an effort to provide the top-level rationale and requirements from which the Mars exploration program could be built (Duke and Budden, 1992). This group was asked to generate three key products: a Mars mission rationale, Mars exploration objectives, and a list of key issues and constraints, to be used by the Mars Study Team (members listed in Table 2-2) to define the technical details of a Reference Mission. The workshop attendees identified six major elements of the rationale for a Mars exploration program.

Table 2-1 Mars Exploration Consultant Team

Dr. David Black Director Lunar and Planetary Institute Houston, Texas	Dr. George Morgenthaler University of Colorado Boulder, Colorado
Dr. Michael Carr U.S. Geological Survey Menlo Park, California	Dr. Robert Moser Chama, New Mexico
Dr. Ron Greeley Dept. of Geology Arizona State University Tempe, Arizona	Dr. Bruce Murray California Institute of Technology Pasadena, California
Dr. Noel Hinners Lockheed Martin Denver, Colorado	Mr. John Niehoff Science Applications International Corporation Schaumburg, Illinois
Dr. Joseph Kerwin Skylab Astronaut Lockheed Martin Houston, Texas	Dr. Carl Sagan Center for Radiophysics and Space Research Cornell University Ithica, New York
Mr. Gentry Lee Frisco, Texas	Dr. Harrison Schmitt Apollo 17 Astronaut Albuquerque, New Mexico
Dr. Roger Malina Center for EUV Astrophysics University of California Berkeley, California	Dr. Steven Squyers Cornell University Ithica, New York
Dr. Christopher McKay NASA Ames Research Center Moffett Field, California	Mr. Gordon Woodcock Boeing Defense and Space Group Huntsville, Alabama

Table 2-2 Mars Study Team

Dr. Geoff Briggs NASA Ames Research Center Moffett Field, California	Mr. Kent Joosten NASA Johnson Space Center Houston, Texas
Ms. Jeri Brown NASA Johnson Space Center Houston, Texas	Mr. David Kaplan NASA Johnson Space Center Houston, Texas
Ms. Nancy Ann Budden NASA Johnson Space Center Houston, Texas	Dr. Paul Keaton Los Alamos National Laboratory Los Alamos, New Mexico
Ms. Beth Caplan NASA Johnson Space Center Houston, Texas	Mr. Darrell Kendrick NASA Johnson Space Center Houston, Texas
Mr. John Connolly NASA Johnson Space Center Houston, Texas	Ms. Barbara Pearson NASA Johnson Space Center Houston, Texas
Dr. Michael Duke NASA Johnson Space Center Houston, Texas	Mr. Barney Roberts NASA Johnson Space Center Houston, Texas
Dr. Steve Hawley NASA Johnson Space Center Houston, Texas	Mr. Ed Svrcek NASA Johnson Space Center Houston, Texas
Mr. William Huber NASA Marshall Space Flight Center Huntsville, Alabama	Mr. David Weaver NASA Johnson Space Center Houston, Texas

• Human Evolution – Mars is the most accessible planetary body beyond the Earth-Moon system where sustained human presence is believed to be possible. The technical objectives of Mars exploration should be to understand what would be required to sustain a permanent human presence beyond Earth. However, it is not an objective of the Reference Mission to settle Mars but to establish the feasibility of, and the technological basis for, human settlement of that planet.

- Comparative Planetology – The scientific objectives of Mars exploration should be to understand the planet and its history to better understand Earth.

- International Cooperation – The political environment at the end of the Cold War may be conducive to a concerted international effort that is appropriate, and may be required, for a sustained program.

- Technology Advancement – The human exploration of Mars currently lies at the ragged edge of achievability. Some of the technology required to achieve this mission is either available or on the horizon. Other technologies will be pulled into being by the needs of this mission. The new technologies or the new uses of existing technologies will not only benefit humans exploring Mars but will also enhance the lives of people on Earth.

- Inspiration – The goals of Mars exploration are bold, are grand, and stretch the imagination. Such goals will challenge the collective skill of the populace mobilized to accomplish this feat, will motivate our youth, will drive technical education goals, and will excite the people and nations of the world.

- Investment – In comparison with other classes of societal expenditures, the cost of a Mars exploration program is modest.

The workshop attendees then translated these elements into two specific mission objectives. For the first human exploration of Mars:

- A better understanding is needed of Mars—the planet, its history, and its current state. And to answer, as best as possible, the scientific questions that exist at the time of the exploration, a better understanding of the evolution of Mars' climate and the search for past life are pressing issues.

- It is important to demonstrate that Mars is a suitable location for longer term human exploration and settlement.

The following sections discuss the details of the science and exploration rationale as applied to the Reference Mission. Implementation details are in Section 3.

2.3   Science Rationale

Mars is an intriguing planet in part for what it can tell us about the origin and history of planets and of life. Visible to the ancients and distinctly reddish in the night sky, it has always been an attractive subject for imaginative science fiction. As the capability for space exploration grew in the 1960s, it became clear that, unlike Earth, Mars is not a planet teeming with life and has a harsh environment. The images of Mariner 4 showed a Moon-like terrain dominated by large impact craters (Figure 2-1).

Figure 2-1 Orbital image of Mars.

This terrain now is believed to represent ancient crust, similar to the Moon's, formed in an initial period of planetary differentiation. Mariner 9 showed for the first time that Mars was not totally Moon-like, but actually exhibits later volcanic and tectonic features. Large volcanoes of relatively recent activity (Figure 2-2) and large crustal rifts due to tensional forces (Figure 2-3) demonstrate the working of internal forces.

Figure 2-2 Olympus Mons, the largest volcano in the solar system.

*Figure 2-3 Across the middle is Valles Marineris, a huge canyon
as long as the United States.*

The absolute time scale is not accurately calibrated; however, by analogy with the Moon, the initial crustal formation may have occurred between 4 billion and 4.5 billion years ago, and the apparent freshness of the large martian volcanoes suggests their formation within the last billion years.

Many scientific questions exist regarding Mars and its history and will continue to exist long after the first human missions to the planet have been achieved. Two key areas of scientific interest are the evolution of martian climate and the possible existence of past life.

Mars' atmosphere now consists largely of carbon dioxide with a typical surface pressure of about 0.01 of Earth's atmosphere (comparable to Earth's atmospheric pressure at an altitude of approximately 30,000 meters or 100,000 feet) and surface temperatures that may reach 25°C (77°F) at the equator in midsummer, but are generally much colder. At these pressures and temperatures, water cannot exist in liquid form on the surface. However, Mariner 9 and the subsequent Viking missions observed features which indicate that liquid water has been present on Mars in past epochs (Figure 2-4).

Evidence for the past existence of running water and standing water has been noted, and the interpretation is that the atmosphere of Mars was thicker and warmer—perhaps much like Earth's early atmosphere before the appearance of oxygen. Three questions arise:

- What was the reason for the change of atmospheric conditions on Mars?

- What are the implications of such changes for environmental changes on Earth?

- Were the conditions on early Mars enough like those of early Earth to guide a search for past life?

These questions are part of the Mars scientific exploration addressed by the Reference Mission, and these questions can be answered only by understanding the geological attributes of the planet: the types of rocks present, the absolute and relative ages of the rocks, the distribution of subsurface water, the history of volcanic activity, the distribution of life-forming elements and compounds, and other geologic features. These attributes all have to be understood in the context of what we know about the Earth, the Moon, and other bodies of our solar system.

Addressing the question of whether life ever arose on Mars can provide a fundamental framework for an exploration strategy because, in principle, the search for past life includes investigating the geological and atmospheric evolution of the planet. It is generally understood that the search for evidence of past life cannot be conducted simply by a hit-and-miss landing-and-looking strategy, but must be undertaken in a step-wise manner in which geological provenances that might be suitable are characterized, located, and studied (Exobiology Program Office, 1995). The characteristics of suitable exploration sites are highly correlated with the search for past or present water on the

Figure 2-4 Dense tributary networks indicative of past presence of liquid water on Mars.

planet. Within the geological framework, strategic questions related to the search for evidence of life can be posed.

- What is the absolute time scale for development of the major features on Mars? This would include determining the time of formation of the martian crust, a range of formation ages for volcanic plains, and the age of the youngest volcanoes. With this information as a guide, the age of formation of water-formed channels should be boundable, and the organogenic element content of martian materials as a function of time may be obtainable. As is inferred from the SNC meteorites which are believed to have originated on Mars (Bogard, et al., 1983 and McSween, 1994), impacts on Mars have preserved samples of the martian atmosphere in shock-produced glasses. Thus, it may be possible to characterize the evolution of the atmosphere from carefully selected samples of impact glass.

- What is the evidence for the distribution in space and time of water on the surface? This would include water combined in widely distributed igneous or clay minerals, in localized deposits such as hydrothermal vents, in subsurface permafrost, in the polar caps, and in the atmosphere. The distribution, age, composition, and mode of formation (minerals formed by reaction with or deposition from heated or cool

aqueous fluids, as found in the SNC meteorites) is of major interest. Can the channels apparently formed by water erosion be demonstrated to have experienced running water? Is there verifiable evidence for the existence of ponds of water? What is the distribution of subsurface permafrost, and can the features interpreted as permafrost collapse be verified?

- What are the distribution and characteristics of carbon and nitrogen—the organogenic elements? Where do they exist in reduced form? In what environments are they preserved in their original state? Is there chemical, isotopic (hydrogen, carbon, nitrogen isotopes), or morphological evidence that will link concentrations of organogenic elements to the past existence of life?

- If organic remains can be found, how extensive are they in space and time? What are their characteristics, variety and complexity? How are they similar or different to biological materials on Earth?

Answers to these questions may be sought through orbital mapping (for example, to determine the distribution of hydrothermal mineral deposits), in situ studies (surface mineralogy, distribution of volatile elements), sample return (age of rock units, detailed chemistry, mineralogy, and isotopic composition), and human exploration with sample return (similar but with more highly intelligent sample collection). The scientific

community debates the precise order of investigative means used to achieve this strategy, but generally concludes that the question of distribution of past life will be of such a difficult nature that sample return will be required and that humans will ultimately choose to carry out the exploration in person.

Given the assumption that humans will take on the bulk of this type of exploration, the key questions become:

- What is the appropriate role and place in the exploration strategy of robotic sample return missions?

- Scientifically, where is the appropriate transition from robotic missions, conducted routinely, and human exploration missions, which may be singular, large, and not reproducible?

General guidelines are needed to answer these questions. Sample return missions should be favored when they can be used to significantly reduce the number of subsequent missions to address the geological modeling of the planet. Sample return missions are likely to be more expensive than one-way missions, so to be cost effective, they must reduce the need for a proportionally larger number of subsequent missions or garner otherwise unobtainable information if their justification is purely scientific. From a scientific perspective, the guidelines for human exploration are similar. If a human exploration mission promises to answer the major strategic questions better than a larger number of robotic explorers, or opens new

modes of exploration that cannot be achieved robotically, then the human mission will be cost effective on scientific grounds.

2.4   Exploration Rationale

Aside from purely scientific benefits, the human exploration of Mars brings with it many tangible and intangible near-term benefits such as:

- New associations between groups or disciplines which previously have not interacted, but because of common objectives in exploration find new strengths and opportunities (for example, new international cooperation).

- New technologies which may be used for practical application on Earth or in other space enterprises (dual-use technologies).

- Education of a new generation of engineers and scientists spurred by the dream of Mars exploration.

In the long term, the biggest benefit of the human exploration of Mars may well be the philosophical and practical implications of settling another planet.

2.4.1   Inhabiting Another Planet

The dream of human exploration of Mars is intimately tied to the belief that new lands create new opportunities and prosperity. In human history, migrations of people have been stimulated by overcrowding, exhaustion of resources, the search for religious or

economic freedom, competitive advantage, and other human concerns. Rarely have humans entered new territory and then completely abandoned it. A few people have always been adventurous enough to adopt a newly found territory as their home. Most of the settlements have eventually become economically self-sufficient and have enlarged the genetic and economic diversity of humanity. The technological revolution of the twentieth century, with high speed communication and transportation and integrated economic activity, may have reversed the trend toward human diversity; however, settlement of the planets can once again enlarge the sphere of human action and life.

Outside the area of fundamental science, the possibility that Mars might someday be a home for humans is at the core of much of the popular interest in Mars exploration. A human settlement on Mars, which would have to be self-sufficient to be sustainable, would satisfy human urges to challenge the limits of human capability, create the potential for saving human civilization from an ecological disaster on Earth (for example, a giant asteroid impact or a nuclear incident), and potentially lead to a new range of human endeavors that are not attainable on Earth.

The settlement of Mars presents new problems and challenges. The absence of a natural environment that humans and most terrestrial fauna and flora would find livable and the current high cost of transportation are the main barriers to human expansion there.

The fact that, once on Mars, humans cannot easily return to the Earth (and then only at specified times approximately 26 months apart) makes it necessary to develop systems with high reliability and robustness.

At the present level of human technological capability, a self-sufficient settlement on Mars stretches our technical limits and is not economically justifiable, but it is imaginable. If, however, transportation costs were to be reduced by two orders of magnitude, such settlements might become economically feasible. What kind of strategy should be followed to explore the concept of humans permanently inhabiting Mars? Three considerations are important.

- Demonstrating the potential for self-sufficiency. This would include understanding the potential to obtain all important materials to support human habitation from the natural materials of Mars. It is most important that humans be able to capture energy for driving processes and have access to natural resources (such as water, oxygen, agricultural raw materials, building materials, and industrial materials) from martian rocks and soil. Demonstrating self-sufficiency requires that resources be located and technology and experience be developed to efficiently extract them from the in situ materials. Much can be done robotically to locate resources prior to arrival of the first human crew. Extraction technology depends on a more detailed understanding of the

specific materials present on Mars and requires the detailed mineralogical and chemical analyses generally associated with sample return missions. An exception is the production of water, methane, and oxygen from the martian atmosphere, which is now known well enough to design extraction technology (Sullivan, et al., 1995). In addition to the extraction and use of martian resources, self-sufficiency undoubtedly requires highly advanced life support systems in which most of the waste product from human activity is recovered and reused, and food is grown on the planet.

• Demonstrating that human beings can survive and flourish on Mars. This will likely be first explored by long-duration missions in Earth orbit and may be continued in the 1/6-g environment of the Moon (Synthesis Group, 1991). Two types of needs—physical and psychological—must be met for humans to survive and flourish on Mars. Physical needs will be met through advanced life support systems, preventive medical sciences (nutrition, exercise, environmental control, etc.), and the capability of medical support for people on Mars. Psychological needs will be met through the design of systems, identification and selection of work for crews, communications with Earth, and a better understanding of human interactions in small communities. Many of these can be addressed through a lunar outpost program or in the

International Space Station program to be conducted in the late 1990s. Some of these concerns can also be addressed on the first human exploration missions to Mars, in which greater risks may be taken than are appropriate for later settlement.

• Demonstrating that the risks to survival faced in the daily life of settlers on Mars are compatible with the benefits perceived by the settlers. Risks to survival can be quantified through the Mars exploration program. However, the benefits will be those perceived by future generations and cannot be addressed here.

2.4.2   *International Cooperation*

The space age gained its start in a period of intense technical and social competition between East and West, represented by the Soviet Union and the United States. Competition during the International Geophysical Year resulted in the Soviet Union being the first to launch a satellite into Earth orbit, which served to challenge and remind the United States that technological supremacy was not solely the province of the United States.

The start of the Apollo program was a political decision based more on the perception of the political and technological rewards to be gained by attacking a truly difficult objective in a constrained time period. The space race began, the United States won it, and a relatively few years later,

the Soviet Union collapsed. Fortunately, the Russians did not view Apollo success as a reason to terminate their space exploration program, and they continued to develop capabilities that are in many areas on a par with United States capabilities. Also, during the post-Apollo time frame, space capability grew in Europe (with the formation of the European Space Agency), Japan, Canada, China, and other countries. With these developments, the basis has been laid for a truly international approach to Mars exploration—an objective in which all humanity can share.

The exploration of Mars will derive significant nontechnical benefits from structuring this undertaking as an international enterprise. It is unnecessary for any country to undertake human exploration of Mars alone, particularly when others, who may not now have the required magnitude of capability or financial resources, do have the technological know-how. An underlying requirement for the Reference Mission is that it be implemented by a multinational group of nations and explorers. This would allow for a continuation of the cooperative effort that is being made to develop, launch, and operate the International Space Station.

2.4.3 Technological Advancement

From the outset, the Reference Mission was not envisioned to be a technology development program. The Mars Study Team made a deliberate effort to use either technology concepts that are in use today or basic concepts that are well understood.

Section 3 of this report will illustrate that much of the technology needed for a Mars mission is either currently available or within the experience base of the spacefaring nations of the Earth. No fundamental breakthroughs are required to accomplish the mission. However, an extended period of advanced development will be required to prepare the systems needed to travel to and from Mars or to operate on the surface of Mars; specifically, high efficiency propulsion systems, life support systems, and an advanced degree of automation to operate, and if necessary repair, processing equipment. At a general level, perhaps two of the most important ways in which the Reference Mission will help advance technology that will benefit more than just this program is to provide the programmatic "pull" to bring technologies to a usable state and the "drive" to make systems smaller, lighter, and more efficient for a reasonable cost.

For any of the technology areas mentioned above (as well as others not mentioned), this program will require systems using these technologies to meet performance specifications and be delivered on schedule, all at a pace perhaps not otherwise required. This applies to any development effort. But for the Reference Mission, many technologies will need to be ready at once, causing many of these systems to advance in maturity much faster than might have otherwise been possible. These mature systems and related technologies will then be available to the marketplace to be

used in applications limited only by the imagination of entrepreneurs.

The matured systems and the technologies behind them will be attractive to entrepreneurs in part because of the effort to make them smaller, lighter, and more efficient. A kilogram of mass saved in any of these systems saves many tens of kilograms of mass at launch from Earth (depending on the propulsion system used) simply because less propellant is required to move the systems from Earth to Mars. Smaller, lighter, or more efficient each translate into a competitive advantage in the marketplace for those who use these technologies.

Among the specific areas of desirable technology advancement is propulsion systems. Even the earliest studies for sending people to the Moon or Mars recognized that propulsion system efficiency improvements have tremendous leverage in reducing the size of the complete transportation system needed to move people and supplies. Chemical propulsion systems are reaching the theoretical limits of efficiency in the rocket engines now being produced. Further improvements in efficiency will require the use of nuclear or electrical propulsion concepts which have the potential of improving propulsion efficiencies by a factor of up to 10, with corresponding reductions in the amount of propellant needed to move payload from one place to another. Both of these propulsion technologies have matured to a relatively high state of readiness in the past, but neither has reached the level

necessary to be used on the Reference Mission. Once developed, these technologies become available for use, perhaps on reusable vehicles, for the ever-increasing traffic in LEO up to geosynchronous altitude.

Another area of tremendous leverage for a mission to other planets is the ability to use resources already there rather than burdening the transportation system by bringing them from Earth. Focusing on understanding what is required for eventual settlement on Mars leads quickly to those technologies that allow the crew to live off the land. Of the known raw materials available on Mars, the atmosphere can be found everywhere and can be used as feedstock to produce propellants and life support resources. Other raw materials (such as water) will eventually be found and used, but sufficient detail is not currently known about their locations and quantities. This is an objective for initial exploration.

Much of the processing technology needed to produce propellants from atmospheric gases already exists and is in use on Earth. However, integrating these technologies into a production plant that can operate unattended for a period of years, including self-repair, is an area where additional development effort will be required. (Chemical processing plants on Earth are making significant progress toward autonomous operation even now.) In this area, the Reference Mission will adapt the existing technologies at the time of the Reference Mission rather than pull those

technologies up to the levels needed by the program. Regardless of how this technology is developed, the advantages in manufacturing and materials processing will be significant.

Life support systems is another specific area where advancing the state of the art can significantly reduce the overall size of the systems launched from Earth. The same technologies that produce propellants can also produce water and breathable gases for human crews. These resources can be used as makeup for losses in a closed or partially closed life support system, and can also serve as an emergency cache should primary life support weaken or fail. Life support for this Reference Mission can take advantage of developments already made for International Space Station and submarine use. Developments in support of the Reference Mission are likely to return technologies that are smaller, more efficient, and perhaps less costly than those available at the time.

Important in all of these areas is a focus on ensuring that the cost to manufacture and operate these systems is affordable in the current economic environment. The design-to-cost concept is not currently well understood in the aerospace industry, and any advancements in this area will benefit development programs well beyond those connected with the Reference Mission. Developing the tools needed to determine costs that are as easy to use as the tools used to predict system performance is one of the key technology areas that will help make the

Reference Mission possible. Equal with this is instilling an attitude of cost consciousness in the engineering community that will design and produce these systems. The importance of cost as a design consideration and providing the tools to accurately forecast cost should be incorporated in the educational system that trains these engineers.

2.4.4   *Inspiration*

It can be argued that one role of government is to serve as a focusing agent for those events in history that motivate and unify groups of people to achieve a common purpose. Reacting to conflicts quickly comes to mind as an example. For the United States, World War II and the Persian Gulf War are examples of how a nation was unified in a positive sense; the Viet Nam War is an example of how the opposite occurred.

It can also be argued that a role of government is to undertake technical and engineering projects that can inspire and challenge. The great dam building projects in the American West during the 1930s is an example of the government marshaling the resources to harness vast river systems for electrical power and irrigation to allow for population growth. The Interstate Highway System is another example that receives little fanfare but has changed the way we live. The government incentives to private entities that led to the development of the vast intercontinental rail system in the last century is another example.

Few government efforts can collectively motivate, unify, challenge, and inspire. The Apollo program was one such example that focused a national need to compete with another nation in a very visible and high profile manner; the Reference Mission can serve as another. In this instance, the undertaking provides a focus for the human need to struggle and compete to achieve a worthy goal—not by competing against each other but rather against the challenges presented by a common goal.

2.4.5   Investment

Scientific investigation, human expansion, technology advancement, and inspiration are not attainable free of charge. Resources must be devoted to such a project for it to succeed; and at a certain level, this can be viewed as denying those resources to other worthy goals. The Reference Mission costs are high by current space program standards, and additional effort is needed to reduce these costs. The total program and annual costs of the Reference Mission range from 1 percent to 2 percent of the current Federal budget—still far below other Federal programs. If this program expands to an international undertaking, the costs incurred by each partner would be reduced even more.

A debate must still occur to determine if this project is a worthwhile investment of the public's resources. But the use of these resources should be viewed as more than just an effort to send a few people to Mars. This project will be investing in a growing part of the infrastructure that affects our everyday life: the use of space for business, commerce, and entertainment. Just as space projects do now, the Reference Mission can serve as a focal point for invigorating the scientific, technical, and social elements of the education system, but with a much longer range vision.

2.5   Why Not Mars?

Several impediments may severely hamper the implementation of a program for the human exploration of Mars. Some impediments are due simply to the fact that they have not been evaluated in sufficient detail to gauge their impact. Others are simply beyond the control of this or any other program and must be taken into account as the program advances. The following paragraphs discuss some of these impediments as viewed by the Mars Study Team and others considering programs of this type (Mendell, 1991).

2.5.1   Human Performance

It is a known fact that the human body undergoes certain changes when exposed to extended periods of weightlessness—changes that are most debilitating when the space traveler must readapt to gravity. The most serious known changes include cardiovascular deconditioning, decreased muscle tone, loss of calcium from bone mass, and suppression of the immune system. A variety of countermeasures for these conditions have been suggested, but none

have been validated through testing for long-term, zero-g spaceflight. The Russians have had some success with long periods of daily exercise to maintain cardiovascular capacity and muscle tone, but monotonous and time-consuming exercise regimes affect the efficiency and morale of the crew.

Artificial gravity is often put forward as a possible solution. In this case, the entire spacecraft, or at least that portion containing the living quarters for the crew, would be rotated so that the crew experiences a constant downward acceleration that simulates gravity. It is generally assumed that the Coriolis effect (the dizziness caused by spinning around in circles) will fall below the threshold of human perception if the spacecraft is rotated at a slow rate. It is not known whether simulation of full terrestrial gravity is required to counteract all of the known deconditioning effects of weightlessness, or whether the small residual Coriolis effect will cause some disorientation in crew members. No data from a space-based facility exists, and the space life science research community is split over the viability of artificial gravity as a solution.

Deconditioning is a critical issue for Mars missions because the crew will undergo high transient accelerations during descent to the martian surface. Depending on the physiological condition of the crew, these accelerations could be life threatening. Once on the surface of Mars, the crew must recover without external medical support and must perform a series of demanding tasks. The

time required for recovery is particularly important if the surface stay is short (as has been proposed for "opposition-class" missions).

No one knows whether exposure to a gravity field lower than the Earth's will reverse the deconditioning induced by weightless space travel. And if some level of gravity does halt the deconditioning effects, what level is too low? In other words, if a crew arrives on Mars in good physical condition, what will their condition be after spending an extended period of time under martian gravity? Artificial gravity cannot be provided easily on the martian surface, and Apollo missions to the Moon were too short to produce observable differences between the condition of the astronauts who went to the surface and those who remained weightless in orbit.

The human body's reaction to Mars surface conditions, other than gravity, is also not yet known. The Viking missions to Mars found a highly reactive agent in the martian soil, an explanation for which has not yet been agreed to by the scientific community. Without understanding this agent's chemical behavior, its impact on human crews cannot be determined. No matter how carefully the Mars surface systems are designed and no matter how carefully the crews handle native materials, small amounts of the martian atmosphere and soil will be introduced into crew living compartments during the course of the mission. It will be necessary to better characterize the Mars environment and assess

its impact on the crew. Assuring the health and safety of the crew will be of obvious importance.

Psychiatrists and psychologists agree that piloted missions to Mars may well give rise to behavioral aberrations among the crew as have been seen on Earth in conditions of stress and isolation over long periods of time. The probability of occurrence and the level of any such anomalous behavior will depend not only on the crew members individually but also on the group dynamics among the crew and between the crew and mission support personnel on Earth. In general, the probability of behavior extreme enough to threaten the mission will decrease with an increased crew size. However, the expense of sending large payloads to Mars to support a large crew will limit the number of people in any one crew. At the present time, little effort has been spent developing techniques for crew selection that will adequately guarantee psychological stability on a voyage to Mars and back. Russian experience suggests that a crew should train together for many years prior to an extended flight.

2.5.2 *System Reliability and Lifetime*

The spacecraft and surface elements will likely be the most complex systems constructed up to that point in time, and the lives of the crew will depend on the reliability of those systems for at least 3 years. By comparison, a Mars mission will be of a duration at least two orders of magnitude greater than a Shuttle mission, and there will

be no opportunity for resupply. Either the systems must work without failure or the crew must have adequate time and capability to repair those elements which fail.

Particularly important to the success of piloted Mars missions will be testing of integrated flight systems under conditions similar to the actual mission for periods of time similar to, and preferably much greater than, the actual mission. Integrated flight testing is truly critical if the flight system is the first of its kind. Unfortunately, if history is a guide, budget pressures will cause program management to search for substitutions for full-up flight testing. (For full-up flight testing, hardware identical to that used in flight is operated for periods of time equal to or greater than the actual mission which allows weaknesses or failures to be identified and corrected. This is the most expensive way to test, in terms of time and money.) After all, most of the expense of a mission to Mars is in launch and operations, two categories of expense for a flight test whose magnitude would be similar to that of an actual mission. And what possible motivation would there be for a crew to spend 2 or 3 years in orbit pretending to go to Mars?

Somewhere in a large, complex program, a manager will take a shortcut under pressure from budget or schedule reasons, and the consequences will not always be obvious to program management. As a result, the reliability of the product will be overestimated. And management always expresses a very human tendency to believe

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good news. (This can be illustrated by the change in the official estimates of the reliability of the Shuttle before and after the Challenger tragedy.) In short, significant risk is introduced when relying on a product that has not been tested in its working environment, whether it is a new car, a complex piece of software, or a spacecraft.

2.5.3 Political Viability and Social Concerns

The human exploration of Mars is likely to be undertaken for many of the reasons already cited as well as others not presented here. To a large degree, the responsibility for taking action based on these reasons is in the realm of political decision makers as opposed to commercial concerns or other spheres of influence. Thus, support for this type of program must be sustained in the political environment for a decade or more in the face of competition for the resources needed to carry it out.

Perhaps the closest analogy to a possible international Mars exploration program is the International Space Station, which has been an approved international flight program for over 10 years. During those 10 years, the configuration of the Station has changed several times and the number of and level of commitment from partners has changed significantly. Also during this time, Russia, initially a significant competitor, has turned into one of the larger partners in the endeavor. And all of this has taken place prior to launching the first element of the Station.

Shortening development time can be beneficial if the project remains focused on its requirements and can avoid changes imposed by external forces.

If an institution wishes to be supported with public funds for a long-duration project, then the institution must be sophisticated enough to plan visible milestones, which are comprehensible to the public, at intervals appropriate to the funding review process. Historically, NASA has been reasonably successful at maintaining funding of decade-long programs in the face of an annual budget review. The vast majority of the programs are understood by all to have a finite duration. After a satellite has been launched and operated for a given period of time, it either fails or is shut off. Neither NASA nor the U.S. Congress are yet comfortable with open-ended programs such as the Shuttle or International Space Station or human settlement of the solar system.

The decades-long time frame for human exploration of Mars cannot be supported until the role of the space program is well integrated into the national space agenda and the exploration of space is no longer considered a subsidy of the aerospace industry. To accomplish this, the space program must show concern for national and international needs (visible contributions to technology, science, environmental studies, education, inspiration of youth, etc.) while maintaining a thoughtful and challenging agenda of human exploration of space in which the public can feel a partnership.

Finally there is the political concern of back-contamination of Earth. This is as much a social issue as a technical one. Some segments of the population will object to any Mars mission on these grounds. The two tenets of a successful defense against such opposition are to ensure that prudent steps are taken at all phases of the project to minimize risks and to demonstrate that the value of the mission is high enough to merit the residual minuscule risk.

2.6 Summary

This section has woven together several key elements of a rationale for undertaking the Reference Mission: human evolution, comparative planetology, international cooperation, technology advancement, inspiration, and investment. Several challenging aspects must be resolved before the first human crews can be sent to Mars. But the Reference Mission has a longer range view and purpose that makes these challenges worth the effort to overcome. If, at some future time, a self-sufficient settlement is established on Mars, with the capability of internal growth without massive imports from Earth, the benefit will be to the eventual descendants of the first settlers, who will have totally different lives and perspectives because of the initial investment made by their ancestors.

2.7 References

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3. Mission and System Overview

3.1   Introduction

Previous studies of human exploration of Mars have tended to focus on spacecraft and flight, rather than on what the crew would do on the surface. The Reference Mission takes the point of view that surface exploration is the key to the mission, both for science and for evaluation of the potential for settlement. As a consequence, the Reference Mission architecture allows for a robust surface capability with significant performance margins: crews will explore in the vicinity of the outpost out to a few hundred kilometers, will be able to study materials in situ and in a surface laboratory, and will iterate their findings with their exploration plan. In addition, the development and demonstration of the key technologies required to test settlement issues will provide a substantial workload. To make surface exploration effective, the supporting systems (such as EMU, life support, vehicles, robotics) must be highly reliable, highly autonomous, and highly responsive to the needs of the crew. Some needs may not be anticipated during crew preparation and training, which will significantly challenge the management and operations systems.

An infinite number of designs are possible for a mission of this type. The approach taken here is based on two general principles.

- A hierarchy of requirements (starting from mission objectives) is followed, which, as they gain greater depth and definition, merge with the proposed implementation through a set of system specifications (note that the Reference Mission has followed these requirements down to the system level only).

- A reasonable number of alternatives will be considered, through trade studies at each level of definition allowing comparisons and choices.

3.1.1   Mission Objectives

Section 1 of this report discussed a series of workshops conducted by NASA to define a set of objectives and supporting rationale for a Mars exploration program. The workshop attendees (see Table 2-1) identified and recommended for adoption three objectives for analysis of a Mars exploration program and the first piloted missions in that program.

They are to conduct:

- Human missions to Mars and verify that people can ultimately inhabit Mars.

- Applied scientific research for using martian resources to augment life-sustaining systems.

- Basic scientific research to gain new knowledge about the solar system's origin and history.

A Mars Study Team composed of NASA personnel representing most NASA field centers (see Table 2-2) used inputs from the adopted objectives to construct the Reference Mission. In addition, the Study Team recognized that past mission studies had characterized piloted Mars missions as inherently difficult and exorbitantly expensive. Therefore, the Mars Study Team added three objectives. These were to:

- Challenge the notion that human exploration of Mars is a 30-year program that will cost hundreds of billions of dollars.

- Challenge the traditional technical obstacles associated with sending humans to Mars.

- Identify relevant technology development and investment opportunities.

3.1.2 Surface Mission Implementation Requirements

To satisfy the objectives for the Reference Mission, the Mars Study Team developed a series of capabilities and demonstrations that should be accomplished during surface mission activities. Table 3.1 defines the activities and capabilities that must exist to meet the first three program objectives to the next level of detail. The three objectives added by the Study Team are useful in selecting among feasible mission implementation options that could be put forth to satisfy the capabilities and demonstrations listed in the table.

3.1.2.1 Conduct Human Missions to Mars

From the point of view of the surface mission, conducting human missions implies that the capability for humans to live and work effectively on the surface of Mars must be demonstrated. This includes several sub-objectives to:

- Define a set of tasks of value for humans to perform on Mars and provide the tools to carry out the tasks.

- Support the humans with highly reliable systems.

- Provide a risk environment that will maximize the probability of accomplishing mission objectives.

- Provide both the capability and the rationale to continue the surface exploration beyond the first mission.

Table 3-1 Capabilities and Demonstrations for Surface Mission Activities

Conduct Human Missions to Mars
a. Land people on Mars and return them safely to Earth.
b. Effectively perform useful work on the surface of Mars.
c. Support people on Mars for 2 years or more without resupply.
d. Support people away from Earth for periods of time consistent with Mars mission durationss (2 to 3 years)
e. Manage space operations capabilities including communications, data management, and operations planning to accommodate both routine and contingency mission operational situations; and understand abort modes from surface or space contingencies.
f. Identify the characteristics of space transportation and surface operations systems consistent with sustaining a long-term program at affordable cost.

Conduct Applied Science Research to Use Mars Resources to Augment Life-Sustaining Systems
a. Catalog the global distribution of life support, propellant, and construction materials (hydrogen, oxygen, nitrogen, phosphorous, potassium, magnesium, iron, etc.) on Mars.
b. Develop effective system designs and processes for using in situ materials to replace products that otherwise would have to be provided from Earth.

Conduct Basic Science Research to Gain New Knowledge About the Solar System's Origin and History
a. Using robotic and human investigations, gain significant insights into the history of the atmosphere, the planet's geological evolution, and the possible evolution of life.
b. Identify suitable venues at Mars, in the martian system, and during Earth-Mars transits for other science measurements.

These then require a set of functional capabilities on the surface, including habitats, surface mobility systems, and supporting systems (such as power and communications systems).

3.1.2.2 Conduct Applied Scientific Research to Use Mars Resources to Augment Life-Sustaining Systems

This objective will require that an assessment be made of the location and availability of specific resources (such as water) that are useful for human habitation or transportation. It will also require that

effective system designs be developed and demonstrated to extract and use indigenous resources. Opportunities exist to use indigenous resources as demonstrations in the life support subsystem, in energy systems as fuel or energy storage, and as propellant for spacecraft. These may eventually develop into essential systems for the preservation of the outpost. In addition, the following habitation activities and demonstrations satisfy the first and second objectives.

• Demonstrate that martian habitability has no fundamental limitations due to uniquely martian characteristics such as

low gravity, absence of a magnetic field, soil toxicity, or the radiation environment.

- Demonstrate that self-sufficiency can be achieved on the local scale of a Mars base. This includes providing a reasonable quality of life and reasonably low risk for the crews, and should include operating a bioregenerative life support system capable of producing food and recycling air and water.

- Determine the potential for expansion of base capabilities using indigenous resources. This would include the successful extraction of life support consumables from the martian environment and storage for later use.

- Investigate the biological adaptation of representative plant, animal, and microbial species to the martian environment over multiple generations.

These activities and demonstrations are aimed at establishing the feasibility and approach required to move beyond the exploratory phase toward the development of long-term activities on the planet. They influence the selection of elements that are included in the surface systems (habitats, mobility, life support, power, and communications systems).

To the support facilities identified in the previous section must be added exploration systems (orbital or surface), resource extraction and handling systems, and additional systems for producing food and recycling air and water.

3.1.2.3 Conduct Basic Scientific Research to Gain New Knowledge About the Solar System's Origin and History

This will require that a variety of scientific explorations and laboratory assessments be carried out on the surface of Mars by both humans and robots. The scientific research will not be conducted completely at any one site, which will create a need for crew member mobility and transportation systems to support exploration, the specialized tools required outside the outpost to collect and document materials, and the facilities inside the outpost to perform analyses.

The principal science activities and demonstrations for Mars exploration include answering the following questions.

- Has Mars been a home for life?

This set of objectives will combine field and laboratory investigations in geology, paleontology, biology, and chemistry. The underlying assumption is that this question will not have been answered by previous robotic Mars exploration programs, and the best way to get an answer is through judicious use of humans on Mars as field geologists and laboratory analysts. Recent evidence indicating past life on Mars found in a martian meteorite has placed increased emphasis on this question (McKay, et al., 1996).

• What are the origin and evolution of Mars, particularly its atmosphere, and what does it tell us about Earth?

This set of objectives involves geology and geophysics, atmospheric science, meteorology and climatology, and chemistry. Iterative sampling of geological units will be required as well as monitoring of a global network of meteorological stations. (A global network will most likely be established by robotic elements of the program.)

• What resources are available on Mars?

The resource discovery and verification of accessibility will require investigations in geology, atmospheric science, and chemistry. A general strategy for accomplishing this will begin with a global mapping (from orbit) of selected elemental and mineralogical abundances. This activity is best suited for a robotic spacecraft sent prior to the flight of the first human crew. Robotic missions are also likely for verifying the abundances and making an initial assessment of accessibility of the resources. The data gathered will also be important for selecting likely sites for the surface outpost to be used by human crews.

3.1.2.4 Surface Operations Philosophy

In addition to the facilities and equipment mentioned above, the crew must have a general operating philosophy for conducting activities, demonstrations, and experiments on the surface. The targeted investigations to be carried out from the Mars outpost depend on humans and automated rover sample collectors having accessibility to interesting or significant sites at increasing distances from the outpost. Figure 3-1 shows a photomosaic of the Candor region of the Valles Marineris in which the location of an outpost could address fundamental questions of Mars' origin and history. This region is located roughly between 70 degrees and 75 degrees west longitude and between 2.5 degrees and 7.5 degrees south latitude. A general geological map of the region of the outpost site should be prepared using data gathered by robotic missions prior to selecting and occupying the initial site.

Once the outpost is established, exploration activity will consist of surface observations made by robotic vehicles and human explorers, collection of samples, and examination of samples in the outpost laboratory. Crews will be given broadly stated scientific questions or exploration objectives to be addressed in relatively large regions near the outpost site. Operations will not be as highly choreographed over the 600-day surface stay-time as they are for current spaceflight missions. The crews and Earth-based supporting investigators will plan campaigns lasting days or weeks, eventually extending to months, but always with the assumption that replanning may be necessary based on discoveries made. It is likely that a strategy of general reconnaissance followed by detailed investigations will be followed. The outpost laboratory will be outfitted to provide mineralogical and chemical analyses and, depending on technical development, it

Desired
Landing
Area
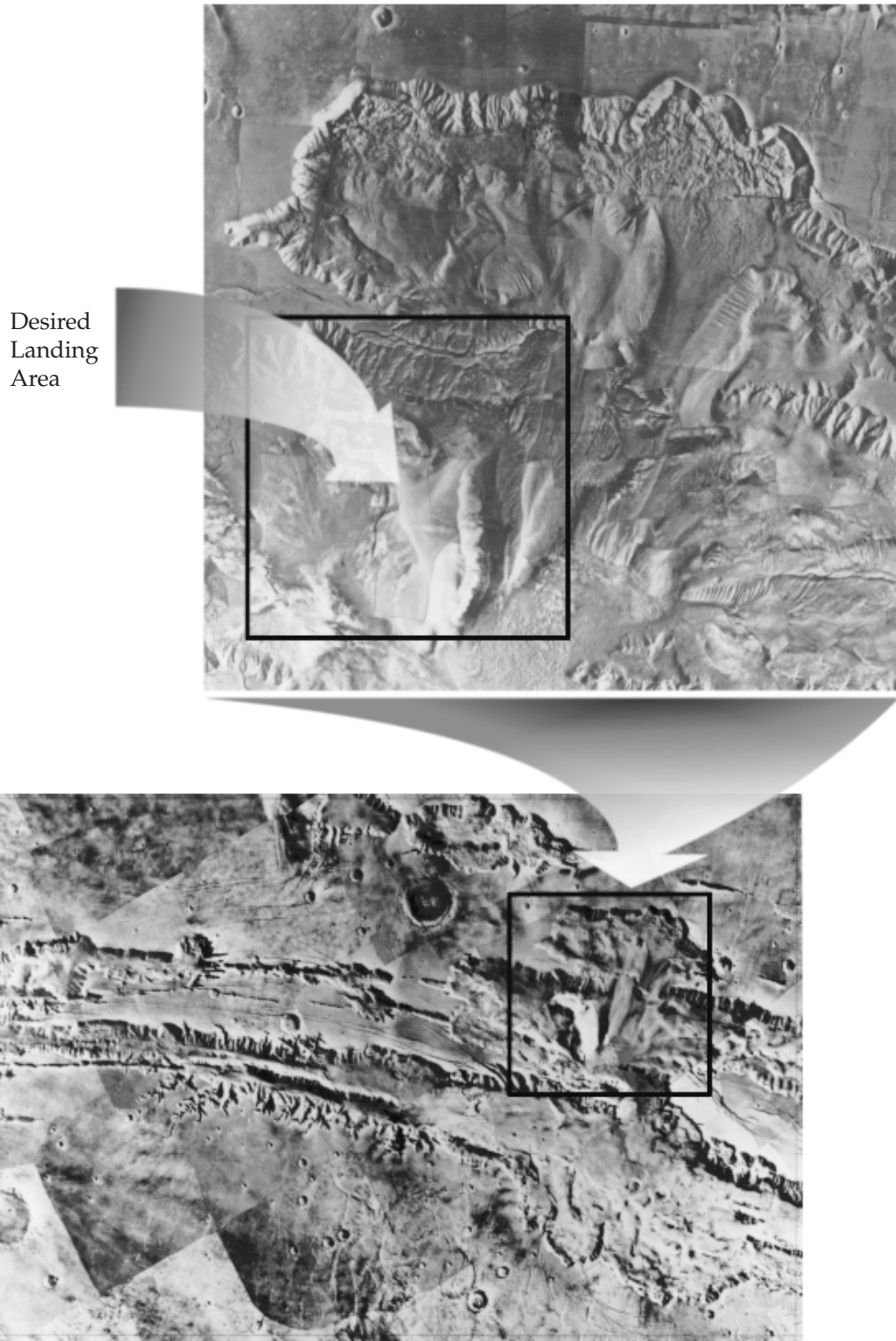
Figure 3-1 A regional map illustrating potential locations for a Mars outpost.

may be possible to perform simple kinds of geochronologic analysis. The purpose of these studies will be to support the field investigations, answer "sharper" questions, and allow human explorers to narrow their focus to the sites of optimum sample collection. Ultimately, selected samples will be returned to Earth for more detailed analysis.

Science equipment, experiments, and tools must be proven in order for the exploration and science objectives of the missions to be accomplished, and their selection is at the core of the argument that humans can effectively perform scientific research on the planet. Failure to equip humans properly will be a failure to take advantage of their unique potential. Over-equipping them may be counterproductive as well, at least from the cost aspect of transporting unneeded equipment to Mars. The exploration and science objectives to be performed on the surface can be broken into four categories: field work, telerobotic exploration, laboratory and intravehicular activity experiments, and preparation of materials for return to Earth.

- Observations related to exobiology, geology, and martian atmosphere studies will be made by humans in the field. Samples and data will be collected and returned to the outpost laboratory for analysis. The information from the analyses will be used to plan or replan future traverses as scientific and exploration questions are sharpened.

Information will be transmitted to scientists on Earth so they can participate in the replanning activity. Crews will also emplace geophysical and meteorological instruments to measure internal properties and atmospheric dynamics. Drilling short depths into the surface should be standard capability. At some point it will be appropriate to drill deeply into the surface to address stratigraphic issues and to locate and tap into water reservoirs.

- The Mars crews will also have the capability to operate telerobotic systems conducting even broader exploratory tasks using the ability to communicate with and direct these systems in near real-time. Some teleoperated rovers (TROVs) may be emplaced before crews arrive on Mars and may collect samples for assembly at the Mars outpost. The TROVs may be designed to provide global access and may be able to return samples to the outpost from hundreds of kilometers distance from the site. These robotic systems may also emplace geophysical monitoring equipment such as seismometers and meteorological stations.

- Scientific experiments will also be conducted that are uniquely suited to being performed on the surface of Mars. These will typically be experiments that make use of the natural martian environment (including reduced gravity) or involve interaction with martian

surface materials. Studies will be performed on biological systems, best performed in conjunction with an experimental bioregenerative life support system. The deployment of a bioregenerative life support capability will be an early activity after crew landing. Although this system is not required to maintain the health and vitality of the crew, it will improve the robustness of the life support system and is important to the early objectives of the outpost. Field samples will be studied in laboratory facilities shared between the geosciences, biosciences, and facilities support systems. For example, analytical systems used to monitor organisms in the biological life support system may also be used to monitor the environment of the habitat in general. Some analytical capabilities (such as gas chromatographs) find use in both geological and biological analysis. All samples and data (geological, biological, medical, etc.) will be documented and cataloged for later research.

- One crew task will be to select and package samples for return to Earth for more detailed study. This will require the creation of a minicuratorial facility and procedures to ensure that uncontaminated samples are returned to Earth.

As experience grows, the range of human exploration will grow from the local to the regional. Regional expeditions, lasting several weeks and using mobile facilities, may be conducted at intervals of a few months. Between these explorations, analysis in the laboratory will continue. The crew will also spend a significant portion of time maintaining and ensuring the continuing functionality of life support and materials processing systems and performing maintenance on robotic vehicles and EVA suits (systems should be designed to help keep these activities to a minimum).

Crew activities related to living on another planet should be viewed not only as experiments but also as activities necessary to carry out the mission. With minor modifications in hardware and software, ordinary experiences can be used to provide objective databases for understanding the requirements for human settlement.

To optimize the performance of the mission, it will be necessary to pick a landing site primarily on the basis of satisfying mission objectives. However, the landing site must be consistent with landing and surface operational safety. Detailed maps of candidate landing sites should be available to define the safety and operational hazards of the site, as well as to confirm access (by humans or robotic vehicles) to scientifically interesting locations. Depending on the results of prior missions, it would be desirable to site the outpost where water can be readily extracted from minerals or from subsurface deposits.

3.1.3 Ground Rules and Assumptions

Translating these goals and objectives into specific missions and systems required adopting a number of guidelines and assumptions.

• Balance technical, programmatic, mission, and safety risks. Mars exploration will not be without risks. However, the risk mitigation philosophy as well as the acceptability of the mission concept to the public, its elected leaders, and the crews will be critically important in the technical and fiscal feasibility of these missions. Mars is not "3 days away," and overcoming the temptation to look back to Earth to resolve each contingency situation may be the most challenging obstacle to overcome in embarking upon the human exploration of Mars.

• Provide an operationally simple mission approach emphasizing the judicious use of common systems. For example, an integrated mission in which a single spacecraft with all elements needed to carry out the complete mission is launched from Earth and lands on Mars to conduct the long exploration program is not feasible due to launch mass considerations alone. It is necessary to determine the simplest and most reliable set of operations in space or on the surface of Mars to bring all of the necessary resources to the surface where they are to be used. A strategy emphasizing multiple uses for single

systems can potentially reduce the total program costs and enhance crew safety and system maintainability.

• Provide a flexible implementation strategy. Mars missions are complex, so multiple pathways to the desired objectives have considerable value in ensuring mission success.

• Limit the length of time the crew is continuously exposed to the interplanetary space environment. Doing this will reduce the physiological and psychological effects on the crew and enhance their safety and productivity. In addition, the associated life science concerns are partially mitigated. It is assumed that crews will arrive at Mars in good health, that full physical capability can be achieved within a few days, and that crew health and performance can be maintained throughout the expedition.

• Define a robust planetary surface exploration capacity capable of safely and productively supporting crews on the surface of Mars for 500 to 600 days each mission. The provision of a robust surface capability is a defining characteristic of the Reference Mission philosophy. This is in contrast to previous mission studies that have adopted short stay-times for the first or first few human exploration missions and focused attention principally on space transportation.

- Be able to live off the land. The capability to manufacture resources at Mars, particularly propellants, has long been known to have significant leverage in terms of the amount of material that must be launched from Earth. It also provides a risk reduction mechanism for the crew when viewed as a cache of life support consumables to back up those brought from Earth. Additional system development effort will be required, but the advantages outweigh the cost and development risk, particularly if the infrastructure supports more than one human exploration expedition.

- Rely on reasonable advances in automation to perform a significant amount of the routine activities throughout the mission. This includes a capability to land, set up, operate, and maintain many of the Mars surface systems needed by the crew prior to their arrival.

- Ensure that management techniques are available and can be designed into a program implementation that can substantially reduce costs.

- Use the Earth-Mars launch opportunities occurring from 2007 through 2014. A 2009 launch represents the most difficult opportunity in the 15-year Earth-Mars trajectory cycle. By designing the space transportation systems for this opportunity, particularly those systems associated with human flights, they can be flown in any opportunity with faster

transit times for the crew or increased payload delivery capacity for cargo. This enhances program flexibility.

- Examine at least three human missions to Mars. The initial investment to send a human crew to Mars is sufficient to warrant more than one or two missions. Each mission will return to the site of the initial mission, with missions two and three launching in the 2012 and 2014 launch opportunities, respectively. This approach permits an evolutionary establishment of capabilities on the Mars surface and is consistent with the stated goals for human exploration of Mars. Although it is arguable that scientific data could be enhanced by landing each human mission at a different surface site, the goal of understanding how humans could inhabit Mars seems more logically directed toward a single outpost approach. This leaves global exploration to robotic explorers or perhaps later human missions.

3.2   Risks and Risk Mitigation Strategy

Several related but also separable aspects of risk are associated with a Mars mission and must be considered in designing the Reference Mission. Reference Mission activities will inevitably be hazardous because they are conducted far from home in extreme environments. However, the hazards can be reduced by proper design and operational protocols. Before a Mars

exploration program is approved, it will be necessary to decide whether the elements of risk to the enterprise can be reduced to a level consistent with the investment in resources and human lives.

3.2.1 Risks to Human Life

Crews undertaking the human exploration of Mars will encounter the active space environment, the in-space environment, and the planetary surface environment.

The active space environment includes launch from Earth, maneuvers in near-Earth space, launch on a trajectory to Mars, entry and landing on Mars, launch from Mars, Mars orbital maneuvers, launch on a trajectory to Earth, reentry of Earth's atmosphere, and landing on Earth. Because these are energetic events, the risk is relatively high. In 100 launches of United States manned spacecraft and a similar number of Russian spacecraft, the only fatal accidents have occurred in launch or landing. Once in space, the environment has been relatively benign. (Apollo 13 was an exception. En route to the moon, it experienced an equipment failure which jeopardized the crew. Because of the characteristics of the Earth-Moon trajectories and the spacecraft design, it was possible to recover the crew. This type of risk can be addressed in part by the Mars exploration architecture, and can be different for humans and cargo.)

The quiescent in-space environment is relatively benign from the point of view of explosions and other spacecraft accidents.

However, there are important and potentially deadly environmental hazards (such as radiation and meteoroid damage) which must be addressed. Two radiation hazards exist. First and most dangerous is the probability of a solar proton event (SPE) which is likely to occur during any Mars mission. Solar proton events can rise to the level where an unshielded person can acquire a life threatening radiation dosage. However, shielding with modest amounts of protective material can alleviate this problem. The task becomes one of monitoring for events and taking shelter at the appropriate time. Galactic cosmic rays, the other radiation hazard, occur in small numbers, are very energetic, and can cause deleterious effects over a long period of time. For astronauts in LEO, exposure to cosmic radiation has been limited to that level which could induce an additional 3 percent lifetime risk of cancer (curable or incurable). Because of a policy that radiation hazards should be kept as low as reasonably achievable, spacecraft and space operations must be designed to minimize exposure to cosmic rays. The health risk today from radiation exposure on a trip to Mars cannot be calculated with an accuracy greater than perhaps a factor of 10. The biomedical program at NASA has given high priority to acquiring the necessary health data on HZE radiation, including the design shielding materials, radiation protectant materials, and SPE monitoring and warning systems for the Mars crew. (For additional discussion and explanation of this topic, see NASA, 1992; Townsend, et al., 1990; and Simonsen, et al., 1990.)

The planetary surface is the third environment which provides risks to crews. Because operational experience on Mars is limited, this environment is the least understood. As the objective of human exploration of Mars will be to spend time on the surface of Mars, extensive EVA will be required as part of the mission. EVAs will involve exiting and reentering pressurized habitats and conducting a variety of activities on the surface in space suits or other enclosures (including vehicles). In this area, accidents and equipment failures are the biggest concerns. These risks must be addressed by examining a combination of detailed information about the surface environment, designing and testing hardware, and training the crew. To some extent, EVA can be reduced or simplified by using telerobotic aids operated by the crew from their habitat. (The risks associated with the habitat itself are probably similar to those faced in free space, with somewhat more benign radiation and thermal environments.) Finally, the presence of dust on Mars will present risks, or at least annoyances, to surface operations. Robotic missions to Mars prior to human expeditions should improve understanding of the surface hazards crews will encounter.

3.2.2   Risks to Mission Success

The risk of a Mars exploration mission is measured by the degree to which the program objectives can be accomplished. A successful trip to and from Mars, without accomplishing any surface exploration objectives, would be only minimally successful. Mission risk is related to the integrated capability of the crew and their systems to conduct the mission. For the crew or the systems to fail to perform puts the mission at risk of failure. On the human side, this requires attention to health, safety, performance, and other attributes of a productive crew. On the system side, this requires that systems have low failure rates, have robust backups for systems that may fail or require repair, and be able to operate successfully for the required period of the mission. Strategies to minimize failure can be designed at the architecture level or at the system level.

3.2.3   Risks to Program Success

Program risk is a term that refers to the programmatic viability of the exploration program—that is, once the program has been approved, what are the risks that it will not be completed and the exploration not undertaken? These are programmatic issues that in many cases seem less tractable than the technical risks. They can be influenced when management of the enterprise fails to meet milestones on schedule and cost, when unforeseen technical difficulties arise, or when political or economic conditions change. They can be mitigated by sound program management, good planning, and advocacy or constituency building on the political side.

3.2.4 Risk Mitigation Strategy

The riskiest part of the first exploration missions to Mars may well be the risk of accident on launch from Earth, and the energetic events of launches and landings during other phases of the mission are likely to make up the remaining high risk parts of the mission. Yet, the environment on the surface of Mars will be new and untried, the missions will be long, and the opportunities to make up for error small. Therefore, a conscious approach to minimizing risks on the martian surface must be adopted. For a starting point, it is assumed that this risk must be smaller than the combined risks of all of the energetic events. Design requirements will have been developed with this in mind.

The strategy for reduction of risks on the surface involves four levels of consideration. At the top level, the mission architecture provides for assurance that all systems will operate before crews are launched from Earth. The strategy must be flexible in allowing subsequent robotic missions to replace any systems shown not to be functional prior to sending crew. This, in turn, places design requirements on the hardware to allow problems to be identified, isolated, fixed in place if possible, and bypassed if necessary through the addition of a parallel capability sent on a subsequent flight.

The second level of risk reduction involves providing redundancy through the overlapping functional capabilities between various systems, the ability to repair any life-critical systems, and the provision of a suitable suite of replacement systems as backups to the prime systems. The following priorities are recommended.

- Crew health and safety are top priority for all mission elements and operations; life-critical systems are those absolutely required to ensure the crew's survival. This implies that life-critical systems will have two backup levels of functional redundancy; if the first two levels fail, the crew will not be in jeopardy but will not be able to complete all mission objectives. At least the first level of backup is automated. (This is a fail operational/fail operational/fail-safe system.)

- Completing the defined mission to a satisfactory and productive level (mission-critical) is the second priority. This implies that mission-critical objectives will have one automated backup level. (This is a fail operational/fail-safe system.)

- Completing additional, possibly unpredicted (mission-discretionary), tasks which add to the total productivity of the mission is third priority. The crew will not be in jeopardy if the mission-discretionary systems fail, and a backup is not needed. (This is a fail-safe system.)

The systems contributing to this backup strategy were assumed to be provided by either real redundancy (multiple systems of the same type) or functional redundancy (systems of a different type which provide the required function). Recoverability or

reparability by the crew will provide yet additional safety margins.

The third level of risk reduction involves the automation of systems including fault detection, failure projection, and maintenance activities, and the provision of data that demonstrate current status and predict future states. Such systems are not only conservative of crew time, but also more effective and precise, particularly on routine monitoring and control tasks.

The fourth level of risk reduction is related to crew training and proficiency. The biggest concern in this area is that the crew will be away from the traditional Earth-based training environment for years at a time. Those areas with direct human involvement—EVA, life support systems, high capacity power systems, propellant production and storage, mobile vehicles, and other complex facilities—all carry a high risk for accident, particularly if training is not recent or crew members become overconfident. Crews will most likely be required to participate in continuous task training for safety awareness requirements.

3.3   Flight Crew

Humans are the most valuable mission asset for Mars exploration and must not become the weak link. The objective for humans to spend up to 600 days on the martian surface places unprecedented requirements on the people and their supporting systems. Once committed to the mission on launch from LEO, the crew must be prepared to complete the full mission without further resupply from Earth. Unlimited resources cannot be provided within the constraints of budgets and mission performance. Their resources will either be with them or will have already been delivered to or produced on Mars. So trade-offs must be made between cost and comfort as well as performance and risk. Crew self-sufficiency is required because of the long duration of their mission and the fact that their distance from Earth impedes or makes impossible the traditional level of communications and support by controllers on Earth. The crews will need their own skills and training and specialized support systems to meet the new challenges of the missions.

Crews should be selected who will agree to conduct operational research willingly and openly. Crew members should be selected who can relate their experiences back to Earth in an articulate and interesting manner, and they should be given enough free time to appreciate the experience and the opportunity to be the first explorers of another planet.

Because the objectives of the missions are to learn about Mars and its capability to support humans in the future, there will be a minimum level of accomplishment below which a viable program is not possible. Survival of humans on the trip there and back is not a sufficient program objective.

3.3.1   Crew Composition

The number of crew members to be taken to Mars is an extremely important parameter

for system design, because the scale of the habitats, space transportation system, and other systems supporting the mission are directly related to the number of crew members. This, in turn, will have a direct relationship to the cost of the first missions. The size of the crew also is probably inversely proportional to the amount of new technology which must be developed to allow all tasks to be performed. Because of communication time delays between Earth and Mars, some functions that have previously been performed by people on Earth will be carried out autonomously or by crew members. Generally, there will be a high degree of automation required for routine operations on the Mars journey to allow crew members to do specialized tasks.

For the Reference Mission study, it was assumed that crew health and safety are of first priority in successfully achieving mission objectives and that the surface system design requirements for operability, self-monitoring, maintenance, and repair will be consistent with the identified minimum number of crew members. The crew size and composition was determined in a top-down manner (objectives → functions → skills → number of crew members + system requirements) as the systems have not been defined in a bottoms-up manner based on an operational analysis of the system.

The Mars Study Team workload analysis assumed that the crew would spend available time in either scientific endeavors or habitation-related tasks. From that analysis,

lists of required skills were developed. Expertise is required in three principal areas.

• Command, control, and vehicle and facility operations functions. These functions include command, management, and routine and contingency operations (piloting and navigation, system operations, housekeeping, maintenance, and repair of systems). Maintenance must be accomplished for facility systems, human support systems (medical facilities, exercise equipment, etc.), EVA systems, and science equipment.

• Scientific exploration and analysis. This area includes field and laboratory tasks in geology, geochemistry, paleontology, or other disciplines associated with answering the principal scientific questions.

• Habitability tasks. These tasks include providing medical support; operating the bioregenerative life support system experiment; performing biological, botanical, agronomy, and ecology investigations; and conducting other experiments directed at the long-term viability of human settlements on Mars.

The types of crew skills needed are shown in Table 3-2 (Clearwater, 1993). If each skill is represented by one crew member, the crew size would be too large. Personnel will have to be trained or provided the tools to perform tasks which are not their specialty.

Table 3-2 Surface Mission Skills

Specialized Operations and Services	Focused Objectives	In-Common
Mechanical Systems Operations, Maintenance and Repair Tool-Making	Geology Geochemistry Paleontology Geophysics including Meteorology and Atmospheric Science	Management/planning Communications Computer Sciences Database Management
Electrical Systems Operations, Maintenance and Repair Electronics Systems Operations, Maintenance and Repair	Biology Botany Ecology Agronomy Social Science	Food Preparation • routine greenhouse operations • plants to ingredients • ingredients to food Vehicle Control Navigation Teleoperated Rover Control
General Practice Medicine Surgery Psychology	Biomedicine Psychology	Journalism Housekeeping

Special skill requirements appear to be in the areas of medicine, engineering, and geoscience.

- Medical treatment. In a 3-year mission, it is very likely that an accident or disease will occur. At least one medically trained person will be required as well as a backup who is capable of conducting procedures under the direction of medical experts on Earth (through telemedicine).

- Engineer or technician. A person skilled in diagnosing, maintaining, and repairing mechanical and electrical equipment will be essential. A high degree of system autonomy, self-diagnosis, and self-repair is assumed for electronic systems; however, the skill to

identify and fix problems, in conjunction with expert personnel on Earth, has been repeatedly demonstrated to be essential for space missions.

- Geologist-Biologist. A skilled field observer-geologist-biologist is essential to manage the bioregenerative life support system experiment. All crew members should be trained observers, should be highly knowledgeable of the mission science objectives, and should be able to contribute to the mission science.

Other factors will also contribute to the final determination of crew size: system autonomy, simultaneous operations, contingency situations, human factors, and international participation.

- Electronic and mechanical equipment must be highly autonomous, self-maintained or crew-maintained, and possibly self-repairing. The amount of time taken to do routine operations must be minimized through system design. In principle, the operation of supporting systems (such as power, life support, in situ resource recovery) should be transparent to the crew. The best approach in this area is to define the requirement for technological development based on the mission requirements for a given crew size.

- Simultaneous operations will be required during the nominal mission. All crew members will be fully occupied during their assigned working hours,

and a minimum number of crew members will be required by the distribution of tasks. For example, EVAs are likely to require at least two people outside the habitat at any one time in order to assist each other. A third person is likely to be required inside to monitor the EVA activities and assist if necessary. If other tasks (repair, science, bioregenerative life support system operation) are required to be done simultaneously, the number of crew members may need to be increased.

- Specific contingency situations and mission rules have not been established for the Reference Mission because it is too early in the design phase. However, the choice of what the crew will be allowed to do or not do can impact the size of the crew. For example, during exploration campaigns, mission rules may require that some portion of the crew be left in the main habitat while the remainder of the crew is exploring in the mobile unit. It will be necessary to have a backup crew to operate a rescue vehicle in case the mobile unit has a problem. If the exploration crew requires three people, the requirement to have one driver for a backup unit and one left at the outpost implies a crew of not less than five.

- In terms of human factors considerations, the psychological adjustment is more favorable in larger crews of six to eight than in smaller

crews of three to five. However, the psychological environment may be met by system and support provisions rather than by the crew size itself.

- It is conceivable that each country that makes a major contribution to an international Mars exploration mission will demand representation on the crew. Currently, a Mars crew might be patterned after the International Space Station with representatives from the United States, Russia, European Space Agency, and Japan. However, in an enterprise of this magnitude, Third World representatives might also be selected by the United Nations.

At a summary level, the five most relevant technical fields required by the exploration and habitation requirements include mechanical engineer, electrical and electronics engineer, geologist, life scientist, and physician-psychologist. These fields should be represented by a specialist, with at least one other crew member cross-trained as a backup. Crew members would also be cross-trained for the responsibilities of a wide variety of support tasks as well as tasks of command and communications.

The result of the workload analysis indicates that the surface mission can be conducted with a minimum crew of five, based on the technical skills required. However, loss or incapacitation of one or more crew members could jeopardize mission

success. Therefore, a larger crew may be required to address the risk issues. Currently, the Reference Mission is built on the assumption of a crew of six.

3.3.2 Crew Systems Requirements

To survive, the crew will need adequate shelter, including radiation protection; breathable, controlled, uncontaminated atmosphere (in habitats, suits, and pressurized rovers); food and water; medical services; psychological support; and waste management. During the 4- to 6-month transit to Mars, the chief problems will be maintaining interpersonal relationships needed for crew productivity and maintaining physical and mental conditioning in preparation for the surface mission. On the Mars surface, the focus will turn to productivity in a new and harsh environment. The transit environment is likely to be a training and conditioning environment, the surface environment is where the mission-critical tasks will be done.

For long-duration missions with inevitably high stress levels, the trade-off between cost and crew comfort must be weighed with special care. High quality habitats and environmental design features are critical to assuaging stress and increasing crew performance—conditions that will greatly increase the likelihood of mission success. Providing little more than the capability to survive invites mission failure.

Not all amenities need be provided on the first mission. The program should be

viewed as a sequence of steps which, over time, will increase the amount of habitable space on the surface, increase the amount of time available to the crew to devote to mission objectives and personal activities, increase the amount of crew autonomy, improve the quality of food, increase access to privacy, and increase the quality and quantity of communications with Earth. In addition, experience in Mars surface operations may reduce some of the stresses associated with the unfamiliarity of the environment.

The quality of life can be enhanced by access to and use of indigenous resources. In the near term, use of indigenous resources reduces some of the mission risks (creation of caches, use of local resources for radiation shielding, etc.). In the long term, use of local resources may allow more rapid expansion of usable space. Achieving the capability to produce water and oxygen from local resources may have physical and psychological benefits over continued recycling (for example, reducing limitations on water utilization for hygiene purposes). The ability to grow food on site also has an enhancing psychological effect. The psychological impacts of these developments is difficult to quantify, however real the effects may be.

Finally, crew support by intelligent robots and automated systems appears to be a good investment from the point of view of total mission productivity. The workload analysis indicates that the total amount of time spent in the field (on foot or in a rover) by a crew member will be from 10 percent to 20 percent of the amount of their time on Mars. Automated or teleoperated rovers could extend the effective field time by crew members.

3.4 Mission Operations

Central to the success of the Reference Mission is the accomplishment of all activities associated with mission objectives. To this end, crew operations are an essential part of ensuring program success and must be factored into all aspects of program planning. All crew activities throughout each mission, from prelaunch through postlanding, constitute crew operations. The majority of crew activities fall into four categories: training, science and exploration, systems operation and maintenance, and programmatic.

- Training activities include such areas as prelaunch survival training for all critical life support systems, operational and maintenance training on mission-critical hardware, prelaunch and in-flight proficiency training for critical mission phases, and science and research training for accomplishing primary science objectives.

- The majority of science and exploration activities will be accomplished on the surface of Mars. They include, but are not limited to, teleoperated robotic activities, habitability experiments, local and regional sorties, and planetary

science investigations. Supplemental science objectives may be accomplished during other phases of the mission as well.

- During the first mission, a substantial amount of crew time will be spent operating and maintaining vehicle systems. This time allocation is expected to decrease with subsequent missions as the systems and operational experience base matures.

- Lastly, programmatic activities for the crews include publicity, documentation, reporting, and real-time activity planning.

This report does not make specific conclusions regarding hardware requirements, facilities requirements, and training programs, but a number of recommendations and guidelines regarding these areas have been developed and tailored to the various mission phases that will be experienced by each crew sent to Mars. While these and other crew activities may not be seen as directly affecting program success, all areas contribute to the successful completion of each mission and are, therefore, essential to the overall success of the Reference Mission.

3.4.1   Training Guidelines

The key to successful operations is having well prepared, knowledgeable team members. This knowledge and preparation is most effectively obtained by training for nominal and contingency operations.

Extensive training in these areas will improve overall mission success as well as contribute to meeting science and exploration objectives. Several overriding principles must govern the way training is conducted for the Reference Mission. Due to time constraints, crew training in preparation for the first mission must be done concurrently with vehicle and training facility development. The first crew and mission controllers will be supplanting operational training with involvement in system design and testing. This will provide the mission team with the needed system familiarity which would otherwise come from operational training exercises. Operations input on system designs also has the added benefit of enhancing vehicle functionality and operability (for example, nominal daily operations such as housekeeping, food preparation, and system maintenance will benefit from input by the actual users).

Additional prelaunch training must emphasize developing a working knowledge of life-critical and mission-critical elements. Because reliance on Earth-based ground control becomes more difficult and less time-responsive as the mission progresses toward Mars, crew self-sufficiency becomes essential. In-depth training on life-critical and mission-critical systems will enable crews to become more self-sufficient. Contingency survival training for failures in critical life support systems will also be required as real-time ground support will not be possible during Mars surface operations and similar remote phases of flight.

Extensive preflight and in-flight training on critical event activities (such as major propulsive maneuvers, Mars atmospheric entry, surface sorties, and Earth atmospheric entry) will be required to ensure crew proficiency during these busy time periods. The need for such training will require preflight development of a well-defined activity plan for all critical events. Significantly less preflight training will be required for noncritical, mission-success-oriented activities such as surface science operations. The initial surface operations required for the establishment of the Mars surface base and preliminary surface science activities will be well defined before the first crew departs. Subsequent exploration and science activities will depend on the findings from the initial scientific investigations. As a result, training for more than the initial science activities will not be feasible. Instead, it will be necessary to ensure that crews have the skills to enable them to plan and prioritize real-time activities in support of the overall mission objectives. Some planning assistance and direction will be provided by ground personnel; however, the responsibility for detailed planning and execution will reside with the crew. They are on the surface and have firsthand knowledge of environmental and logistical considerations.

Due to the length of the mission and length of time between critical event activities, proficiency training will be necessary during all phases of the mission. In flight and on the martian surface, training for

critical events will ensure that crews are adequately prepared for both nominal and contingency situations. From Earth launch until Mars ascent and TEI is about 2 years which necessitates an ongoing training regime to maintain proficiency. The Earth-based training the crews received 2 years earlier prior to Earth launch will not be sufficient. Training for the Mars atmospheric entry and landing phase will be conducted by the crew during the transit between Earth and Mars. While on the martian surface and intermixed with other surface activities, the crew will conduct proficiency training for the critical Mars ascent phase, subsequent docking with the ERV, and trans-Earth propulsive maneuver. In-flight and surface training requirements dictate the need for effective training facilities in the habitat vehicles or in the ascent vehicles. Design and development of such facilities will require further investigation and is beyond the scope of this preliminary report.

Documentation in the form of computer-based libraries must be available for operational instruction, maintenance of and troubleshooting systems, and hardware failures. Reliable and immediate access to this type of information will supplement crew training for all types of activities from mission-discretionary to life-critical. Extensive computer-based resources will have the added effect of increasing crew self-sufficiency during remote mission phases.

The final, but by no means least significant, element of crew training will be

the feedback provided by the early crews on training applicability and effectiveness related to all mission phases. Feedback from the first crew in particular will need to be incorporated into training procedures, hardware, and facilities to be used by subsequent crews. An effective channel for incorporating this feedback into redesign and upgrading of systems and procedures will be essential for follow-on crew training.

3.4.2   Science and Exploration

The majority of science and exploration activities will be accomplished on the surface of Mars. They include, but are not limited to, teleoperated robotic activities, habitability experiments, local and regional sorties, and planetary science investigations. Additional science activities which supplement the primary science objectives may be accomplished during other phases of the mission as well; however, the largest portion of time and activity allocated in support of science and exploration will occur on the planetary surface.

Initial surface science activities will be well defined before each crew departs Earth. Detailed activity planning to maximize the crews useful science and exploration time will increase overall mission success and will be necessary to ensure the successful completion of many primary science objectives and mission safety requirements. Many investigative results designed to satisfy safety requirements (for example, tracking crew health) will contribute to satisfying science

objectives as well. Detailed identification of safety requirements and related activities is not required until later in the mission planning process and will not be discussed here.

Subsequent exploration and science activities will depend on the findings from the initial scientific investigations. As a result, it will be necessary for crews to do real-time science activity planning to continue research activities. Principal investigators and ground support personnel will provide the guidelines for use in planning priorities of mission objectives. However, the detailed procedures for executing science activities must be left, in general, to the crews who have firsthand knowledge of the unique environmental and logistical considerations of this mission. Additionally, eliminating the excessive ground planning and replanning activities which have been customary for near real-time manned space operations will reduce cost.

Beyond the initial investigations, several surface science and exploration activities can be identified preflight as targets for detailed planning and execution: telerobotic exploration and local and regional surface sorties. Such preflight planning will maximize the crew's useful science time, maximize science return, improve crew safety on difficult exercises, and increase overall mission success.

3.4.3 Systems Operations and Maintenance

During the first mission, a substantial amount of crew time will likely be spent operating and maintaining vehicle systems. This time is expected to decrease with subsequent missions as the systems and operational experience base mature. However, until that time, the more familiar the crews are with all systems, the less time operations and maintenance will take from science and exploration activities. To enhance crew familiarity with the numerous vehicle systems prior to launch, crews should be involved in the design and testing of primary vehicle systems. The resulting intimate knowledge of the vehicle systems has the added benefit of supplementing crew training on their operational use. Another way to facilitate crew familiarity is to ensure that system designs are modular and easily repairable. The simpler and more familiar the design, the easier it is to repair and maintain.

Due to the nature of the Reference Mission program design (where vehicles are placed in a standby mode and subjected to hostile environments for long durations), in-depth vehicle and system checkouts will be required periodically. Crew participation in these activities should be minimized but may be necessary due to their access to some of the system hardware. Such access and participation may make the crews uniquely suited for analysis of anomalous results that might appear in the system testing.

Where applicable, autonomous vehicle health monitoring and testing will enable crew members to use their time performing science and exploration activities. In conjunction with this automation, access to hardware and software documentation for all systems can expedite operations and maintenance activities which require crew participation. Additionally, due to large resource requirements, some of the vehicle operations, such as long-term health monitoring, trend development or prediction, and failure analysis, may be accomplished by ground system support personnel. The delineation between which system functions are automated, crew-managed, or ground-support-managed is not clear and is subject to a host of variables. Some of the considerations to be used in making this determination are crew useful time, availability of supporting documentation, knowledge of system performance (that is, are we operating outside the envelope?), time criticality of failure recognition and recovery, and constraints on development time and cost. General guidelines of responsibility for vehicle operations are best determined early in the design process as automation of functions will affect mission and vehicle design.

3.4.4 Programmatic Activities

Programmatic activities for the crews include publicity, documentation, reporting, and real-time activity planning. These types of activities are not usually seen as directly affecting program success. They do, however,

and if properly planned and coordinated, will enhance crew performance and interaction. Like vehicle performance, crew performance is key to a successful mission.

Successful team performance and interaction depends on having defined roles and responsibilities and the flexibility to handle real-time events. For complex programs like the Reference Mission, this is important not only among crew member teams, but also among ground support personnel teams and between ground support and the crews. For the crews, knowing who is responsible for what and when makes for smoother operations and can alleviate some of the stress associated with long-term, small space, personnel interaction. For ground and crew interaction, clear rules governing who is in charge of what activities and who determines what gets done and when are essential for maximizing mission and science objective returns and alleviating confusion especially during remote operations. This will enhance operational performance when combined with a flexible operational architecture allowing crews to create and optimize the methods required to handle real-time events and achieve set objectives and goals. (Further discussion on ground operations and team interaction can be found in Section 3.8.)

Public affairs activities have been and always will be an integral part of crew activities. While they absorb resources (mostly time), they also bring public and political support to programs and contribute to program success. Crew resources from preflight through postlanding will have to be allocated in support of this activity.

Another element which contributes to program success is the crew feedback on all aspects of the mission. Their input on system designs, operations, science activities (for example, appropriateness, preparedness, required hardware), and training effectiveness is necessary for the continued improvement and enhancement of follow-on missions. Along these same lines, documentation of all activities (such as procedural changes, lessons learned, observations, hardware discrepancies) is a time-consuming but necessary crew activity. (Using various electronic systems rather than similar paper systems for documentation preparation will provide savings in terms of mass, reliability, reduced consumables, etc.) Crew records can be used to contribute to mission feedback as well as documentation. Documentation and feedback are important, especially for the first crew, to ensure optimal use of the subsequent crew's time and to enhance the chances of success of future missions of this type.

3.4.5 Activity Planning

The level of crew operations in training, science and exploration, systems operations and maintenance, and programmatic activities varies throughout different phases of the mission; however, some characteristics are consistent throughout the phases. For instance, life-critical or mission-critical

activities, regardless of mission phase, require detailed planning and precise execution. In contrast, non-life-critical or mission-critical science and exploration activities may rely on real-time procedures generated by the crew whose guidelines for planning will be to achieve set mission objectives and goals. Guidelines for crew activity planning must incorporate the flexibility to adapt to the crew's experience as they learn to live and work in a new environment.

In general, crew activity planning must be done using a relatively fixed format and timeline. This will allow crew members to readily adapt to the various environments in which they will be expected to work and live. Having regular awake and sleep times, consistent meal times, etc., from phase to phase will help the crew adapt to mission phase transitions. Having a consistent length workday is also important. With the Mars day lasting nearly 25 hours, adhering to an Earth-based daily schedule of 24 hours would routinely have the crew awake during martian night. A consistent 25-hour day throughout all phases of flight should be considered.

A typical work schedule on the Space Shuttle has crew members working throughout an entire flight, only getting time off during extremely long flights (those approaching 2 weeks in duration). For missions that can last a number of years, a consistent long-term work schedule must be developed that will give crew members sufficient time off yet maintain productivity

and the success of mission objectives. Feedback from the crew will be important during the early phases of this mission, as both ground support and flight crew members adapt to the unique environmental and operational challenges of the mission.

3.4.5.1 Prelaunch Phase

Crew activities during the prelaunch phase of the mission will concentrate on training activities for all mission phases. Early on in the program development, crew involvement in design and testing of primary systems will help facilitate crew familiarity with the systems and enhance applicability of system designs. The resulting intimate knowledge of the vehicle systems has the added benefit of supplementing crew training on their operational use. Extensive training on nominal everyday operations (such as housekeeping and food preparation) will also make the crew more comfortable in their changing environments. Strong emphasis on critical life support and mission-critical systems training will also be required.

An important part of crew training activities in this prelaunch phase will be participation in integrated training activities with scientists and systems engineers. Preflight interaction with the science community, in the form of experimental exercises (crews learn to conduct scientific investigations) and exploration exercises (crews simulate local and remote sortie operations) will enhance overall mission success and scientific return. This will benefit

not only the crew but also the ground science and systems teams by forcing them to interact in a way that will be unique to remote operations.

Crew involvement in integrated training for critical activities (such as launch, injection phase, Earth orbit systems checkout, Mars landing phase, return phases) will be needed to ensure crew proficiency and performance during these phases. Simulations which stress the crew and ground support by introducing failures and abort scenarios will help ensure crew safety should such instances occur during the mission.

In addition to prelaunch training activities, extensive medical testing will be required of the crew during this time. Their long- and short-term health will be critical factors in the success of this type of long-duration mission.

3.4.5.2 Earth Launch Phase

The Earth launch phase is defined as the crew activities required to support mission activities from launch through TMI and subsequent powerdown of nonessential hardware. It is expected that some systems used during the launch phase will not be required until later in the mission. The hardware which fits in this category will be placed in a quiescent mode to conserve resources.

During the Earth launch phase of the mission, the crew's primary focus will be to ensure a safe launch and Mars injection.

Nominal actions directly associated with the launch are expected to be minimal. Once in orbit, crew activities will center on a complete checkout of vehicle systems prior to leaving Earth orbit while near real-time communications with ground support are possible. This checkout will include all life-critical, mission-critical, and mission-discretionary systems with appropriate actions being taken for anomalies on each system according to its criticality. Such a checkout, which will be as automated as possible, will require some crew and ground support actions either for testing or for troubleshooting failures.

While in Earth orbit but before TMI, limited time or personnel may cause some of the less critical pre-TMI testing to be deferred. For instance, testing on mission-discretionary hardware intended for use only on the martian surface may be delayed until later in the transit to Mars. Such decisions will be more appropriately made when vehicle system checkout requirements are identified during the design process. Additionally, such real-time decisions may be made based on assessments of other activities during the Earth orbit phase.

Training activities will not be scheduled during the Earth launch through TMI phase of the mission as the crew will have been trained for these activities prior to launch. Additionally, with the exception of those activities related to crew health maintenance and monitoring, planned science activities will not be performed during this high

systems activity time frame. Medical testing and assistance may be required during this phase as crew members adapt to the change in environment. (The number of crew members who typically do not experience space sickness during the first few days of weightlessness is just one in three based on 171 Shuttle crew members (Reschke, et al., 1994).) Any serious life- or mission-threatening crew illness prior to TMI will be reason to abort the mission.

Throughout all mission phases, documentation of activities and feedback on training effectiveness will be required of all crew members. This will be essential in order to make effective use of the training time of the follow-on crew and the program's training hardware. Due to the high systems activity during this phase, documentation and other programmatic activities will be either minimal or deferred to a later time.

3.4.5.3 Trans-Mars Phase

The trans-Mars phase of the mission is defined as crew activities from post-TMI system powerdown through Mars Orbit Insertion (MOI) preparation. This interplanetary transit phase will be fairly homogeneous from the standpoint of environment and crew activity. Crew activities related to vehicle systems are expected to be minimal. Only nominal operations (housekeeping, food preparation, etc.) will be required unless mission-discretionary systems testing has been postponed until after TMI. This decision may be made prior to launch based on time or personnel constraints or based on the result of earlier failures. Activities for failure analysis and troubleshooting will be accomplished on an as needed basis.

The relatively quiescent vehicle system activity during the transit phase makes it well-suited for crew training activities. During this time, additional training time can be made available for the training above and beyond the preflight training that is required to maintain crew proficiency during the relatively long Mars transit time. The need for in-flight training will require that training simulators be available to the crew in the transit-habitat vehicle. Critical events that will require training during this time are MOI, landing, and Mars launch activities. Additional time may also be made available for training and review of payload and science hardware to be used on the surface.

During the transit phase, time may be available for limited science activities. The primary restriction on conducting interplanetary science activities will likely be mass related. Interplanetary science (astronomy, solar observations) is not the primary science objective for this type of mission; and, as such, related hardware will only be provided for crew use if mass margins exist at the appropriate point in the design process. However, there may be opportunities for useful scientific data return which can "piggy-back" on instruments provided for crew safety issues. An example would be conducting some solar science

experiments as part of meeting requirements for crew safety (as in solar flare detection). Also, medical testing will be required periodically throughout this phase to verify crew health. Related studies on crew adaptation to the space environment and other health-related biomedical science experiments may benefit from such testing.

As with all mission phases, documentation of activities and feedback on training effectiveness will be required of all crew members in order to make effective use of the follow-on crew's training time. Additionally, the information will provide engineers on Earth with guidelines for upgrading and improving the vehicle systems and training hardware. Transit time is ideal for documenting current and earlier phases of the mission.

Due to the high interest in such a mission, the crew will be required to participate in numerous public affairs activities. International participation in this type of mission will only increase press demands on crew time. Press and crew exchanges will be particularly productive during relatively quiescent periods early in the transit phase when communication lag times are short. As communication lag time increases, the necessity for crew autonomy will become evident. However, communication with Earth will still have to be provided for failure assistance and crew personal interaction with Earth. Communication activities will be higher during the initial and critical mission phases,

and appropriate time must be allocated during the crew schedule for such activities.

3.4.5.4 Mars Landing Phase

The Mars landing phase is a very dynamic phase of the mission and is defined as the time from MOI preparation through postlanding crew recovery and surface system activation. Many of the activities during this time frame will have been planned in detail before launch and perhaps updated during the interplanetary transit.

Prior to MOI the crew will have to prepare the transit-habitat vehicle for transition from a zero-g to a partial-g surface vehicle. All peripherals, supplies, and hardware that have been taken out for use during transit will have to be safely stowed. Nonessential equipment will be powered down in exchange for equipment necessary for this phase of flight. During this time, the crew will have to checkout or verify the operational status of all hardware and software required for the upcoming critical MOI and landing activities.

Pre-MOI activities must be initiated early enough to allow sufficient time to troubleshoot any failures or discrepancies prior to the critical phase. Many of the activities during this phase will, by necessity, be automated. However, crew intervention and override must be available due to the uniqueness and criticality of this phase of the mission (for example, doing critical activities without real-time support in a new and unique environment) and in general as a backup to the automated systems.

After landing, a thorough vehicle checkout will be necessary due to the drastic transition in operational environment from vacuum and zero g to a planetary surface environment. Initially, the only checkout which will be done will be on those systems required to certify that crew safety and life-support systems and their backups are operational.

Crew training activities during the latter part of the transit phase and the early part of the landing phase will intensely focus on critical activities for the MOI and landing phase so that the crew is adequately prepared for upcoming events. Again, this will require that adequate training facilities be available to the crew on the transit-habitat vehicle.

Minimal science activities will be done during the Mars landing phase. Time may be available for limited orbital observations to take advantage of the unique opportunity to photograph and gather remotely sensed data of Mars on approach and from orbit. However, this will depend on the available mass allocated for this type of equipment, the success of the higher priority critical systems, and the training activities during this time frame.

Due to the high systems activity during this phase, documentation and other programmatic activities will be minimal. Those activities necessary to improve the follow-on crew's training time and program training hardware will be deferred until the crew has time available.

On approach and on the surface of Mars, communication lag time with Earth will be near or at its maximum. During such a critical phase of flight, crew functions will, of necessity, be virtually autonomous from Earth-based support. Some communication with Earth will still have to be provided for failure assistance and vehicle health monitoring of trend data. Such requirements may drive the need for regular, perhaps continuous, communications capability with Earth.

3.4.5.5 Mars Surface Phase

The Mars surface phase is defined as postlanding recovery operations to prelaunch operations. In general, this phase of the mission will receive a minimal amount of mission-specific planning and training prior to departing Earth; its focus will be on the mission's primary science and exploration activities which will change over time to accommodate early discoveries. A general outline of crew activities for this time period will be provided before launch and updated during the interplanetary cruise phase. This outline will contain detailed activities to ensure initial crew safety, make basic assumptions as to initial science activities, schedule periodic vehicle and system checkouts, and plan for a certain number of sorties. Much of the detailed activity planning while on the surface will be based on initial findings and therefore cannot be accomplished before landing on Mars. However, the crew will be provided with

extensive, but not mission-specific, training related to scientific investigation and vehicle systems. This will assist the crew in planning specific activities in these areas, as required, while on the martian surface.

Initial postlanding systems activities will focus on hardware testing and verification for life support, then mission-critical, and finally mission-discretionary systems. The initial phase of these checkouts must be done without the requirement for EVAs. EVAs will be restricted until sufficient data have been collected to fully characterize the immediate martian environment. Once it has been confirmed that the martian environment is not a threat to crew health or mission success (assuming this has not been done by prior robotic missions), EVAs may then be accomplished to complete required systems testing and verification.

During the crew stay-time on the surface of Mars, additional full-scale testing and verification of some hardware will be required. After vehicle system checkout of the crew habitat shortly after crew arrival, activities for joining the crew habitat with a previously landed laboratory may begin. Complete connection of these two vehicles will be accomplished after a full verification of each vehicle's individual integrity is completed. Also during the initial postlanding time frame, verification and system status check of the vehicles needed for crew launch and Earth return will be required. While much of this activity will be autonomous and supervised by ground

operations personnel, crew involvement provides the crew with confidence in their return systems, enables visual verification of ascent vehicle system integrity, and allows for crew interaction or intervention in anomaly troubleshooting on surface hardware. Beyond annual, comprehensive vehicle checkouts, system activities for the crew will consist of maintenance, housekeeping, consumables tracking, and repair operations.

Initial science activities during the surface phase will concentrate on verifying crew health and safety on the martian surface. Atmospheric, chemical, and biological studies of the immediate environment surrounding the crew habitat will be critical to ensure crew safety. Once the immediate environment is characterized and potential threats well understood, planning for future local and regional sorties may begin. Some general planning of these initial science activities may be done in advance; however, much of the crew activity will depend on the initial findings and therefore cannot be prepared prior to launch. The crew must be provided with enough expertise and applicable hardware and resources to help them deal with potential unforeseen discoveries and obstacles to their investigations.

Prior to the first EVA and sortie, robotic exploration may map local areas and allow investigators to seek out interesting sites for regional sorties. Mission preparation will have assumed a minimum number and type of EVAs; however, adaptation to real-time

discoveries will be necessary for many of these excursions.

Additional biomedical health science activities performed on the crew will be required during the surface phase as well. Safety issues, health examinations, investigations to gather data on low-g adaptation, and long-term physiological effects on the crew will also be conducted during the surface phase.

As with other phases of flight, there may be opportunities for some scientific data return which can piggy-back on instruments provided for crew safety issues. For instance, limited solar science may be provided in part for crew safety issues (as part of solar flare detection), thus providing opportunity for additional solar science observations while on the martian surface.

Training during surface operations will be periodic to maintain proficiency for mission-critical activities (such as launch and Earth return). Additional training activities, on an as needed basis, may be required for activities such as sorties and EVAs.

Documentation of activities and feedback on training effectiveness will be required of all crew members in order to make effective use of the follow-on crew's training time. The information will provide engineers on Earth with guidelines for upgrading and improving the vehicle systems and training hardware. Additional documentation of scientific experiments and results will need to be relayed to Earth for use by the science teams in analysis and future planning.

Time will also be allocated for public affairs events. These types of events will not be interactive due to the time lag, but will be recorded and subsequently transmitted to Earth. Requests from news media and other organizations will be reviewed, scheduled, and then relayed to the crew through mission management personnel on Earth. Activities such as these will require a flexible planning architecture in which crew and ground support both participate.

All of the above mentioned surface activities will require some level of communication with mission teams on Earth—both science and systems teams. Analysis of the communication requirements will result from a combination of system data requirements, crew health data requirements, crew personal communications, and science data requirements.

3.4.5.6 Mars Launch Phase

The Mars launch phase is a very dynamic phase of the mission and is defined as the activities from preparation for launch through TEI and nonessential hardware powerdown. Many of the activities during this time frame will have been planned in detail prior to launch from Earth.

Before committing the crew to Mars ascent and Earth return activities, full systems checkout of the MAV and ERV is required. Because both vehicles are critical to crew safety and survival, sufficient time must be provided prior to launch to verify systems and troubleshoot any anomalous indications

prior to crew use. Additional crew time will be spent preparing the surface habitat and other facilities for an untended mode. Such activities will include stowing any nonessential hardware, safing critical systems and their backups, and performing general housekeeping duties which will facilitate use of the facilities by future crews.

Once the crew has prepared all surface equipment for departure, the actual departure activities will begin. Detailed activities for this departure will have been prepared and simulated on Earth, so a detailed plan for Mars launch through TEI will be available and executed at the appropriate time. Contingency scenarios will also have been planned prior to Earth launch, and enough time will be allocated during ascent and rendezvous activities to enable successful operations within these contingencies. After successful launch, rendezvous with the return vehicle, and TEI, the crew will again place nonessential hardware in a quiescent mode for the return trip.

In the time period leading up to the Mars launch phase, the crew will spend an increasing amount of time training and preparing for this extremely critical phase of the mission. In particular, the rendezvous with the ERV will require attention. Sufficient training facilities must be available on the surface to ensure crew proficiency in these activities prior to execution. Also, physiological training for the return to a zero-g and eventually a one-g environment will be dramatically increased during prelaunch.

During this most critical of time frames, other activities such as public affairs events and documentation of activities will be minimized. Due to the critical nature of this mission phase, communication transmissions to Earth will be necessary for failure assistance and vehicle health monitoring. However, due to the nature of the lag time and the criticality of events, vehicle and crew activities will remain fairly autonomous.

3.4.5.7 Trans-Earth Phase

The trans-Earth phase is defined as the post-TEI powerdown through preparation for Earth landing. This interplanetary transit phase will be fairly homogeneous from an environment and crew activity standpoint. The crew activities related to vehicle systems are expected to be minimal. Only those activities required for nominal operations will be required (housekeeping, food preparation, etc.).

Crew training activities during this time frame will focus on the critical Earth entry and landing phase of flight. This will drive an ERV hardware requirement to provide the crew with adequate simulators and on-board training facilities to maintain proficiency in vehicle operations. The crew will also begin a regime of zero-g countermeasure activities (such as exercise, lower body negative pressure, etc., depending on the best available knowledge at the time) to prepare themselves physically for return to a one-g environment.

Again, due to the relatively quiescent system activity during the transit phase, time

may be available for the crew to do limited science activities. The restrictions on interplanetary science activities will be mass related. Medical testing will be required periodically throughout this phase in order to meet biomedical science objectives and verify crew health for entry.

During this time frame, documentation activity will be extremely important due to the fact that the next crew will be launched prior to the return crew's landing. Additionally, the information will provide engineers on Earth with guidelines for upgrading and improving the vehicle systems and training hardware. Due to time considerations, some handover documentation for the next crew will have been prepared prior to leaving Mars. Final transfer of vehicle status is recommended to be direct from crew to crew to prevent confusion and ensure thoroughness. Some aspects of the hand over may be filtered through ground support in order to simplify communications requirements.

Due to the high interest in such a mission, the crew will be required to participate in numerous public affairs activities. Quiescent periods of transit time can provide opportunities for press and crew interaction.

3.4.5.8 Earth Entry and Landing

The Earth entry and landing phase is defined as the crew activities which support preentry preparation through landing and crew health recovery. Because it is not currently known how prolonged low-g and zero-g environments will affect the human physiology, the main focus of this phase of flight will be the safe return and recovery of the crew.

Crew activities related to vehicle systems will be emphasized prior to entry. System checkout will be required with sufficient time prior to entry to allow for troubleshooting any failures and guarantee a safe crew landing. Upon landing, vehicle safing and powerdown will be required. Due to the high probability of lower than normal physical capability among the crew, many of the postlanding system activities should be automated.

No training or science activities will be planned during this critical phase of flight. Crew health monitoring will be conducted for the purposes of crew health and safety. Also, due to the time-critical nature of this phase, documentation will be minimal and will pertain only to crew preparedness and system performance.

3.4.5.9 Postlanding

The postlanding phase of crew operations is defined as the activities conducted after vehicle powerdown through mission termination. In most instances, mission termination will not be a well-defined time and may be different for different members of the crew as crew involvement in additional program activities is subject to various conditions.

Face-to-face debriefings with the engineers responsible for individual systems and vehicles will be beneficial after landing. Such meetings can be more productive and provide more information than written documentation. Feedback on all training activities and facilities throughout the mission will also be beneficial postlanding as it will facilitate the training of follow-on crews.

Medical testing after landing will continue as part of long-term health monitoring. This may be required for an indefinite period of time. Some effects from the mission may not appear until months or even years after the flight phases of the mission have ended. Therefore, the crew members should be subject to periodic medical testing for observation of long-term effects of the mission. It may also be necessary to satisfy quarantine issues, whether real or political, immediately upon return to Earth. (Quarantine issues will have to be addressed early in the mission planning phases to ensure that adequate facilities are available when and if they are needed.)

Formal documentation of all aspects of the mission will be required of all crew members after landing. Additional emphasis will be placed on providing engineers on the ground with guidelines for upgrading and improving vehicle systems and training hardware.

Due to the high interest in such a mission, the crew will be required to participate in many public events and debriefings after they return to Earth.

3.5 Mission Design

The focus of this section is to describe a feasible sequence of flights on specific trajectories with specific systems that accomplish Reference Mission goals and objectives. Foremost among the choices that must be made is the type of trajectory to use. It must be one that can accomplish mission objectives using a reasonable transportation system and at the same time address the risk mitigation strategy and still provide for flexibility within a development and flight program. Other assumptions made that affect the "how" of mission implementation are discussed as part of the overall mission strategy. With these elements in place, this section presents a discussion that includes such information as launch and arrival dates, payload manifests, and crew activities for each flight in the set studied for this Reference Mission.

3.5.1 Trajectory Options

Trajectory options between Earth and Mars are generally characterized by the length of time spent in the Mars system and the total round-trip mission time. The first option is typified by short Mars stay-times (typically 30 to 90 days) and relatively short round-trip mission times (400 to 650 days). This is often referred to as an opposition-class mission, although this report has adopted the terminology "short-stay" mission. The trajectory profile for a typical short-stay mission is shown in Figure 3-2. This class has higher propulsive requirements than the often
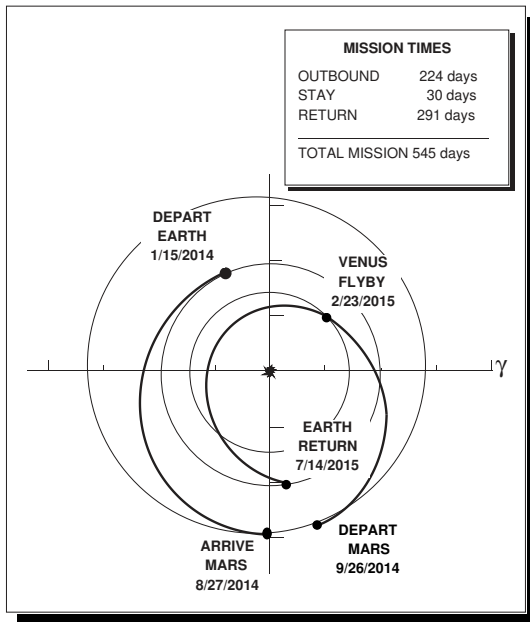
MISSION TIMES

OUTBOUND   224 days
STAY   30 days
RETURN   291 days

TOTAL MISSION 545 days

DEPART
EARTH
1/15/2014

VENUS
FLYBY
2/23/2015

EARTH
RETURN
7/14/2015

ARRIVE
MARS
8/27/2014

DEPART
MARS
9/26/2014

Figure 3-2 Typical short-stay mission profile.

MISSION TIMES

OUTBOUND   224 days
STAY   458 days
RETURN   237 days

TOTAL MISSION   919 days

Earth Launch
1/17/2014

Depart Mars
11/30/2015

Earth Return
7/24/2016

Arrive Mars
8/29/2014

Figure 3-3 Typical long-stay mission profile.

considered long-stay missions, and typically requires a gravity-assisted swingby at Venus or the performance of a deep-space propulsive maneuver to reduce total mission energy and constrain Mars and Earth entry speeds. Short-stay missions always have one short transit leg, either outbound or inbound, and one long transit leg, that requires close passage by the Sun (0.7 AU or less). A significant characteristic of this class of trajectory is that the vast majority of the round-trip time, typically over 90 percent, is spent in interplanetary space. The second mission class consists of long-duration Mars stay-times (as much as 500 days) and long total round-trip times (approximately 900 days). This mission type is often referred to as

conjunction-class, although this report has adopted the terminology "long-stay" mission. These represent the global minimum-energy solutions for a given launch opportunity. The trajectory profile for a typical long-stay mission is shown in Figure 3-3.

Within the long-stay category of missions, the option exists to dramatically decrease the transit times to and from Mars through moderate propulsive increases. The total round-trip times remain comparable to those of the minimum-energy, long-stay missions; but the one-way transits are substantially reduced, in some cases to less than 100 days, and the Mars stay-times are increased modestly to as much as 600 days. The round-trip energy requirements of this class, referred to as a "fast-transit" mission, are similar to the short-stay missions even though the trajectories are radically different. The profile for a typical fast-transit mission is shown in Figure 3-4.

Figure 3-4 Fast-transit mission profile.

3.5.2 Trajectory Selection Factors

Three factors make the selection of the trajectory class critical to the Reference Mission. First, the selection must be consistent with achieving the Mars exploration goals and objectives. Second, the selection must be consistent with the risk philosophy of the Reference Mission. And third, for programmatic reasons, the trajectory class selection must provide the flexibility to conduct missions in all opport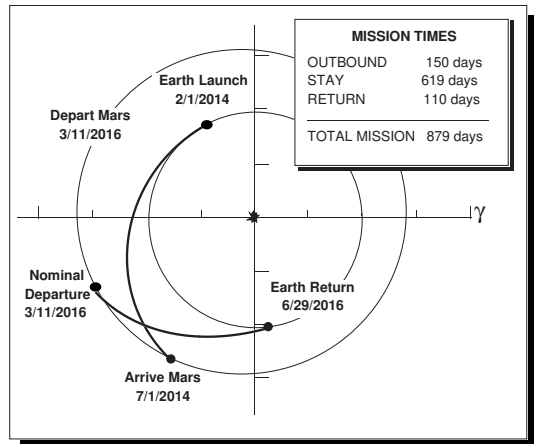unities within the 15-year Earth-Mars trajectory cycle and to conduct missions supporting the evolution of Mars exploration objectives and implementation strategies.

3.5.2.1 Satisfying Reference Mission Goals and Objectives

The goals and objectives of the Reference Mission focus on allowing human crews to spend the greatest amount of time on the surface of Mars for the investment made to transport them there and to learn as much as

possible about how humans react in this environment. Verifying the ability of people to inhabit Mars requires more than a brief stay of 30 days at the planet. In addition, the low return on investment associated with a 30-day stay at Mars (of which significantly less than 30 days would actually be productively spent on the Mars surface due to the crew adaptation to the Mars gravity, crew preparations for Mars departure, etc.) was considered unacceptable. Following the August 1992 Workshop (Duke, et al., 1992), it was decided that the "Plant the Flag" mission objective was not a tenable rationale to support the substantial investment involved. Consequently, a long-stay trajectory option was considered to be best able to satisfy the greatest number of mission goals and objectives.

3.5.2.2 Satisfying Reference Mission Risk Strategy

The applicability of each of the previously discussed mission types to the human exploration of Mars has been the subject of much debate. The general opinion is that the initial flights should be short-stay missions performed as fast as possible (so-called "sprint" missions) to minimize crew exposure to the zero-g and space radiation environment, to ease requirements on system reliability, and to enhance the probability of mission success. However, when considering "fast" Mars missions, it is important to specify whether one is referring to a fast **round-trip** or a fast-**transit** mission. Past

analyses have shown that decreasing round-trip mission times for the short-stay missions does **not** equate to fast-transit times (that is, less exposure to the zero-g and space radiation environment) as compared to the long-stay missions. **Indeed, fast-transit times are available only for the long-stay missions.** This point becomes clear when looking at Figure 3-5 which graphically displays the transit times as a function of the total round-trip mission duration. Although the short-stay mission has approximately half the total duration of either of the long-stay missions, over 90 percent of the time is spent in transit, compared to 30 percent for the fast-transit mission.

The interplanetary ionizing radiation of concern to mission planners consists of two components: galactic cosmic radiation (GCR) and solar particle events. NASA policy establishes that exposure of crews to radiation in space shall not result in heath effects exceeding acceptable risk levels. At present, acceptable risk levels are based on not

Figure 3-5 Round-trip mission comparisons.

exceeding long-term cancer risk by more than 3% above the natural cancer death probability (which is approximately 20% lifetime risk for the US population as a whole). At present, the information required to calculate acceptable risk from radiation exposure during a Mars mission, especially for the GCR, is not available. Although doses (the average physical energy deposition by incident particles) can be calculated, the conversion of this information into a predicted radiation risk cannot be done accurately. The National Research Council recently issued a report estimating the uncertainty in risk predictions for GCR can be as much as 4-15 times greater than the actual risk, or as much as 4-15 times smaller.

Current knowledge does allow for some qualitative conclusions to be drawn. Radiation risk on the Mars surface, where the GCR fluence is attenuated by 75 percent due to the Mars atmosphere and the planet itself, is likely to involve less risk than a comparable length of exposure in interplanetary space. If the difference in radiation effectiveness between the interior of a shielded spacecraft and a habitat on the surface of Mars is not considered, the GCR fluence to which crews are exposed during a 500 plus day transit to Mars is equivalent to approximately 125 days of Mars surface exposure. A significant reduction in transit time, to 100 days for the one-way transit, would result in a radiation exposure comparable to the short-stay mission. Thus, the risk to crews on fast-transit missions may be even less than the risk
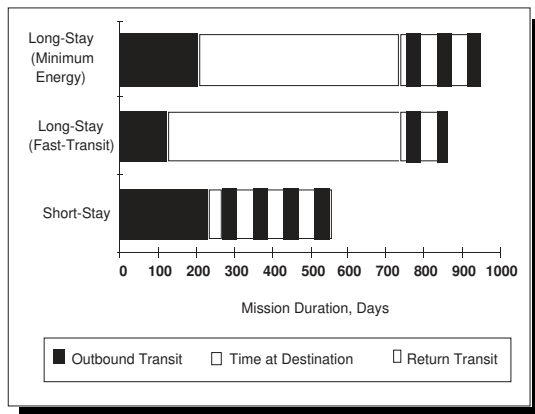
to crews on short-stay missions, not only because of minimized exposure to GCR but also reduced probability of exposure to solar particle events in interplanetary space.

A similar analysis of mission classes is involved in considering the crew's exposure to the zero-g environment during transits to and from Mars. Significant physiological changes occur when zero-g time begins to be measured in weeks or months. (Bone decalcification, immune and cardiovascular system degradation, and muscular atrophy are a few of the more unpleasant effects.) Research on the effects of long-term zero-g on the human body is in an elementary stage. At the time of the writing of this report, the longest continuous stay in space by a U.S. astronaut is the 181 days of Shannon Lucid (aboard the Russian MIR Space Station); the longest stay by a Russian cosmonaut is 366 days. In none of the cases were crews exposed to zero-g/partial-g/zero-g sequences similar to that projected for Mars missions. Current data indicates that recovery in a one-g environment can be fairly rapid (a few days), but development of full productivity could require significantly more time. Upon arrival on the martian surface, the crew will need to spend some currently unknown, but probably short, time re-adapting to a partial-g field. This may be of concern for the short-stay missions where a substantial portion of the surface stay-time could be consumed by crew adaptation to martian gravity. Conversely, ample time will be available for the crew to regain stamina and productivity during the long surface stays associated with the minimum-energy, fast-transit missions.

Several potential solutions to the physiological problems associated with zero-g transits to and from Mars may exist: countermeasures (exercise, body fluid management, lower body negative pressure), artificial-g spacecraft, and reduced transit times.

The usefulness of countermeasures to reduce some of the zero-g effects is still unknown. Russian long-duration crews have experienced physiological degradation even when rigorous exercise regimens have been followed. However, most of these effects seem to be quickly ameliorated upon return to a one-g environment, at least when immediate medical aid is available.

Rotating the Mars transfer vehicle (MTV) and ERV is a method of providing an artificial-g environment for the crew and is most often associated with low-performance propulsion systems, or the short-stay class of trajectories (since both require long transit times). Studies have indicated that the MTV design mass penalties are on the order of 5 percent to 20 percent if artificial g is incorporated. Depending on the specific configuration, there may also be operational complications associated with artificial-g spacecraft including EVA, maintenance, and the spin-up/spin-down required for midcourse maneuvering and rendezvous and docking.
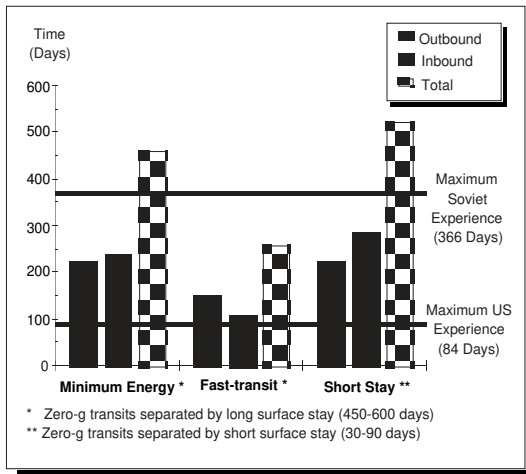
Figure 3-6 Microgravity comparisons for various mission classes.

Figure 3-6 illustrates some example transit times for minimum-energy, fast-transit, and short-stay missions. Note that all **one-way** transits are within the Russian zero-g database.

However, the surface stay-times for short-stay missions are typically 1 to 3 months. It is unknown whether such a short time spent in a 0.38-g field will counteract 5 months of outbound zero-g exposure. In contrast, the one-way trip times of representative fast-transit missions are **nearly within the current U.S. zero-g database,** which will certainly be augmented by normal International Space Station operations prior to executing human interplanetary missions. Also note that the fast-transit mission's zero-g transfer legs are separated by a substantial period of time in the martian gravitational field. This long period on the surface of Mars

may prove sufficient to ameliorate the physiological effects of the relatively short outbound transit.

3.5.2.3 Satisfying Reference Mission Program Flexibility

Finally, the selection of trajectory type depends on its allowance for flexibility to respond to mission opportunities and implementation strategies. The higher energy, short-stay missions significantly vary in both propulsive requirements and round-trip flight times across the 15-year Earth-Mars trajectory cycle. Additionally, these missions generally require the use of a Venus swingby maneuver to keep propulsive requirements within reason. However, these swingbys are not always available on the return transit leg and must be substituted in the outbound transit leg. Because the transit leg containing the Venus swingby is the longer of the two, the crew will spend up to 360 days on the trip to Mars, with any associated physiological degradation occurring at the beginning of the mission—that is, prior to the crew's arrival at Mars. These variations in the trajectory energy requirements can significantly impact the configuration of the Earth-Mars transportation elements for different Earth-Mars opportunities. Programmatically, such a result is unattractive. In contrast, the minimum-energy, long-stay missions exhibit very little variation over the 15-year cycle, while the fast-transit long-stay missions reflect only moderate variations across the same 15-year cycle. In addition, neither

mission requires a Venus swingby or travel inside the Earth's orbit around the Sun.

3.5.3 *Mission Design Strategy*

Keeping the Reference Mission goals and objectives in mind, numerous alternatives were considered that could successfully accomplish the basic mission. Two major considerations that drove many of the mission design-related selections include:

- Reducing the amount of propellant needed to move mission hardware from one location to another (propellant mass is the single largest element of all components in the Reference Mission)

- Extending the amount of time spent by the crew conducting useful investigations on the surface of Mars.

The alternatives selected by the Mars Study Team that impact mission design strategy have been grouped into six major areas and are presented here. Other alternatives will be discussed in subsequent sections.

3.5.3.1 Trajectory Type

The discussion presented in the previous section led to the selection of the fast-transit, long-stay class trajectories. However, the amount of reduction sought in the Earth-Mars and Mars-Earth transit times must be balanced with other considerations. Reductions below 180 days in the one-way transit times (for the 2009 opportunity, the worst case) would require either significant

propulsive capability improvements or would necessitate much larger interplanetary spacecraft launched into LEO for the human missions, thereby requiring assembly and docking in LEO and higher ETO launch rates. Indeed, others have demonstrated that reductions in trip times reach a point of diminishing returns from the space transfer vehicle design perspective (Drake, 1991). Thus, a C3 leaving Earth of 20 to 25 km^2/sec^2 appears to be appropriate for human missions. This results in maximum Earth-Mars transit times of approximately 180 days (2009 opportunity) and minimum transit times of approximately 120 days (for the 2018 opportunity, the best case). Similarly, a C3 leaving Mars of ~16 km^2/sec^2 appears to be appropriate for human missions, resulting in similar Mars-Earth transfer times for these opportunities. (C3 is a measure of the energy required to get from Earth to Mars or vice versa. Specifically, C3 is the square of the velocity of departure from a planet. Low C3s are desirable because there is a direct correlation between C3 and the size of the transportation system.)

3.5.3.2 Split Mission Strategy

The split mission approach has been adopted for the Reference Mission because it allows mission elements to be broken into manageable pieces rather than trying to integrate all necessary hardware elements for a single, massive launch. For this mission, "manageable" was defined to mean pieces that can be launched directly from Earth and sent to Mars, using launch vehicles of the

Saturn V or Energia class, without rendezvous or assembly in LEO. A key attribute of the split mission strategy is that it allows cargo to be sent to Mars without a crew, during the same launch opportunity or even one or more opportunities prior to the crew's departure. This creates a situation where cargo can be transferred on low energy, longer transit time trajectory, and only the crews must be sent on a high-energy, fast-transit trajectory. By using a low energy transfer, the same transportation system can deliver more payload to the surface of Mars at the expense of longer flight times. Spacing the launches needed to support a mission across two launch windows allows much of the infrastructure to be pre-positioned and checked out prior to committing crews to their mission. When combined with the decision to focus all Mars surface infrastructure at a single site, this approach allows for an improved capability to overcome uncertainties and outright failures encountered by the crews. Launches of duplicate hardware elements, such as ERVs, on subsequent missions provides either backup for the earlier launches or growth of capability on the surface.

3.5.3.3 Aerocapture

Mars orbit capture and the majority of the Mars descent maneuver will be performed using a single biconic aeroshell. The decision to perform the Mars orbit capture maneuver aerodynamically was based on the fact that an aeroshell will be required to perform the Mars descent maneuver no matter what method is used to capture into orbit about Mars, and current technology can develop an aeroshell with a mass that is equal to or less than the propulsion system required for capture. Thus, the strategy assumed the development of a single aeroshell that can be used for both Mars orbit capture and descent maneuvers. Given the demands on a descent aeroshell of the Mars entry and landing requirements, the additional capability to permit aerocapture is considered modest.

3.5.3.4 Surface Rendezvous

The hardware elements launched as part of the split mission approach must come together on the surface of Mars, which will require both accurate landing and mobility of major elements on the surface to allow them to be connected or moved into close proximity. The alternative was to link major components either in Earth orbit or in Mars orbit prior to entry and landing. Previous studies (NASA, 1989) indicated that the heat shields for vehicles with the combined mass implied by such an orbital rendezvous approach would be exceedingly large and difficult to launch and assemble in orbit. Precision landing has been demonstrated for the Moon (Apollo 12), and studies indicate (Barton, et al., 1994) that available guidance and control systems combined with a simple beacon transmitting from the surface (assumed to be carried by the first element at the site) are sufficient to allow a vehicle to land at a designated location on Mars with uncertainties measured in meters.

3.5.3.5 Use of Indigenous Resources

The highly automated production of propellant from martian resources is another defining attribute of the Reference Mission. The hardware necessary to produce and store propellants using raw materials available on Mars (in this case, carbon dioxide from the atmosphere) is less massive than the propellant needed to depart the martian surface for orbit (Ash, et al., 1978). It is now apparent that the technology for producing methane and liquid oxygen from the martian atmosphere and some nominal hydrogen feedstock from Earth is not only an effective performance enhancement but also appears to be technologically feasible within the next few years. Splitting the launch of mission elements allows the propellant production capability to be emplaced, checked out, and operated prior to committing the crew to launch from Earth. In addition to spacecraft propulsion, this production capability on Mars can provide fuel for surface transportation, reactants for fuel cells, and backup caches of consumables (water, oxygen, and trace gases) for the life support system. All of these features allow for smaller amounts of consumable material to be launched from Earth and contributes to the goal of learning how to live on Mars.

3.5.3.6 Mars Orbit Rendezvous and Direct Entry at Earth

The last element of mission design is returning the crew to Earth. There are potentially three significant propulsive maneuvers associated with the return: departing from the martian surface, departing from Mars orbit, and capturing into Earth orbit. Several alternatives are associated with these three events, the proper selection of which can result in a significant savings in propellant and thus in mass that must be launched from Earth. Three key choices affecting this portion of the mission are made in the Reference Mission. First, the Earth-return transit habitat used by the crew is left in Mars orbit. While the outbound habitat could have been used for this task, the propellant needed to lift it is significant; and it is considered more valuable as part of a growing surface infrastructure. The entire ERV is composed of the TEI stage and the Earth-return transit habitat. The ERV is delivered to Mars orbit fully fueled, and it loiters there for nearly 4 years before being used by the crew in returning to Earth. Second, the crew is not captured into an Earth orbit at the completion of the mission, but descends directly to the surface much as the Apollo astronauts did when returning from the Moon. The Earth crew capture vehicle (ECCV) has the necessary heat shield for Earth reentry. Third, the crew rides into Mars orbit in a dedicated ascent capsule.

3.5.4 Mission Sequence

Figure 3-7 illustrates the mission sequence analyzed for the Reference Mission. In this sequence, three vehicles will be launched from Earth to Mars in each of four launch opportunities starting in 2007. The

ETO FLIGHT

Years: 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018

- **1** — ERV loiter; Δ Crew 1 TEI; Δ ERV-1 parks in LMO; Δ Crew 1 Earth return
- **2** — Δ MAV-1 landing
- **3** — Δ Initial Habitat landing
- **6** — Crew 1: launch Δ; Δ Landing; Δ Crew 1 ascent
- **4** — ERV loiter; Δ Crew 2 TEI; Δ ERV-2 parks in LMO; Δ Crew 2 Earth return
- **5** — Δ MAV-2 landing
- **9** — Crew 2 launch Δ; Δ Landing; Δ Crew 2 ascent
- **7** — ERV loiter; Δ Crew 3 TEI; Δ ERV-3 parks in LMO; Δ Crew 3 Earth return
- **8** — Δ MAV 3 landing
- **12** — Crew 3 launch Δ; Δ Landing; Δ Ascent
- **10** — ERV loiter; Δ ERV 4 LMO
- **11** — Δ MAV 4 landing

ERV: Earth Return Vehicle
MAV: Mars Ascent Vehicle
TEI: Trans Earth Injection
LMO: Low Mars Orbit

Figure 3-7 Mars Reference Mission sequence.

first three launches will send infrastructure elements to both Mars orbit and to the surface for later use. Each remaining opportunity analyzed for the Reference Mission will send one crew and two cargo missions to Mars. The cargo missions will consist of an ERV on one flight and a lander carrying a habitat and additional supplies on the second. This sequence will gradually build up assets on the martian surface so that at the end of the third crew's tour of duty, the basic infrastructure could be in place to support a permanent presence on Mars.

3.5.4.1 First Mission: 2007 Opportunity

In the first opportunity, September 2007, three cargo missions will be launched on minimum energy trajectories direct to Mars (without assembly or fueling in LEO). The first launch delivers a fully fueled ERV to Mars orbit. The crew will rendezvous with this stage and return to Earth after completion of their surface exploration in October 2011.

The second launch delivers a vehicle to the Mars surface which is comprised of an unfueled MAV, a propellant production

module, a nuclear power plant, liquid hydrogen (to be used as a reactant to produce the ascent vehicle propellant), and approximately 40 tonnes of additional payload to the surface. After this vehicle lands on the surface in late August 2008, the nuclear reactor will be autonomously deployed approximately 1 kilometer from the ascent vehicle, and the propellant production facility (using hydrogen brought from Earth and carbon dioxide from the Mars atmosphere) will begin to produce the nearly 30 tonnes of oxygen and methane that will be required to launch the crew to Mars orbit in October 2011. This production will be completed within approximately 1 year—several months before the first crew's scheduled departure from Earth in mid-November 2009.

The third launch in the 2007 opportunity will deliver a second lander to the Mars surface; it will be comprised of a surface habitat/laboratory, nonperishable consumables for a safe haven, and a second nuclear power plant. It will descend to the surface in early September 2008 and land near the first vehicle. The second nuclear power plant will be autonomously deployed near the first plant. Each plant will provide sufficient power (160 kWe) for the entire mature surface outpost, thereby providing complete redundancy within the power function. The outpost laboratory will include tools, spare parts, and teleoperated rovers to support scientific exploration and will provide geological and biological analyses.

Table 3-3 lists the various payload items deployed to the surface during the first opportunity. And Figure 3-8 illustrates the surface outpost configuration after deployment of payloads from the first two cargo landers.

3.5.4.2 Second Mission: First Flight Crew, 2009 Opportunity

In the second opportunity, opening in October 2009, two additional cargo missions and the first crew mission will be launched. Before either the crew or additional cargo missions are launched from Earth in 2009, all assets previously delivered to Mars are checked out and the MAV launched in 2007 is verified to be fully fueled. Should any element of the surface system required for crew safety or critical for mission success not check out adequately, the surface systems will be placed in standby mode and the crew mission delayed until the systems can be replaced or their functions restored. Some of the systems can be replaced using hardware originally intended for subsequent missions and which would have otherwise provided system enhancement; others may be functionally replaced by other systems.

Table 3-4 lists the manifested payloads for launch in the 2009 opportunity.

The first cargo launch in October 2009 is a duplicate of the first launch from the 2007 opportunity, delivering a fully fueled Earth-return stage to Mars orbit. The second cargo launch similarly mirrors the second launch of the 2007 opportunity, delivering a second

Table 3-3 General Launch Manifest: 2007 Launch Opportunity

Flight 1: Cargo	Flight 2: Cargo	Flight 3: Cargo
Surface Payload		
• None	• Ascent Capsule • Empty Ascent Stage • LOX/CH_4 Production Plant • LH_2 Propellant Seed • Power Supply (nuclear-160 kW) • Utility Truck • Pressurized Rover • Additional Payload	• Surface Habitat/Laboratory • Nonperishable Consumables • Power Supply (nuclear-160 kW) • Utility Truck • Spares • Teleoperable Science Rover
Mars Orbit Payload		

• Earth-Return Vehicle
  • Fueled (LOX/CH_4) TEI Stage
  • Transit Habitat
  • Earth-Return Capsule
	• None	• None

Space Transportation Vehicles		
• NTR Transfer Stage • LOX/CH_4 TEI Stage w/Mars Aerobrake	• NTR Transfer Stage • LOX/CH_4 Descent Stage w/Mars Aerobrake	• NTR Transfer Stage • LOX/CH_4 Descent Stage w/Mars Aerobrake

TEI: Trans Earth Injection   LOX: liquid oxygen LH_2:   liquid hydrogen
NTR: Nuclear Thermal Rocket CH_4:   methane

unfueled ascent stage and propellant production module. These systems provide backup or extensions of the previously deployed capabilities. For example, the second MAV and second ERV provide the 2009 crew with two redundant means for each leg of the return trip. If, for some reason, either the first ascent stage or the first ERV become inoperable after the first crew departs Earth in 2009, the crew can use the systems launched in 2009 instead. They will arrive in

plenty of time to be available for the crew's departure from Mars in October 2011. If the MAV and ERV delivered in 2007 operate as expected, then the systems delivered in 2009 will support the second crew of six that will launch to Mars early in 2012.

The first crew of six will depart for Mars in mid-November 2009. They leave Earth after the two cargo missions launched in October 2009, but because they are sent on a fast transfer trajectory of only 180 days, they

Nuclear Power Plant (NUKE-2)

Nuclear Power Plant (NUKE-1)

1 km

Cable

(TROV-1)

(ROV-1)

Communication Tower(s)

MAV-1

PVA Array (PVA-1)

Fuel/LSS ISRU Plant (ISRU-1)

Hydrogen Feedstock

Water Storage

PVA Array (PVA-2)

(Lab/Lab)

(ROV-2)

(TROV-2)

(TROV-3)

500 meters

MAV: Mars Ascent Vehicle
TROV: teleoperated rover
            (unpressurized)
ROV: pressurized rover
LSS: life support system
ISRU: in-situ resource utilization
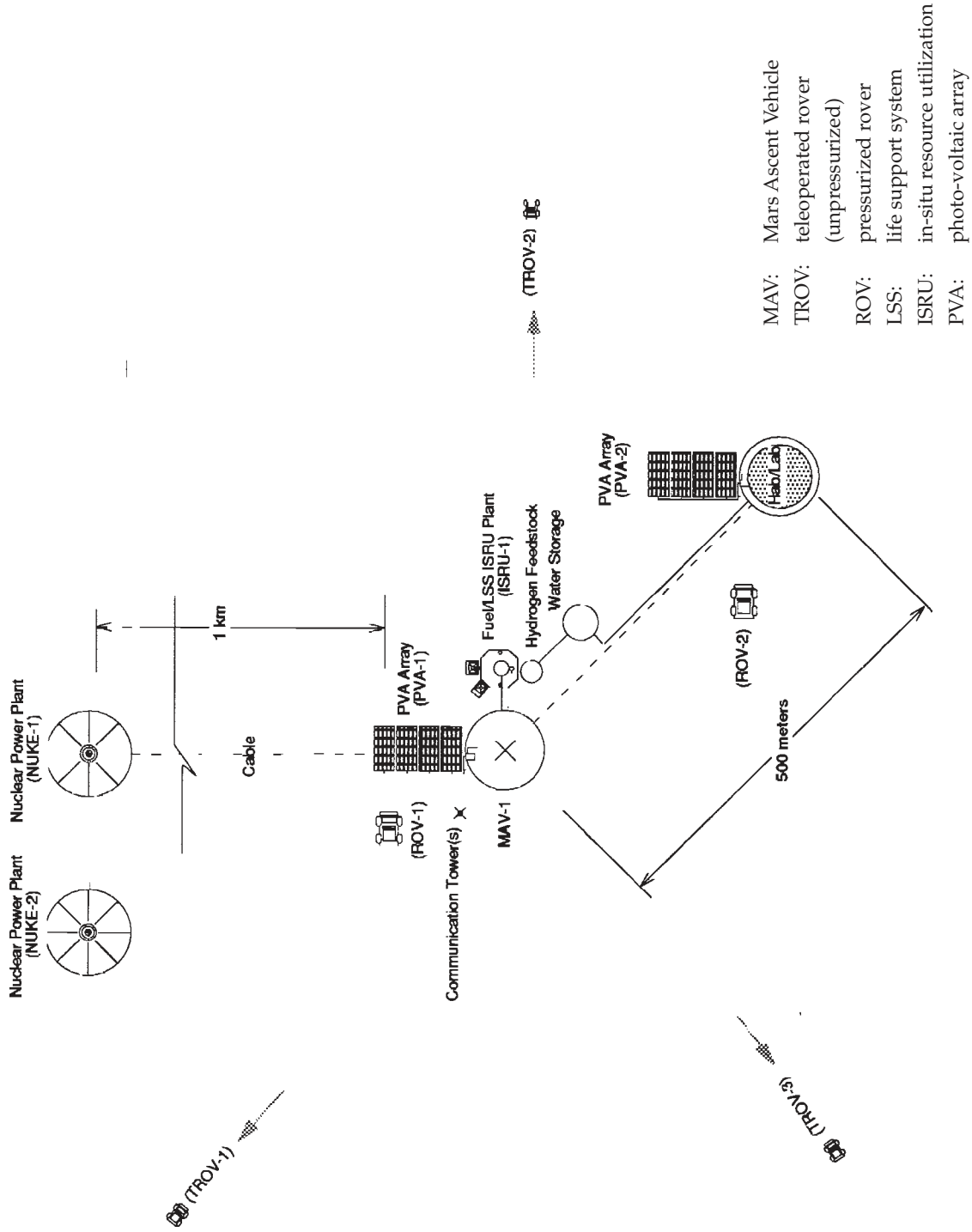PVA: photo-voltaic array

Figure 3-8 Mars surface outpost after deployment of payloads from first two cargo landers.

Table 3-4 General Launch Manifest: 2009 Launch Opportunity

Flight 4: Cargo	Flight 5: Cargo	Flight 6: First Crew
Surface Payload		
• None	• Ascent Capsule • Empty Ascent Stage • LOX/CH_4 Production Plant • LH_2 Propellant Seed • Bioregenerative Life Support Outfitting Equipment • Science: 1 km drill • Science Equipment • Additional Payload /Spares	• Crew • Surface Habitat • Consumables • Spares • EVA Equipment • Science Equipment
Mars Orbit Payload		

• Earth-Return Vehicle
  • Fueled (LOX/CH_4) TEI Stage
  • Transit Habitat
  • Earth-Return Capsule
	• None	• None

Space Transportation Vehicles		
• NTR Transfer Stage • LOX/CH_4 TEI Stage w/Mars Aerobrake	• NTR Transfer Stage • LOX/CH_4 Descent Stage w/Mars Aerobrake	• NTR Transfer Stage • LOX/CH_4 Descent Stage w/Mars Aerobrake

TEI:	Trans Earth Injection	LOX:	liquid oxygen	LH_2:	liquid hydrogen
NTR:	Nuclear Thermal Rocket	CH_4:	methane		

will arrive in Mars orbit approximately 2 months prior to the cargo missions. Once the TMI burn has been completed, the crew must reach the surface of Mars. During the outbound portion of this mission, the crew will use their time to monitor and maintain systems on board the transit spacecraft, monitor and maintain their own physical condition, and train for those activities associated with capture and landing at Mars.

Additional time will be available during the outbound leg to conduct experiments and continue a dialog with Earth-bound science and exploration teams who may revise or refine the initial set of surface activities conducted by this crew. The crew carries with them sufficient provisions for the entire 600-day surface stay in the unlikely event that they are unable to rendezvous on the surface with the assets previously deployed.

The crew will land on Mars in a surface habitat almost identical to the habitat/laboratory previously deployed to the Mars surface. The transit habitat sits atop a descent stage identical to those used in the 2007 opportunity. After capturing into a highly elliptic Mars orbit (250 by 33793 km), the crew descends in the transit habitat to rendezvous on the surface with the other elements of the surface outpost. There is no required rendezvous in Mars orbit prior to the crew descent. This is consistent with the risk philosophy assumed for the Reference Mission.

Figure 3-9 illustrates the surface outpost configuration at the end of the first crew's stay.

Surface exploration activity will consist of diverse observations by robotic vehicles and human explorers, the collection of samples and their examination in the outpost laboratory, and experiments designed to gauge the ability of humans to inhabit Mars. Table 3-5 lists a representative set of science and exploration equipment that will be delivered as part of the cargo on Flight 5. These payloads are simply examples; the selection of specific experimental capability will depend on the requirements of martian science at the time that the missions are defined in detail. There is also a category listed for "discretionary principal investigator (PI) science." This category of experimental equipment will be allocated to investigators who have competed through a proposal and peer review process and are selected for one of these flights. This allows a wider range of

investigations and participants in the exploration of Mars.

Prior to the arrival of the first human crew, teleoperated rovers (TROV) may be delivered to the surface. When the crew arrives, these rovers will be available for teleoperation by the crew. It is also possible for the rovers to be operated in a supervised mode from Earth. If used in this mode, the TROVs may be designed to provide global access and may be able to return samples to the outpost from hundreds of kilometers distance from the site if they are deployed with the first set of cargo missions launched more than 2 years before the crew arrives.

As experience grows, the range of human exploration will grow from the local to the regional. Regional expeditions lasting perhaps 2 weeks, using mobile facilities, may be conducted at intervals of a few months. Between these explorations, analysis in the laboratory will continue. Figure 3-10 (Cohen, 1993) provides a possible surface mission timeline for the first 600-day mission.

The deployment of a bioregenerative life support capability will be an early activity following crew landing. This bioregenerative system is not required to maintain the health and vitality of the crew; however, it will improve the robustness of the life support system and is important to the early objectives of the outpost.

The first crew will stay at the outpost from 16 to 18 months. Part of their duties will be to prepare the outpost site for the receipt of
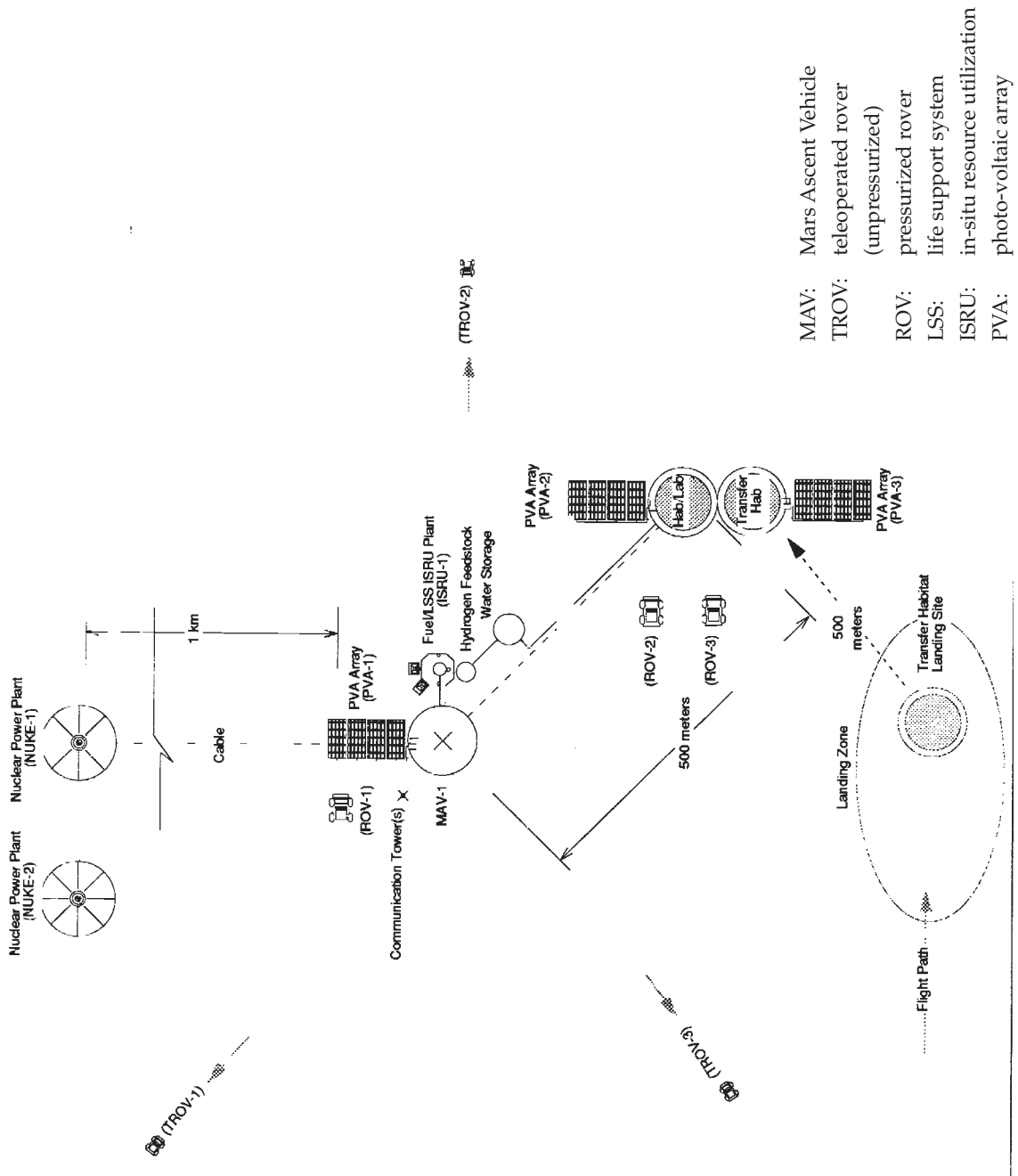
Figure 3-9 Mars surface outpost at the end of first flight crew's stay.

MAV: Mars Ascent Vehicle
TROV: teleoperated rover (unpressurized)
ROV: pressurized rover
LSS: life support system
ISRU: in-situ resource utilization
PVA: photo-voltaic array

Table 3-5 Surface Science Payload for First Flight Crew

Payload Description	Payload Mass (kg)
Field Geology Package: geologic hand tools, cameras, sample containers, documentation tools	335
Geoscience lab instruments: microscopes, geochemical analysis equipment, camera	125
Exobiology laboratory: enclosures, microscopes, culture media	50
Biomedical/bioscience lab	500
Traverse geophysics instruments	400
Geophysics/meteorology instruments (8 sets)	200
10-meter drill	260
Meteorology balloons	200
Discretionary PI science	300
Total	**2370**

additional elements launched on subsequent mission opportunities. Systems associated with the ascent vehicle, although monitored during the entire stay on the surface, will be checked and, if necessary, tested in detail to ensure that they will operate satisfactorily. The surface crew will also spend increasing amounts of time rehearsing the launch and rendezvous phase of the Mars departure to sharpen necessary skills that have not been used in over 2 years. Because the first crew will have to depart before the second crew arrives, surface systems will have to be in standby mode for approximately 10 months.

After their stay on Mars, the crew uses one of the previously landed ascent vehicles to return to orbit, rendezvous with the ERV, and return to Earth. Like the outbound transit leg, the crew rides in a habitat on the inbound transit leg. This habitat is part of the Earth-return stage deployed in a previous opportunity by one of the cargo flights and

typically has been in an untended mode for nearly 4 years prior to the crew's arrival.

During the return portion of the mission, the crew will again spend a significant portion of their time monitoring and maintaining systems on board the transit spacecraft, monitoring and maintaining their physical condition, and training for the activities associated with Earth return. As mentioned previously, the second crew will be in transit to Mars during a portion of the first crew's return to Earth. This implies that a debriefing of the first crew, to gain insight from lessons learned and suggestions for future surface activities, will begin during this return phase. This debriefing will be relayed to the outbound crew so that they can participate in the interaction with the returning crew and modify their plans to take advantage of the first crew's experience.

On landing, the first crew and their returned samples will be placed in quarantine

Mars Surface Mission Time Allocation

(Total Time = 8 crew X 24 hr/day X 600 days = 115,200 hr)

8 crew X 24 hr day = 200)

Personal 14 hr (total 67,200 hr)	Hr/Over head 3 hr (14,400 hr)	Production 7 hr (33,600 hr total)

600 day (or 20 months, or 86 weeks)

Sleep, Sleep Prep, Dress, Undress: 8 hr

Hygiene, Cleaning, Personal Communication: 1 hr

Recreation, Exercise, Relaxation: 1 hr

Eating, Meal Prep, Clean-up: 1 hr

One Day Off Per Week: 3 hr (per day)

General Planning, Reporting, Documentation, Earth Communication: 1 hr

Group Socialization, Meetings, Life Sciences Subject, Health Monitoring, Health Care: 1 hr

System Monitoring, Inspection, Calibration, Maintenance, Repair: 1 hr

Production	
Site Prep, Construction	90 days
Verification	
Week Off	7 days
Local Excursions	
Analysis	100 days
Distant Excursion	10 days
Analysis	40 days
Week Off	7 days
Distant Excursion	
Analysis	
Distant Excursion	
Analysis	
Week Off	100 days
Distant Excursion	
Analysis	
Distant Excursion	
Analysis	
Flare Retreat	15 days
Week Off	7 days
Distant Excursion	
Analysis	
Distant Excursion	100 days
Analysis	
Week Off	7 days
Sys Shutdown Departure Prep	60 days

Charge Fuel Cells
Check Vehicle
Load Vehicle
Plan Excursion
Drive Vehicle
Navigate
Don Suits (X 20)
Pre-breathe (X 20)
Egress (X 20)
Unload Equip
Set up Drill (X 10)
Operate Drill
Collect Samples
In Situ Analysis
Take Photos
Communicate
Disassemble Equip
Load Vehicle
Ingress (X 20)
Clean Suit (X 20)
Stow Suit, Equip
Inspect Vehicle
Secure for night
(Sleep, eat, cleanup
hygiene, etc.
covered)

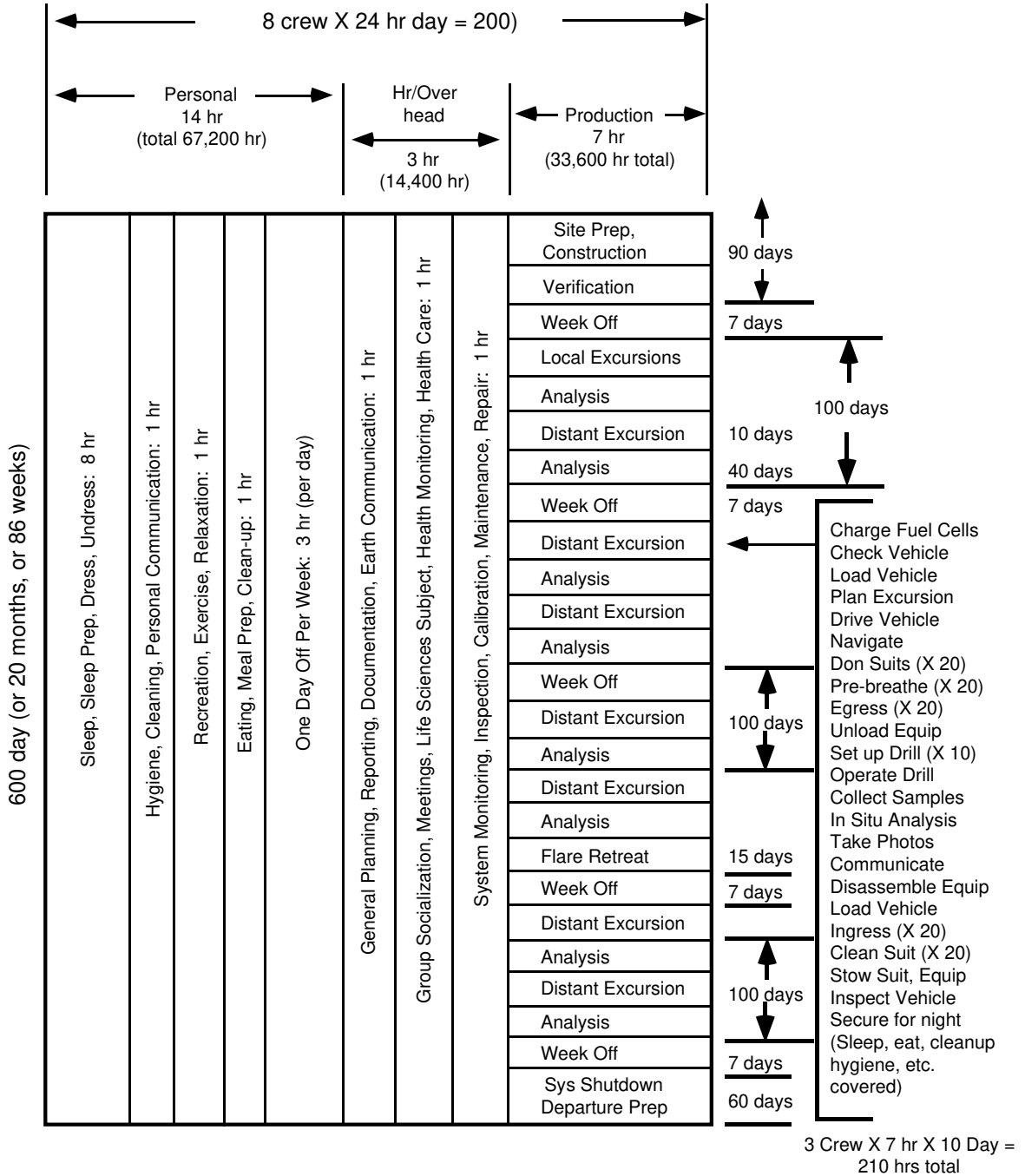3 Crew X 7 hr X 10 Day =
210 hrs total

Figure 3-10 Possible surface mission time line.

in accordance with the protocols in effect at the time. The crew's re-adaptation to a 1-g environment will be monitored in detail to learn more about how the human body adapts to the varying gravity conditions and to better prepare for the return of subsequent crews.

3.5.4.3 Third Mission: Second Flight Crew, 2011 Opportunity

In the third opportunity opening in December 2011, two additional cargo missions and the second crew mission will be launched. As in the second opportunity, all assets previously delivered to Mars are checked out and the MAV is verified to be fully fueled. Any non-mission-critical maintenance items identified by the first crew or items noted prior to the departure of Flights 7 through 9 are added to the spares manifest and delivered with other surface equipment. Table 3-6 lists the manifested payloads for launch in the 2011 opportunity.

Prior to the arrival of the second crew, the ISRU plants are producing not only the propellants needed for the ascent vehicle, but also water, oxygen, and buffer gases to serve as an emergency cache for the life support system. Teleoperated rovers are deployed on extended traverses, perhaps to distances of more than 100 kilometers, to take measure-ments, gather samples, and reconnoiter sites for the human crew to investigate in more detail.

Figure 3-11 illustrates the surface outpost configuration at the end of the second crew's stay.

As before, the second crew will continue with the general type of activities conducted by the first crew: diverse observations by robotic vehicles and human explorers, collection of samples and their examination in the outpost laboratory, and experiments designed to gauge the ability of humans to inhabit Mars. Specific crew activities will build on the lessons learned and questions generated by the first crew. Table 3-7 lists a representative set of science and exploration equipment that will be delivered as part of the cargo on Flight 8. Note in particular that this manifest contains a drill designed to reach depths of 1 kilometer. (The deep drilling operation must be consistent with planetary protection protocols.) This tool will be used to gather subsurface core samples that will help reconstruct the geologic history of Mars, and to try to locate subsurface deposits of water in either liquid or solid form. Such a discovery will substantially enhance the habitability prospects for future crews by possibly upgrading propulsion systems to the use of hydrogen and oxygen and expanding agricultural activities.

The second crew will repeat the activities of the first crew in preparing themselves, the ascent vehicle, and the surface habitat for a departure from Mars during December 2013. The third crew will already be in transit to

Table 3-6 General Launch Manifest: 2011 Launch Opportunity

Flight 7: Cargo	Flight 8: Cargo	Flight 9: Second Crew
Surface Payload		
• None	• Ascent Capsule • Empty Ascent Stage • LOX/CH$_4$ Production Plant • LH$_2$ Propellant Seed • Pressurized Rover • Science Equipment • Additional Payload/ Spares	• Crew • Surface Habitat • Consumables • Spares • EVA Equipment • Science Equipment
Mars Orbit Payload		
• Earth-Return Vehicle • Fueled (LOX/CH$_4$) TEI Stage • Transit Habitat • Earth-Return Capsule	• None	• None
Space Transportation Vehicles		
• NTR Transfer Stage • LOX/CH$_4$ TEI Stage w/Mars Aerobrake	• NTR Transfer Stage • LOX/CH$_4$ Descent Stage w/Mars Aerobrake	• NTR Transfer Stage • LOX/CH$_4$ Descent Stage w/Mars Aerobrake

TEI: Trans Earth Injection   LOX: liquid oxygen   LH$_2$:   liquid hydrogen
NTR: Nuclear Thermal Rocket   CH$_4$:   methane

Mars, again necessitating a debriefing of the second crew, with participation by the third crew, during the return to Earth. Once on Earth, the second crew will likely benefit from observations of the first crew, particularly in the areas of modifications to the re-adaptation regime and quarantine protocols.

3.5.4.4 Fourth Mission: Third Flight Crew, 2014 Opportunity

In the fourth opportunity opening in March 2014, the final two cargo missions and

the third crew mission will be launched. As in the second and third opportunities, all assets previously delivered to Mars are checked out and the MAV is verified to be fully fueled. Any non-mission-critical maintenance items identified by the first two crews or items noted prior to the departure of Flights 10 through 12 are added to the spares manifest and delivered with other surface equipment. Table 3-8 lists the manifested payloads for launch in the 2014 opportunity. As listed, the manifests do not use the full cargo-carrying
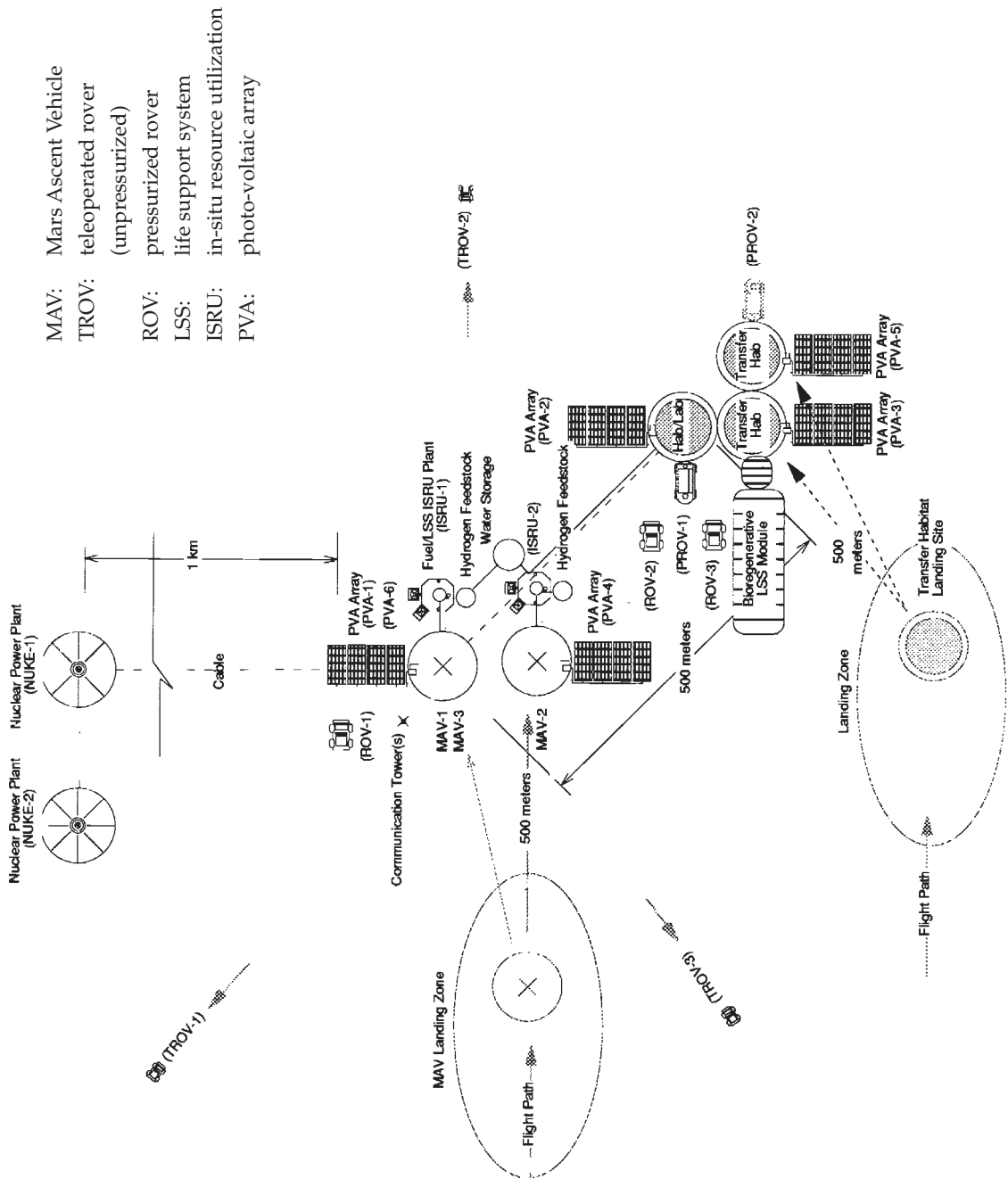
Figure 3-11 Mars surface outpost at the end of second flight crew's stay.

Table 3-7 Surface Science Payload for Second Flight Crew

Payload Description	Payload Mass (kg)
Field Geology Package: geologic hand tools, cameras, sample containers, documentation tools	335
Geoscience lab instruments: microscopes, geochemical analysis equipment, camera	125
Exobiology laboratory: enclosures, microscopes, culture media	50
Biomedical laboratory	500
Plant and animal lab	500
Traverse geophysics instruments	400
Geophysics/meteorology instruments (8 sets)	200
1 kilometer drill	20,000
10-meter drill	260
Meteorology balloons	200
Discretionary PI science	600
Total	**23,000**

capacity of the landers. The experience gained by the first two crews will dictate any additional equipment that can be used to either upgrade existing equipment or add new equipment to enhance the capabilities of this outpost.

Prior to the arrival of the third crew, the ISRU plants are again producing not only the propellants needed for the ascent vehicle, but also water, oxygen, and buffer gases to serve as an emergency cache for the life support system. Teleoperated rovers are again deployed on extended traverses to take measurements, gather samples, and reconnoiter sites for the third crew to investigate in greater detail.

Figure 3-12 illustrates the surface outpost configuration at the end of the third crew's stay. This represents the complete outpost configuration as envisioned by the Mars Study Team. With the facilities and capabilities available at this stage, the surface outpost will be able to support larger crews for longer periods of time. The potential level of self-sufficiency on Mars should also be evident by this time, and a decision can be made regarding any further use or expansion of the outpost.

As before, the third crew will continue with the general type of activities conducted by the first and second crews: diverse observations by robotic vehicles and human explorers, collection of samples and their examination in the outpost laboratory, and experiments designed to gauge the ability of humans to inhabit Mars. Specific crew activities will build on the lessons learned and questions generated by the first two crews and should be focused on providing information needed to determine the future status of the outpost. Table 3-9 lists a representative set of science and exploration

Figure 3-12 Mars surface outpost at the end of third flight crew's stay.

MAV: Mars Ascent Vehicle
TROV: teleoperated rover (unpressurized)
ROV: pressurized rover
LSS: life support system
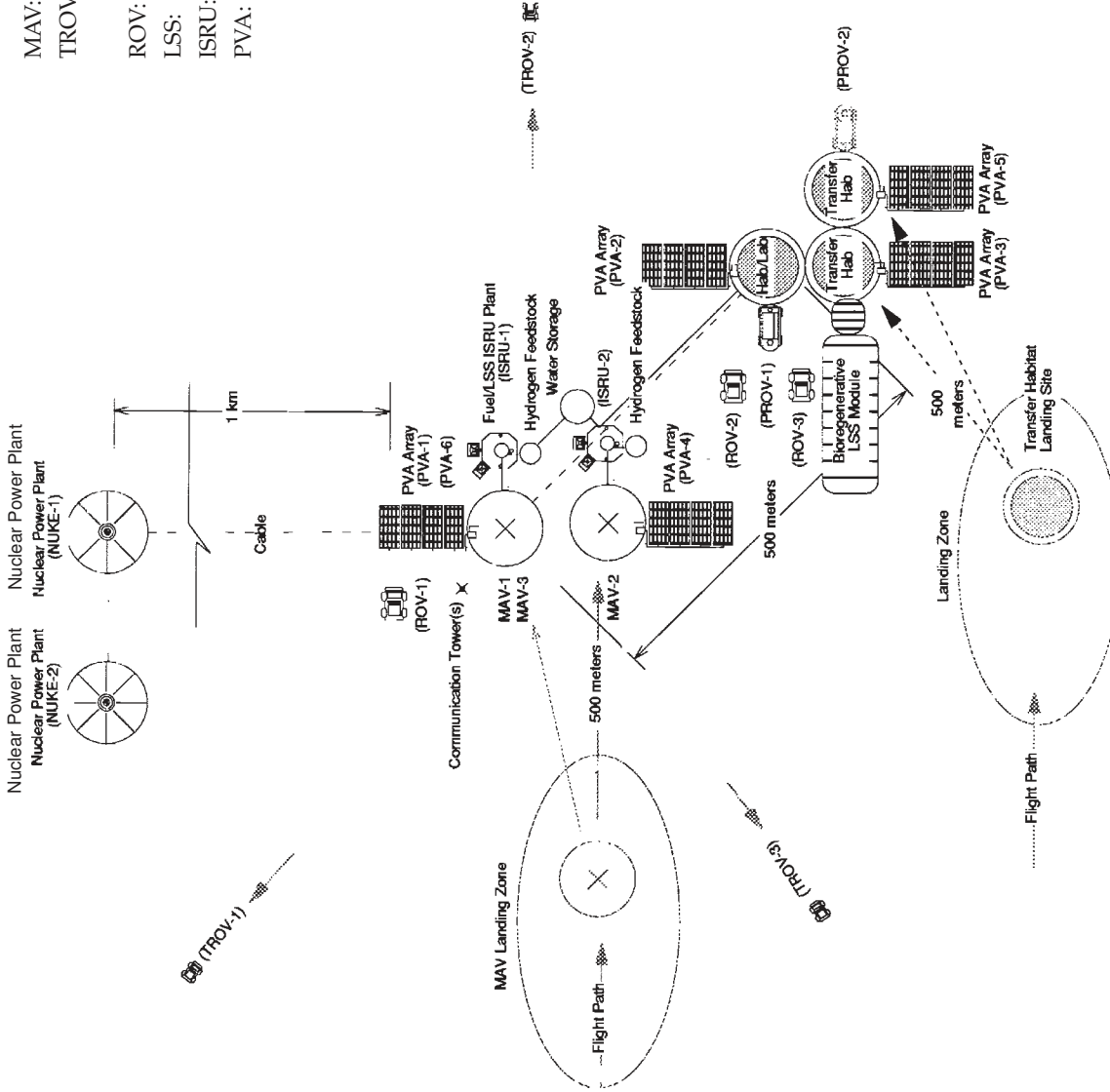ISRU: in-situ resource utilization
PVA: photo-voltaic array

Table 3-8 General Launch Manifest: 2014 Launch Opportunity

Flight 10: Cargo	Flight 11: Cargo	Flight 12: Third Crew
Surface Payload		
• None	• Ascent Capsule • Empty Ascent Stage • LOX/CH$_4$ Production Plant • LH$_2$ Propellant Seed • Science Equipment • Additional Payload/ Spares	• Crew • Surface Habitat • Consumables • Spares • EVA Equipment • Science Equipment
Mars Orbit Payload		

• Earth-Return Vehicle
  • Fueled (LOX/CH$_4$) TEI Stage
  • Transit Habitat
  • Earth-Return Capsule
	• None	• None

Space Transportation Vehicles		
• NTR Transfer Stage • LOX/CH$_4$ TEI Stage w/Mars Aerobrake	• NTR Transfer Stage • LOX/CH$_4$ Descent Stage w/Mars Aerobrake	• NTR Transfer Stage • LOX/CH$_4$ Descent Stage w/Mars Aerobrake

TEI:	Trans Earth Injection	LOX:	liquid oxygen	LH$_2$:	liquid hydrogen
NTR:	Nuclear Thermal Rocket	CH$_4$:	methane		

equipment that will be delivered as part of the cargo on Flight 11.

As with the first two crews, the third crew will repeat those activities necessary to prepare themselves, the ascent vehicle, and the surface habitat for a departure from Mars during January 2016.

3.5.4.5 Mission Summary

This section has illustrated a feasible sequence of missions that can satisfy the Reference Mission goals and objectives. These missions use assumed hardware systems and mission design principles to place the flight crews in the martian environment for the longest period of time at a satisfactory level of risk. The major distinguishing characteristics of the Reference Mission, compared to previous concepts, include:

• No extended LEO operations, assembly, or fueling

• No rendezvous in Mars orbit prior to landing

Table 3-9 Surface Science Payload for Third Flight Crew

Payload Description	Payload Mass (kg)
Field Geology Package: geologic hand tools, cameras, sample containers, documentation tools	335
Geoscience lab instruments: microscopes, geochemical analysis equipment, camera	125
Exobiology laboratory: enclosures, microscopes, culture media	50
Plant and animal lab	500
Traverse geophysics instruments	400
Geophysics/meteorology instruments (8 sets)	200
Advanced Meteorology Laboratory	1000
10-meter drill	260
Meteorology balloons	200
Discretionary PI science	1000
Total	**4070**

- Short transit times to and from Mars (180 days or less) and long surface stay-times (500 to 600 days) for the first and all subsequent crews exploring Mars

- A heavy-lift launch vehicle (HLLV), capable of transporting either crew or cargo direct to Mars, and capable of delivering all needed payload with a total of four launches for the first human mission and three launches of cargo and crew for each subsequent opportunity

- Exploitation of indigenous resources from the beginning of the program, with important performance benefits and reduction of mission risk

- Availability of abort-to-Mars-surface strategies, based on the robustness of the Mars surface capabilities and the cost of trajectory aborts

The characteristics of the hardware systems used in these missions are more completely discussed in the following sections.

3.6   Systems

The following sections discuss the characteristics and performance capabilities of the various hardware elements needed for the Reference Mission. The hardware elements include a launch vehicle large enough to place cargo bound for Mars into a suitable Earth parking orbit, the interplanetary transportation elements necessary to move crew and equipment from Earth to Mars and back, and the systems needed to sustain the crew and perform the proposed exploration activities on the martian surface. Each section describes the principal characteristics of the hardware system as developed by the Mars Study Team.

3.6.1 Operational Design Considerations

Several operational factors related to utilization, training, and repair influence the design of hardware and software systems for all vehicles. Early incorporation of these factors into the vehicle design process will enhance utility and functionality of the systems, prevent costly workarounds late in the development cycle, and maximize overall mission success.

This section discusses some of the design considerations identified as important in the eventual detailed design and construction of systems used for the Reference Mission. While the system descriptions in the sections that follow may not reach a level of detail that reflects the specific topics mentioned here, the design considerations should be considered as guiding principles that should be used as more detailed studies are performed.

A primary operational consideration in system development is the subsequent ease with which users, specifically crew members, can become familiar with the system prior to the mission. The more familiar crew members are with vehicle hardware and software, the less time will be spent on systems operations and the more time will be available for science and exploration activities. By the same token, the more familiar technicians are with the systems, the easier and less costly production, maintenance, and repair will be during the development process. To facilitate this, all vehicles and systems need to use common hardware and software where applicable. System commonality in power sources, interfaces, payload locker sizes, etc., among all vehicles will ease nominal operational activities such as replacements, reconfigurations, and hardware transfers. Commonality will also help maintain corporate knowledge bases and simplify crew operations and repair procedures as experience with one system can be applied to many. The cost savings associated with the use of common hardware and software elements are obvious, and may be increased by using as much off-the-shelf hardware as possible. This, too, helps with familiarity as crews and technicians may have previous experience with similar systems. Repair operations will also be simplified by requiring a smaller set of standard tools for use by the crew during mission execution.

The need for training facilities will have a significant impact on vehicle design. Due to the extended duration of the mission, training facilities will be required on board crew vehicles during various phases of the mission. Trainers on Earth will need to match trainers on vehicles which in turn will need to match actual system performance. The requirement for crew training facilities during various mission phases will place additional hardware and software design constraints on the vehicles. Incorporation of training facilities into appropriate vehicles is an important operational factor influencing the design process.

For both crew safety and operational simplicity, system designs will require some level of automatic fault detection for all life-critical, mission-critical, and mission-discretionary elements. For those elements pertaining to crew safety and mission-critical objectives, auto-fault detection and correction should be incorporated into the design. Crew action should not be required for life-critical systems failures; backup system activation should be automatic. Mission-critical system failures should be as automated as possible, leaving only the most complex tasks (such as complete hardware replacement or repair) to the crew. In addition, many of the routine, yet important, system operations should be automated to the greatest extent possible. For example, an often overlooked aspect of operations is consumables tracking and forecasting for all life-critical and mission-critical systems. Crew time is better spent on science activities than on tracking and forecasting consumables such as propellant, water, and breathable air. Many of these functions are currently done for Space Shuttle crews by flight controllers on the ground. Due to the long delay time in communications during the Reference Mission, maintenance of this function by ground personnel is impractical. Periodic verification of consumables tracking activities by ground personnel can validate the crew activities; however, means by which the crew can independently monitor and forecast propulsive and nonpropulsive consumables while not expending significant resources is a necessity. Where cost effective, mission-

discretionary system failures can require some crew response to enhance mission objectives. A balance between the cost of automation and crew time and training for such activities will be needed. In general, maximizing crew science time and minimizing crew system maintenance and operations throughout the mission will improve overall mission success.

3.6.2 Launch Vehicles

The scale of the ETO launch capability is fundamentally determined by the mass of the payload that will be landed on the martian surface. The nominal design mass for individual packages to be landed on Mars in the Reference Mission is 50 tonnes for a crew habitat (sized for six people) which must be transferred on a high-energy, fast-transit orbit. This in turn scaled the required mass in LEO to about 240 tonnes.

A number of different technologies could be used to construct a single launch vehicle capable of placing 240 tonnes into a 220-nautical mile circular orbit. These launch vehicle concepts used various combinations of past, present, and future U.S. expendable launch vehicle technology and existing launch vehicle technology from Russia and Ukraine. Table 3-10 summarizes some of the key parameters for a representative set of the vehicle options examined (Huber, 1993). Each option is covered in more detail in the following paragraphs.

Option 1 (Figure 3-13) illustrates the capabilities possible through the use of

Energia and Zenit launch vehicle technology combined with STS technology. All of the engines used for this option are existing types that have flown numerous times. The core stage is assumed to be a modification of the existing Energia stage. The modification involves changing the vehicle from one that uses a side-mounted payload container to an in-line configuration with strap-on boosters surrounding the core. The upper stage is a new development using STS external tank technology combined with a single SSME. The shroud is entirely new and would be sized for the largest of the Reference Mission payloads. Note, however, that this combination of largely existing components does not meet the desired payload launch mass.

Option 2 (Figure 3-14) illustrates what is possible if a large launch vehicle makes extensive use of existing STS and Russian technology. The first stage core and upper stage use the SSME, and the propellant tank structure is based on the STS external tank. Strap-on boosters for this vehicle use the Russian RD-170 engine and a newly designed propellant tank structure. Note that this combination also does not meet the desired payload launch mass.

Table 3-10 Launch Vehicle Concepts for the Reference Mission

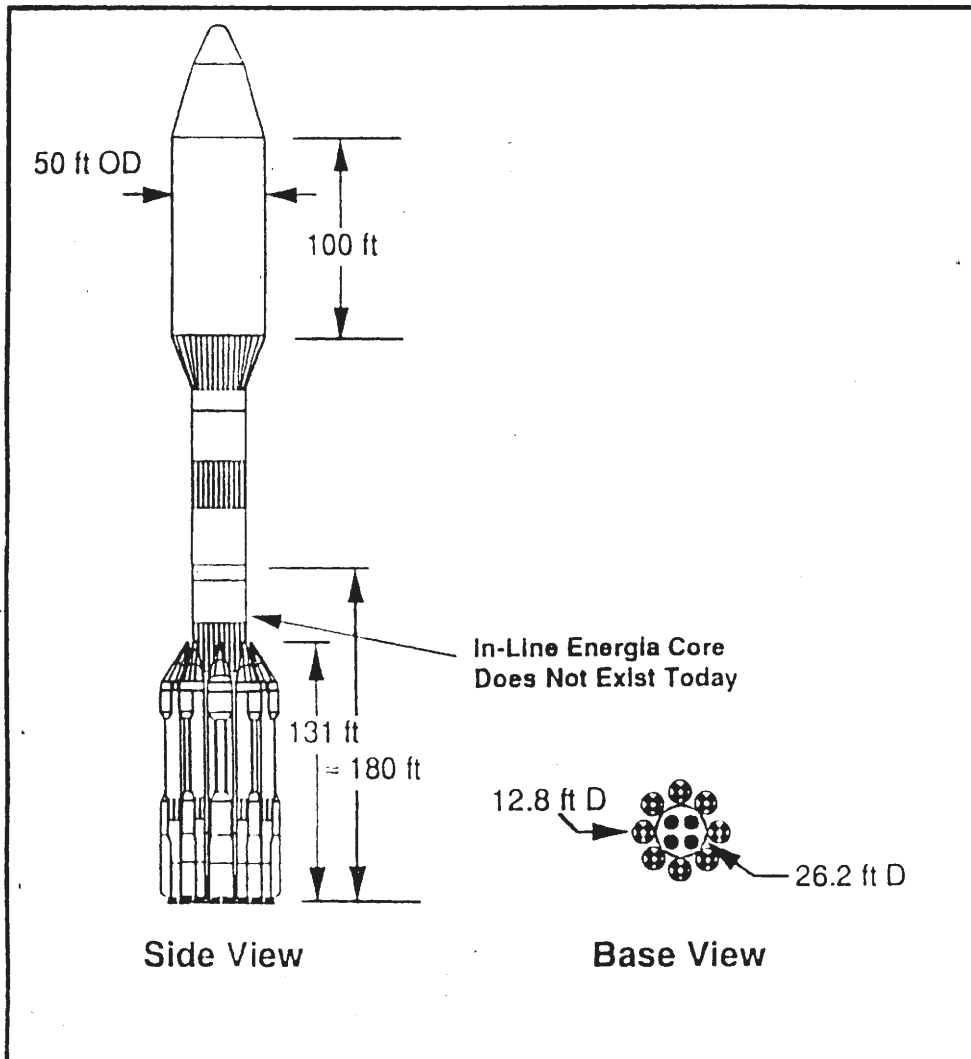| Option	Payload Mass (tonnes) to 220 n.mi. Circular Orbit	Key Technology Assumptions
1	179	Modified Energia core with eight Zenit-type strap-on boosters. New upper stage using a single Space Shuttle Main Engine (SSME).
2	209	New core stage based on Space Transportation System (STS) external tank and SSMEs. Seven new strap-on boosters each use a single RD-170 engine. New upper stage using a single SSME.
3	226	New core stage based on STS external tank and four of the new Space Transportation Main Engines. Four strap-on boosters each with a derivative of the F-1 engine used on the first stage of the Saturn V. New upper stage using a single SSME.
4	289	New vehicle using technology derived from the Saturn V launch vehicle. Boosters and first stage use a derivative of the F-1 engine, and the second stage uses a derivative of the J-2 engine.

50 ft OD

100 ft

**In-Line Energia Core
Does Not Exist Today**

131 ft

≈ 180 ft

12.8 ft D

26.2 ft D

Side View

Base View

Figure 3-13 Mars Energia-derived HLLV with eight Zenit-type boosters.
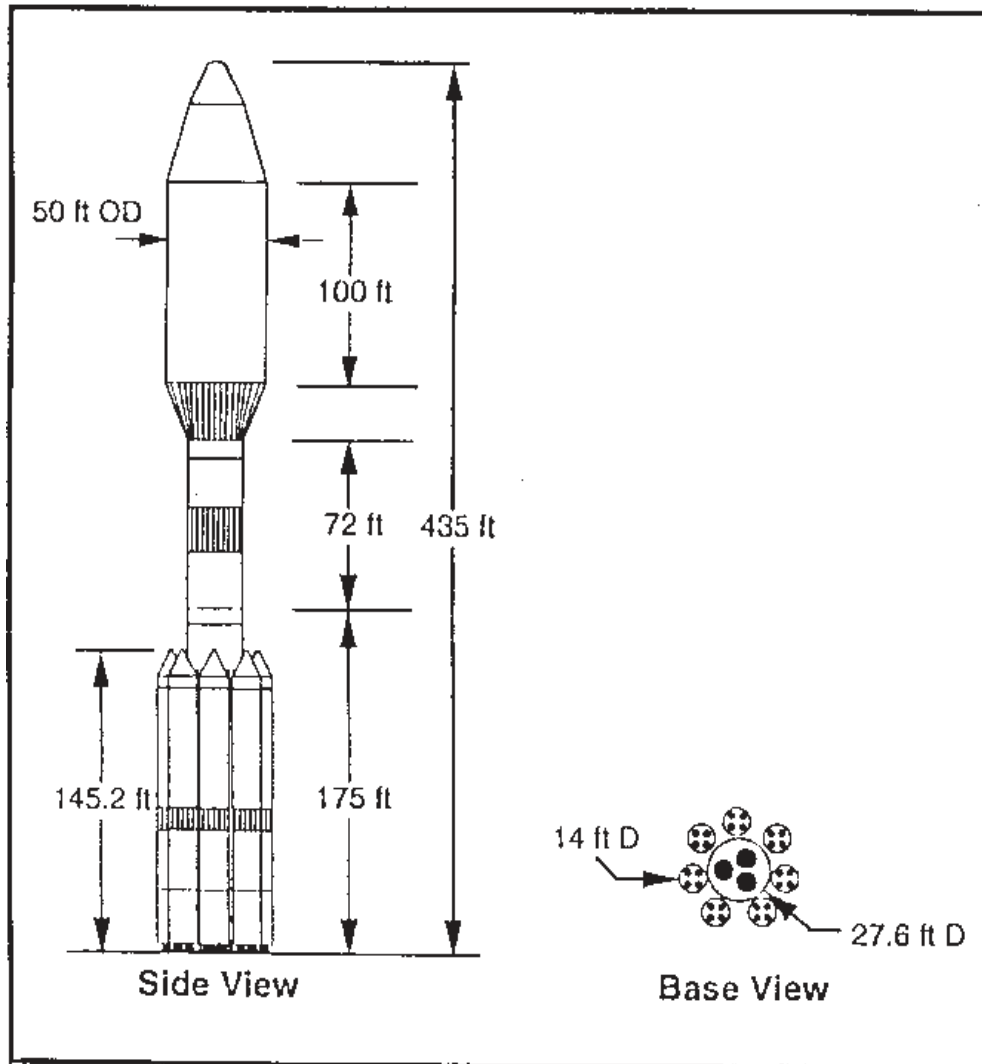
Figure 3-14 STS External Tank-derived HLLV with seven LOX/RP boosters.

Option 3 (Figure 3-15) uses new and old as well as existing technology to create a vehicle that can deliver a payload that is reasonably close to the desired value. The first stage core propellant tank structure is based on the STS external tank but uses newly designed and as yet untested STME engines. The strap-on boosters use an updated version of the F-1 engine that powered the first stage of the Saturn V in conjunction with newly designed propellant tanks. The upper stage is comparable to those discussed for the first two options, using STS external tank technology and a single SSME.

Option 4 (Figure 3-16) is indicative of a launch vehicle that uses technology derived from the Saturn V launch vehicle. The first stage core is virtually identical to the first stage of the Saturn V launch vehicle in its basic size and its use of five F-1A engines. Strapped to this stage are four boosters, each with two F-1A engines and roughly one-third of the propellant carried by the core stage. The second stage uses six of the J-2 engines that powered the second stage of the Saturn V. However, this upper stage is considerably larger than the Saturn second stage.

This last option was the largest of a family of launch vehicles derived using Saturn V launch vehicle technology. Figure 3-17 illustrates some of the other vehicle configurations examined and provides additional information on their capabilities. All of these options can deliver a payload almost as large as the stated need for 240 tonnes in a 220-nautical mile circular orbit.

Because a 240-ton-class launch vehicle would be such a development cost issue, consideration was given to the option of launching several hardware elements to LEO using smaller vehicles, assembling (attaching) them in space, and then launching on the outbound trajectory to Mars. This smaller launch vehicle (with a 110- to 120-ton payload capability) would have the advantage of more modest development costs and is in the envelope of capability demonstrated by the unmodified U.S. Saturn V and Russian Energia programs (Figure 3-18). However, this smaller launch vehicle introduces several potential difficulties to the Reference Mission scenario. The most desirable implementation using this smaller launch vehicle is to simply dock the two elements in Earth orbit and immediately depart for Mars. To avoid boiloff losses in the departure stages (assumed to use liquid hydrogen as the propellant), all elements must be launched from Earth in quick succession, placing a strain on existing launch facilities and ground operations crews. Assembling the Mars vehicles in orbit and loading them with propellants just prior to departure may alleviate the strain on launch facilities, but the best Earth orbit for Mars missions is different for each launch opportunity, so a permanent construction and/or propellant storage facility in a single Earth orbit introduces additional constraints.

Several launch vehicle designs that could provide this smaller payload capability using existing or near-term technology were examined. Figure 3-19 illustrates one possible
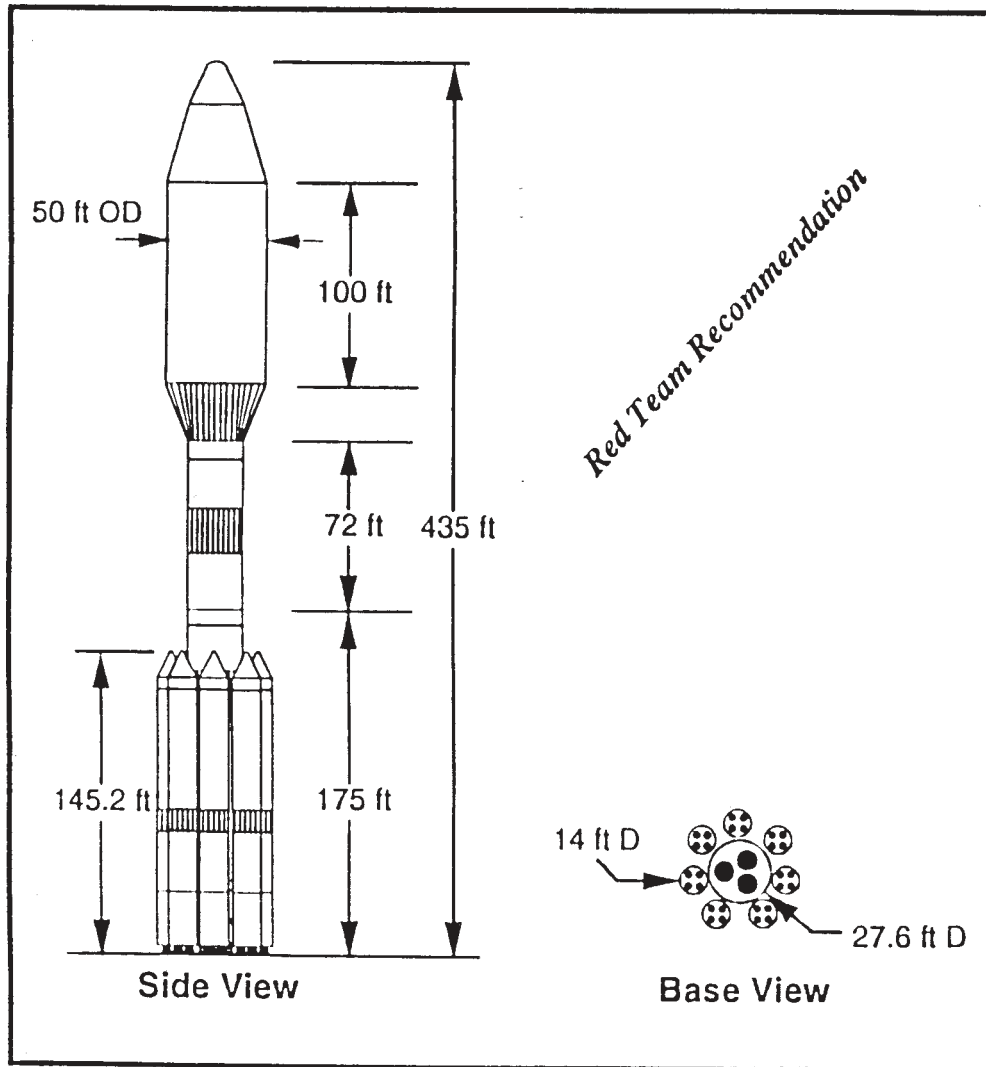
Figure 3-15 STS External Tank-derived HLLV with four strap-on boosters, each having two F-1 engines.
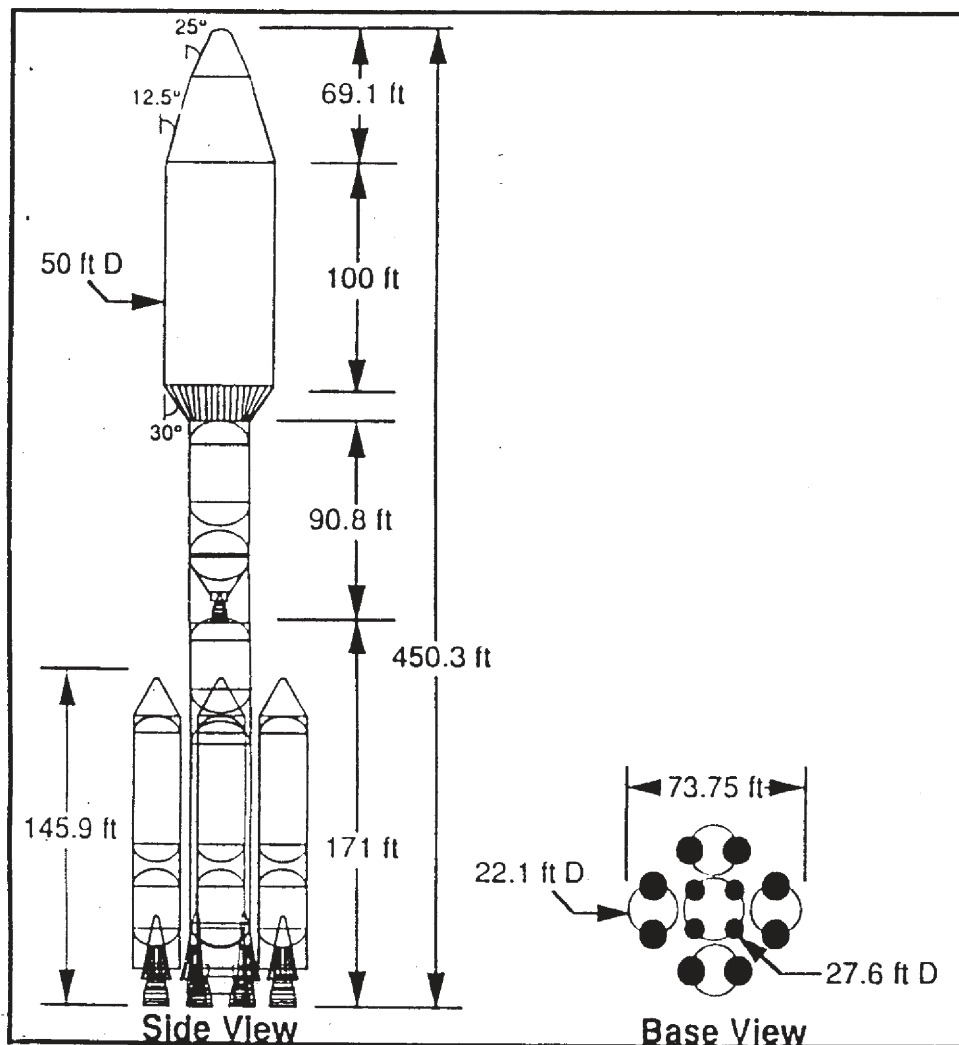
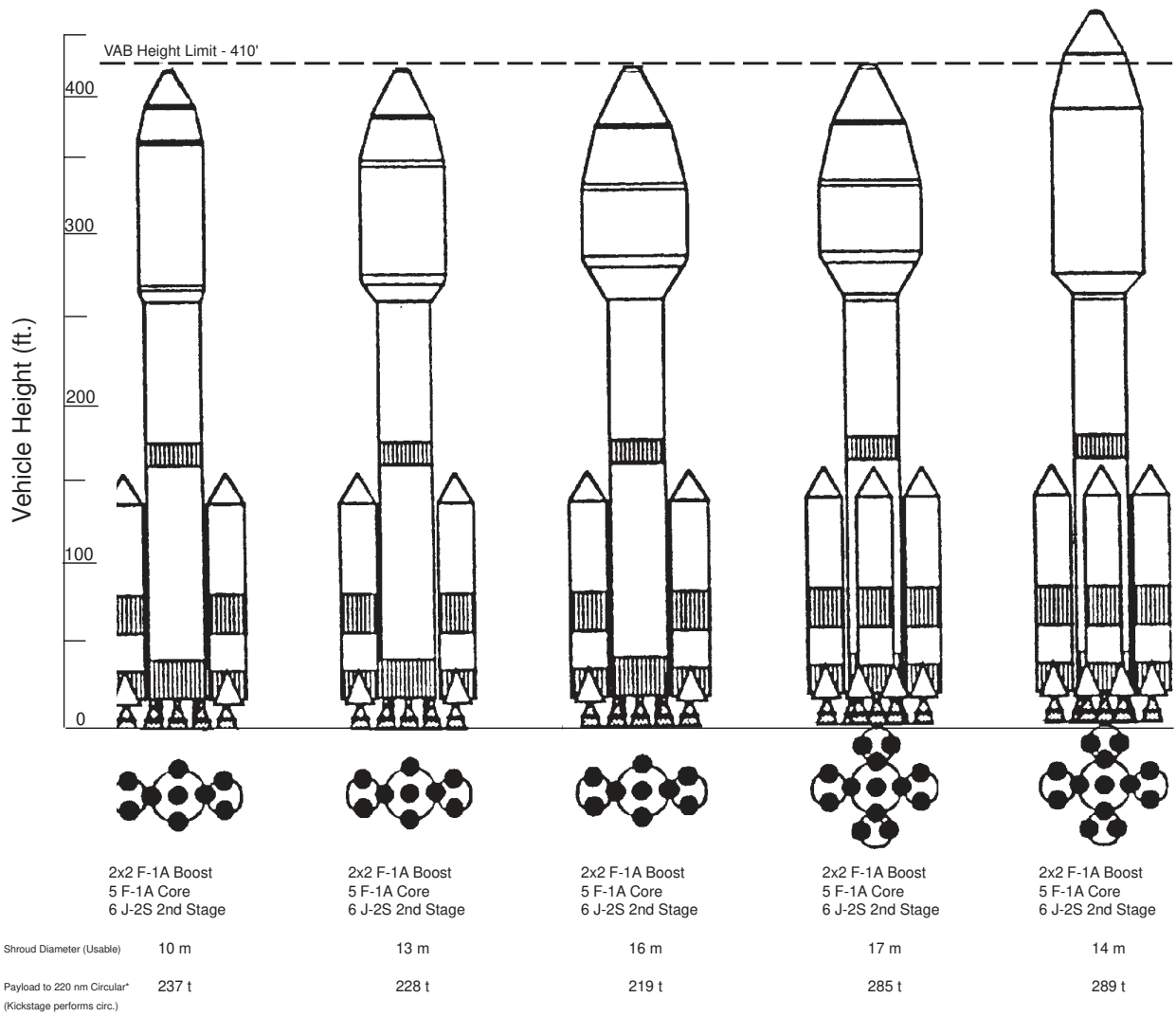**Figure 3-16 Saturn V-derived Mars HLLV with F-1A/J-2S propulsion.**

Figure 3-17 Saturn V-based Mars HLLV concepts.

Figure 3-18 Energia launch vehicle adapted to Mars mission profile.

320 ft

172 ft

27.6 ft D
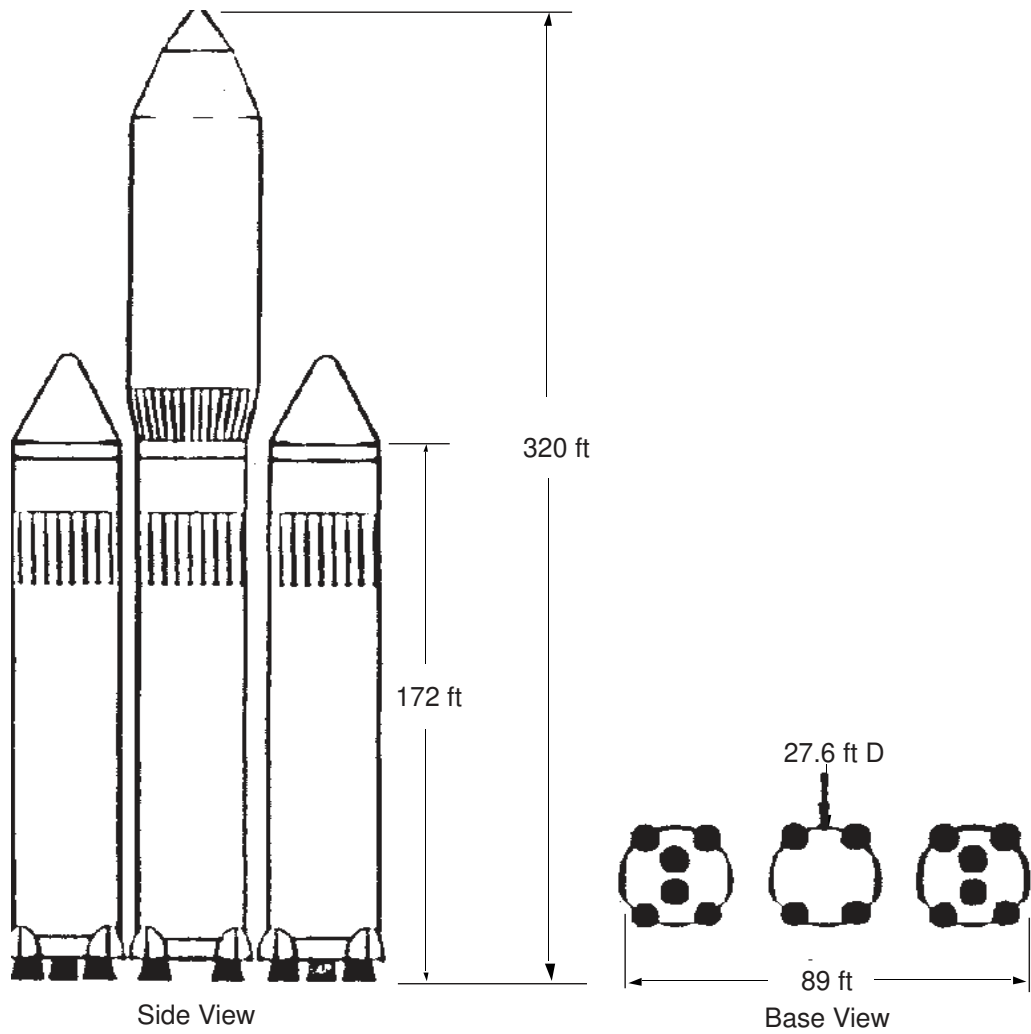
89 ft

Side View

Base View

Figure 3-19 Mars mission launch vehicle with two external tank boosters and kick stage.

vehicle configuration and provides additional information on its capabilities. This particular option uses the STS external tank for its propellant storage and main structure. Engines for the core stage and the two strap-on boosters were assumed to be the STME engine that was under development at the time of this study.

A 240-ton payload-class launch vehicle is assumed for the Reference Mission. However, it is beyond the experience base of any spacefaring nation. While such a vehicle is possible, it would require a significant development effort for the launch vehicle, launch facilities, and ground processing facilities; and its cost represents a considerable fraction of the total mission cost. The choice of a launch vehicle remains an unresolved issue for any Mars mission.

3.6.3   Interplanetary Transportation

The interplanetary transportation system assembled for the Reference Mission consists of seven major systems: a TMI stage, a biconic aeroshell for Mars orbit capture and Mars atmospheric entry, habitation systems for the crew (both outbound and return), a descent stage for landing on the surface, an ascent stage for crew return to Mars orbit, an ERV for departure from the Mars system, and an ECCV (comparable to Apollo) for Earth entry and landing. As mentioned earlier, the Reference Mission splits the transportation of people and equipment into cargo missions and human missions, all of which are targeted to the same locale on the surface and must be landed in close proximity to one another. The transportation strategy adopted in the Reference Mission eliminates the need for assembly or rendezvous in LEO of vehicle elements and for rendezvous of a crew transport vehicle with a Mars lander in Mars orbit, both features of many previous mission designs for Mars (NASA, 1989). But the Reference Mission scenario does require a rendezvous on the surface with previously landed hardware elements and a rendezvous in Mars orbit with the ERV as the crew leaves Mars. The transportation strategy emphasized the use of common elements wherever possible to avoid development costs and to provide operational simplicity.

3.6.3.1 Trans-Mars Injection Stage

A single TMI stage was developed for both piloted and human missions. The stage is designed for the more energetically demanding 2009 human mission and is then used in the minimum energy cargo missions to launch the maximum payload possible to Mars. Because of the energetic trajectories used for human flights and the desire to deliver large payloads to the martian surface, nuclear thermal propulsion was selected for this stage not only for its performance advantages but also because of its advanced, previously demonstrated state of technology development, its operational flexibility, and its inherent mission enhancements and crew risk reduction (Borowski, et al., 1993).

After completion of two TMI burns (required by the selected thrust-to-weight

ratio), the stage is disposed of by allowing it to drift on a relatively stable interplanetary trajectory. Calculations (Stancati and Collins, 1992) using the Planetary Encounter Probability Analysis code indicate that the probability of a collision of a nuclear engine-equipped vehicle and the Earth is quite low. The probabilities of a collision with Earth in one million years are 3.8 percent for the piloted TMI stages and 12 percent for the cargo TMI stages.

The basic TMI stage is shown in Figure 3-20. For piloted missions, the TMI stage uses four 15,000 lb. thrust NERVA* derivative (ND) engines to deliver the crew and their surface habitat/descent stage onto the trans-Mars trajectory. Engines of this size are well within the previous development history of NERVA engines (Borowski, et al., 1993). This version of the TMI stage incorporates a shadow shield between the ND engine assembly and the LH_2 tank to protect the crew from radiation generated by the engines that will have built up during the TMI burns. For cargo missions, this transportation system can deliver approximately 65 tonnes of useful cargo to the surface of Mars or nearly 100 tonnes to Mars orbit (250 I 33,793 km) on a single launch from Earth. The TMI stage for cargo delivery requires only the use of three

_____

From 1955 to 1973, the Nuclear Engine for Rocket Vehicle Application (NERVA) program designed, built, and tested a total of twenty rocket reactors. The feasibility of using low molecular weight LH2 as both a reactor coolant and propellant was convincingly demonstrated.
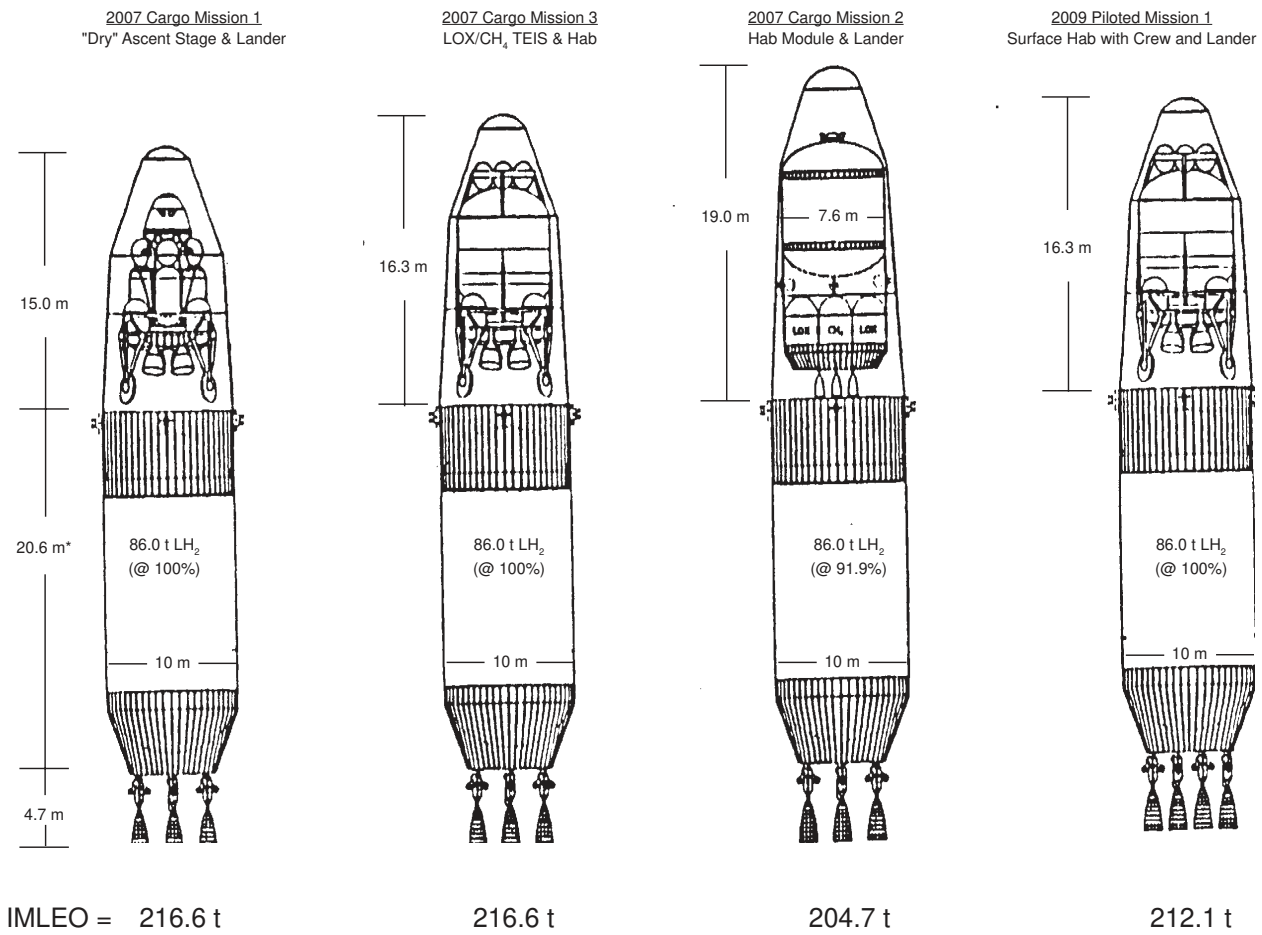
ND engines. So for cost and performance reasons, one ND engine and the shadow shield are removed from this version of the TMI stage.

The TMI stage adopted for the Reference Mission could be designed around any of four reactor options studied by the Team: (1) Rocketdyne and Westinghouse NERVA-derivative reactor (ND), (2) Pratt and Whitney and Babcock and Wilcox (B&W) CERMET fast reactor, (3) Aerojet and B&W particle bed reactor and (4) Russian Energopool and B&W engine concept using the "twisted ribbon" ternary carbide fuel form. Work done in Russia is especially promising, with the possibility of higher Isp (approximately 950 seconds versus a 900-second demonstrated capability by NERVA engines) at a thrust-to-weight ratio of about 3.0 (for a 15,000 pound thrust engine) being a possible development target. The Reference Mission adopts the more conservative ND engine concept, with a projected Isp performance of 900 seconds. Table 3-11 lists the mass estimates for the various components of the TMI stage for piloted and cargo versions. In both versions, this stage is assumed to have a maximum diameter of 10 meters and an overall length of 25.3 meters.

3.6.3.2 Biconic Aeroshell

On each cargo and piloted mission, Mars orbit capture and the majority of the Mars descent maneuver are performed using a single biconic aeroshell. The decision to perform the Mars orbit capture maneuver

2007 Cargo Mission 1	2007 Cargo Mission 3	2007 Cargo Mission 2	2009 Piloted Mission 1
"Dry" Ascent Stage & Lander	LOX/CH$_4$ TEIS & Hab	Hab Module & Lander	Surface Hab with Crew and Lander

15.0 m

20.6 m*

4.7 m

86.0 t LH$_2$ (@ 100%)

10 m

16.3 m

86.0 t LH$_2$ (@ 100%)

10 m

19.0 m   7.6 m

86.0 t LH$_2$ (@ 91.9%)

10 m

16.3 m

86.0 t LH$_2$ (@ 100%)

10 m

IMLEO =   216.6 t   216.6 t   204.7 t   212.1 t

* Expendable TMI Stage LH2 Tank (@ 18.2 m length) sized by 2009 Mars Piloted Mission

IMLEO   Initial Mass to Low Earth Orbit
TEIS   Trans Earth Injection Stage

Figure 3-20 Reference Mars cargo and piloted vehicles.

### Table 3-11 Mass Estimates for TMI Stage Alternatives

TMI Stage Element	Piloted Version	Cargo Version
ND Engines (4 for piloted, 3 for cargo)	9.8	7.4
Radiation Shield	0.9	0.0
Tankage and Structure	18.4	18.4
LH$_2$ Propellant (maximum)	86.0	86.0
Control System Tankage and Propellant	3.1	3.0
Total (tonnes)	**118.2**	**114.8**

using an aeroshell (that is, aerocapture) was based on the fact that this option typically requires less mass than an equivalent propulsive capture stage (Cruz, 1979), and aerodynamic shielding of some sort will be required to perform the Mars descent maneuver no matter what method is used to capture into Mars orbit. Previous Mars mission concepts employing aerocapture have typically used more than one aeroshell to deliver the crew to the surface. The use of two aeroshells was driven by one or both of the following factors. First, Mars entry speeds may have been higher than those proposed for the Reference Mission and therefore more maneuverability and thermal protection were required for this phase of the mission. Second, the mission profile may have required a post-aerocapture rendezvous in Mars orbit with another space transportation element, possibly delivered during the same launch opportunity or during a previous opportunity. Neither of these features is in the Reference Mission. Thus, the strategy employed was to develop a single family of

biconic aeroshells that can be used for both Mars orbit capture and descent maneuvers. Given the demands on a descent aeroshell of the Mars entry and landing requirements, the additional capability to permit aerocapture is considered modest.

The aerodynamic maneuvering and thermal protection requirements for the aeroshells used in the Reference Mission were studied in some detail (Huber, 1993). Based on the studies, it was determined that a biconic aeroshell with similar forward and aft conic sections provided sufficient maneuverability for the aerocapture and entry phases of flight. Figure 3-21 illustrates two of these aeroshells, one for the Mars ascent vehicle and the other for the surface habitat. For this family of aeroshells, the nose section is a 25° half-angle cone ending in a spherical cap. The skirt section is a 4° half-angle cone with a 10-meter diameter base. The skirt section consists of two parts: a fixed length aft section and a variable length center section ("center" indicating its location between the aft skirt and the nose section).
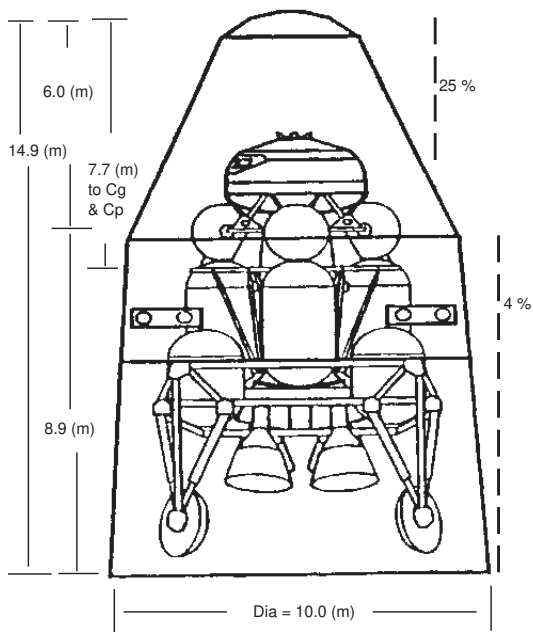
Reference Biconic: 10 (m) Dia by 15 (m)
length. I/D = 0.65 At 25° Angle of Attack
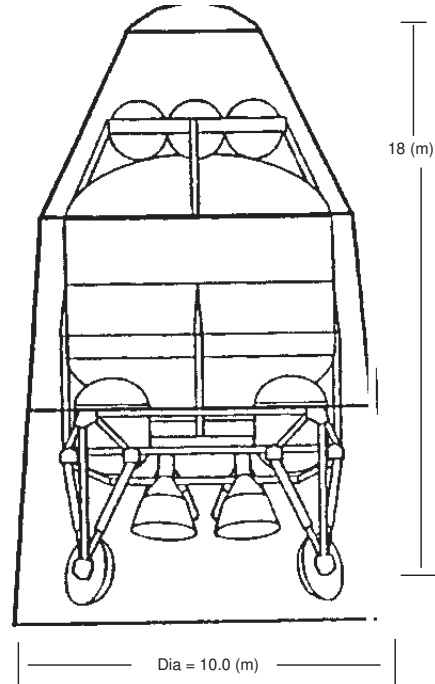
Extended Center Section Biconic
10 (m) Dia by 18 (m) length.

Cg = center of gravity

Cp = center of pressure

Figure 3-21 Biconic aeroshell dimensions for Mars lander and surface habitat modules.

The length of the skirt center section is determined by the size of the payload carried within. Table 3-12 lists the overall lengths of the various aeroshells used in the Reference Mission.

Table 3-12 also lists an estimated mass for the various aeroshells. The Mars Study Team did not conduct a detailed study of the mass of the various aeroshells used. Based on previous studies of aerocapture vehicles, a simple scaling factor of 15 percent of the entry mass was used to determine the aeroshell mass (Scott, et al., 1985). As more detail regarding the aeroshell is developed, variations in aeroshell mass will result caused by differences in the amount of thermal protection material used (some missions are flown on faster trajectories and will encounter higher entry speeds with correspondingly higher heat loads) and in the size of the aeroshell structure. At the present level of this study, the simple scaling factor is considered sufficient to estimate the aeroshell mass.

3.6.3.3 Transit/Surface Habitat

The crew is transported to Mars in a habitat that is identical to the surface habitat/ laboratory deployed robotically on a previous mission. Although a smaller habitat might suffice for a crew of six during the approximately 6 months of transit time, designing the habitat so that it can be used during transit and on the surface results in a number of advantages to the overall mission. Duplicating habitats on the surface provides redundancy during the longest phase of the mission and reduces the risk to the crew. By landing in a fully functional habitat, the crew does not have to transfer from a "space-only" habitat to the surface habitat immediately after landing, allowing them to re-adapt to a gravity environment at their own pace. This approach also allows the development of only one habitat system instead of two or more unique, specialized systems (although some subsystems will have to be tailored for zero-g operation). The performance of the transit habitat may be tested by attaching a development unit to the International Space Station (Figure 3-22).

Each habitation element will consist of a structural cylinder 7.5 meters in diameter and 4.6 meters long with two elliptical end caps (overall length of 7.5 meters). The internal

Table 3-12 Mass and Size Estimates for Biconic Aeroshell Family

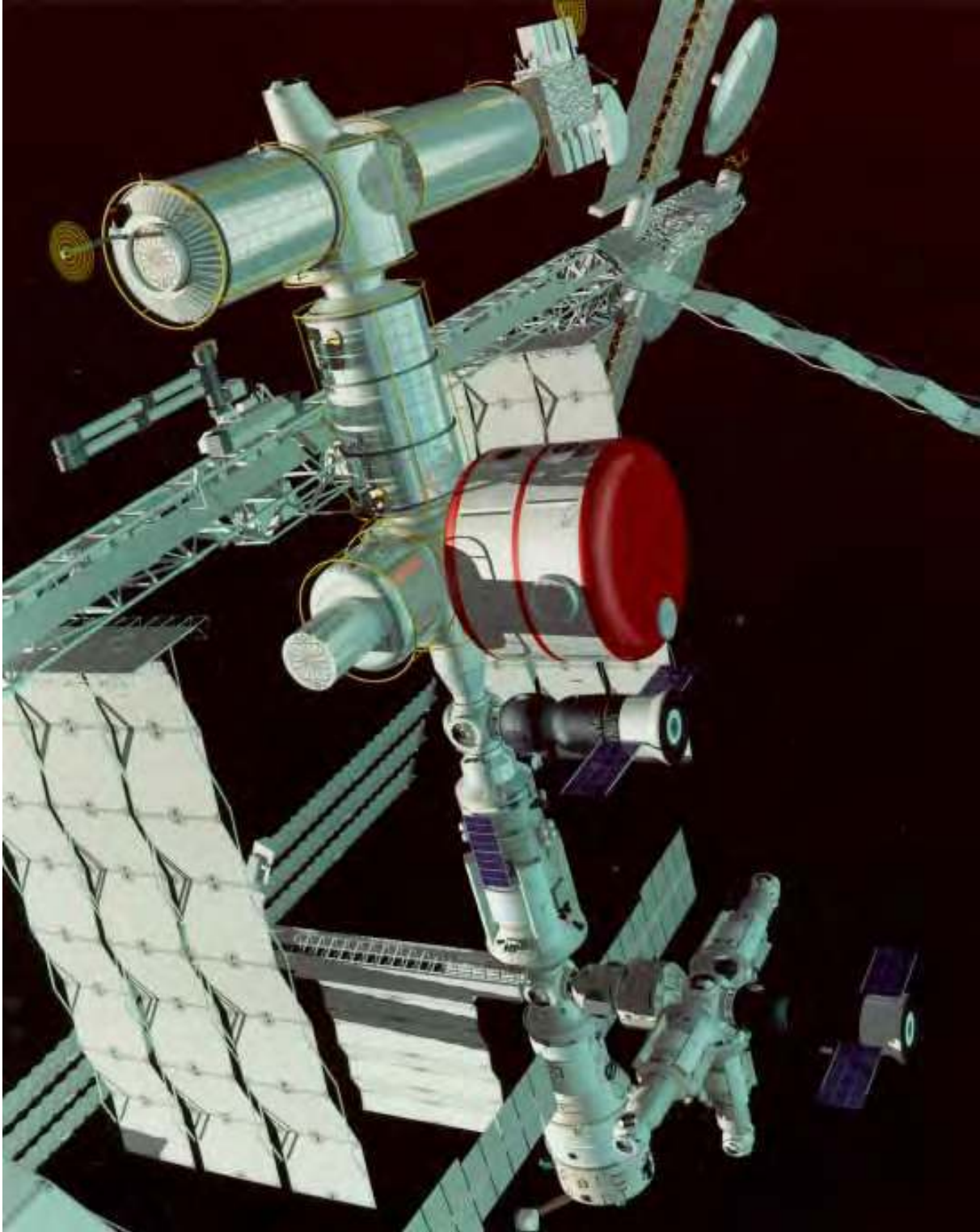| Aeroshell Payload	Mass Estimate (tonnes)	Overall Length (meters)
Ascent Stage and Lander	17.3	15.0
Surface Habitat and Lander	17.3	16.3
TEI Stage and Habitat	17.3	19.0
Surface Habitat with Crew and Lander	17.3	16.3

Figure 3-22 Transit habitat attached to International Space Station.

volume will be divided into two levels oriented so that each "floor" will be a cylinder 7.5 meters in diameter and approximately 3 meters in height. The primary and secondary structure, windows, hatches, docking mechanisms, power distribution systems, life support, environmental control, safety features, stowage, waste management, communications, airlock function and crew egress routes will be identical to the other habitation elements (the surface habitat/ laboratory and the Earth-return habitat). After establishing these basic design features, there exists an endless array of feasible internal architecture designs. Deciding among feasible internal designs involves a trade of resources derived from a specific set of habitation goals. At this level of detail, habitation goals are somewhat subjective and open for discussion. Figures 3-23, 3-24, and 3-25 illustrate one internal arrangement for the transit/surface habitat that was investigated for feasibility and cost purposes.

The Mars transit/surface habitat will contain the required consumables for the Mars transit and surface duration of approximately 800 days (approximately 180 days for transit and approximately 600 days on the surface) as well as all the required systems for the crew during the 180-day transfer trip. Table 3-13 provides a breakdown of the estimated masses for this particular habitat.

Once on the surface of Mars, this transit/ surface habitat will be physically connected with the previously landed surface laboratory,

doubling the usable pressurized volume (to approximately 1,000 cubic meters) available to the crew for the 600-day surface mission. This configuration is illustrated in Figure 3-26 with the first of the transit habitats joined to the previously landed surface habitat/ laboratory.

3.6.3.4 Mars Surface Lander

A single common descent stage was developed for delivery of all hardware systems (the habitats, ascent vehicle, propellant production plant, and other surface cargo) to the surface of Mars. The role of this stage is to complete the descent-to-landing maneuver once the biconic aeroshell ceases to be effective and to maneuver the surface systems into the appropriate relative position at the surface outpost.

The descent stage consists of four subsystems: a basic structure to which all other elements (including payload) are attached, a parachute system to assist in slowing the stage, a propulsion system to slow the stage prior to landing, and a surface mobility system.

The use of parachutes has been assumed to help reduce the descent vehicle's speed after the aeroshell has ceased to be effective and prior to the final propulsive maneuver (Figure 3-27). Sufficient atmosphere is present for parachutes to be more effective than an equivalent mass of propellant.

Figure 3-23 The crew exercise facility component of the countermeasures system designed to inhibit crew degradation from exposure to reduced gravity environments.
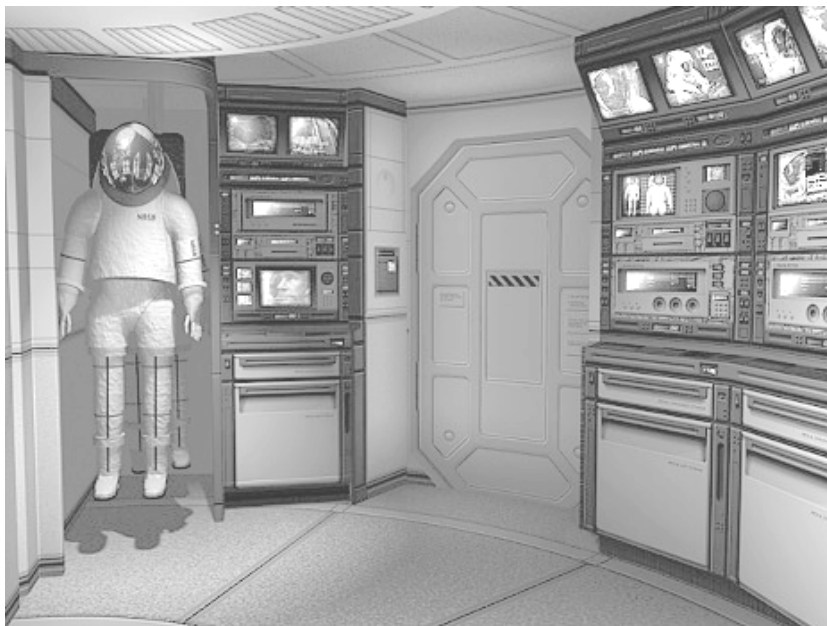

Figure 3-24 EVA suit storage locations are critical in a robust crew safety system.

Figure 3-25 Conceptual Mars habitation module - wardroom design.

Table 3-13 Mars Transit/Surface Habitat Element

Subsystem	Subsystem Mass (tonnes)	Consumables Subtotal (tonnes)	Dry Mass Subtotal (tonnes)
Physical/chemical life support	6.00	3.00	3.00
Plant growth	0.00	0.00	0.00
Crew accommodations	22.50	17.50	5.00
Health care	2.50	0.50	2.00
Structures	10.00	0.00	10.00
EVA	4.00	3.00	1.00
Electrical power distribution	0.50	0.00	0.50
Communications and information management	1.50	0.00	1.50
Thermal control	2.00	0.00	2.00
Power generation	0.00	0.00	0.00
Attitude control	0.00	0.00	0.00
Spares/growth/margin	3.50	0.00	3.50
Radiation shielding	0.00	0.00	0.00
Science	0.90	0.00	0.90
Crew	0.50	0.50	0.00
Total estimate	**53.90**	**24.50**	**29.40**

The propulsion system employs four RL10-class engines modified to burn LOX/CH_4 to perform the post-aerocapture circularization burn and to perform the final approximately 500 meters per second of descent velocity change prior to landing on the surface.

Once on the surface, the lander can move limited distances to compensate for landing dispersion errors and to move surface elements into closer proximity. This allows, for example, the surface laboratory to be connected to the transit/surface habitats. Mobility system power is provided by on-board regenerative fuel cells and from the previously landed pressurized rover. Figure 3-28 illustrates one possible configuration for this lander with its mobility system.

The descent lander is capable of placing approximately 65 tonnes of cargo on the surface. The dry mass of this lander is approximately 4.7 tonnes, and it can carry approximately 30 tonnes of propellant to be used for orbital maneuvers and for the final descent maneuver.

3.6.3.5 Mars Ascent Vehicle

When the surface mission has been completed, the crew must rendezvous with the orbiting ERV. This phase of the mission is
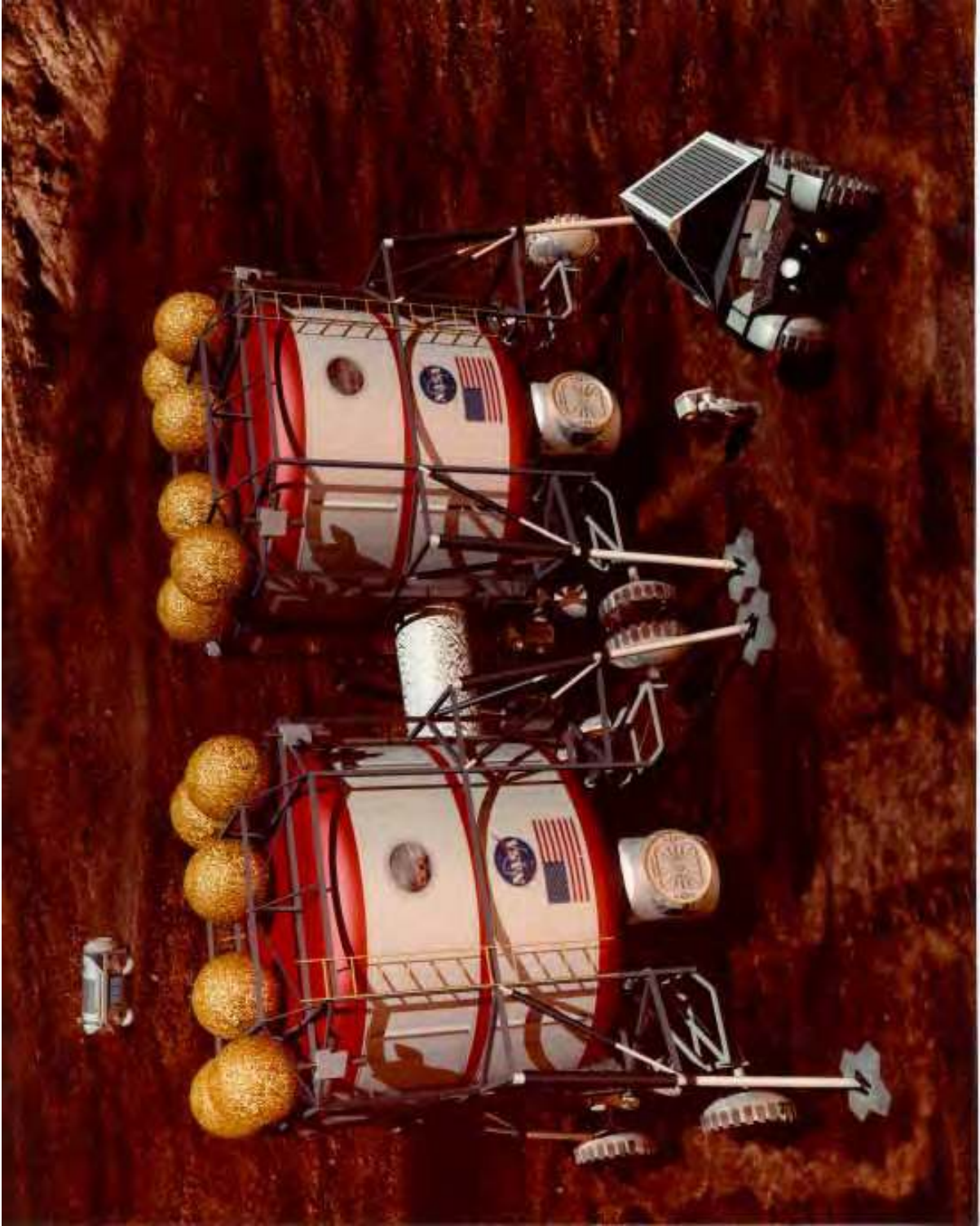
Figure 3-26 Habitat and surface laboratory joined on Mars surface.

3-83

Figure 3-27 Mars surface lander descending on parachutes.

Figure 3-28 Mars surface lander just prior to landing illustrating landing legs and surface mobility system.

accomplished by the MAV which consists of an ascent propulsion system and the crew ascent capsule.

The MAV is delivered to the Mars surface atop a cargo descent stage (Figure 3-29 illustrates the MAV inside the biconic aeroshell and deployed on the surface). The ascent propulsion system is delivered with its propellant tanks empty. However, the same descent stage also delivers a nuclear power source, a propellant manufacturing plant (both discussed in later sections), and several tanks of hydrogen to be used as feedstock for making the required ascent propellant. This approach was chosen because the mass of the power source, manufacturing plant, and seed hydrogen is less than the mass of the propellant required by the ascent stage to reach orbit (Stancati, et al., 1979; Jacobs, et al., 1991; Zubrin, et al., 1991). Not carrying this propellant from Earth gave the Reference Mission the flexibility to send more surface equipment to Mars or to use smaller launch vehicles or some combination of the two options.

The crew rides into orbit in the crew ascent capsule (Figure 3-30). This pressurized vehicle can accommodate the crew of six, their EVA suits, and the samples gathered during the expedition and from experiments conducted in the surface habitat/laboratory. Life support systems are designed for the relatively short flight to the waiting ERV. This ascent capsule does not have a heat shield, as it is not intended for reentering the atmosphere of Earth or Mars. Once the

rendezvous has been completed and all crew, equipment, and samples have been transferred to the ERV, the MAV is jettisoned and remains in orbit around Mars.

The MAV is depicted in Figure 3-31 showing basic dimensions for the vehicle. The ascent propulsion system will require approximately 26 tonnes of propellant to accomplish the nearly 5,600 meters per second of velocity change required for a single-stage ascent to orbit and rendezvous with the previously deployed ERV. The structure and tankage needed for this propellant and the other attached hardware elements have a mass of 2.6 tonnes, including the mass of the engines but not the crew capsule. The ascent propulsion system uses two RL10-class engines modified to burn LOX/CH_4. These engines perform with an average specific impulse of 379 seconds throughout the MAV flight regime.

The ascent crew capsule has a maximum diameter of 4 meters, a maximum height of 2.5 meters, and a mass of 2.8 tonnes. This capsule contains the basic crew life support systems and all guidance and navigation equipment for the rendezvous with the ERV.

3.6.3.6 Earth-Return Vehicle

Returning the crew from Mars orbit to Earth is accomplished by the ERV which is composed of the TEI stage, the Earth-return transit habitat, and the ECCV. The ERV is delivered to Mars orbit with the TEI stage fully fueled, and it loiters there for nearly 4 years before being used by the crew returning
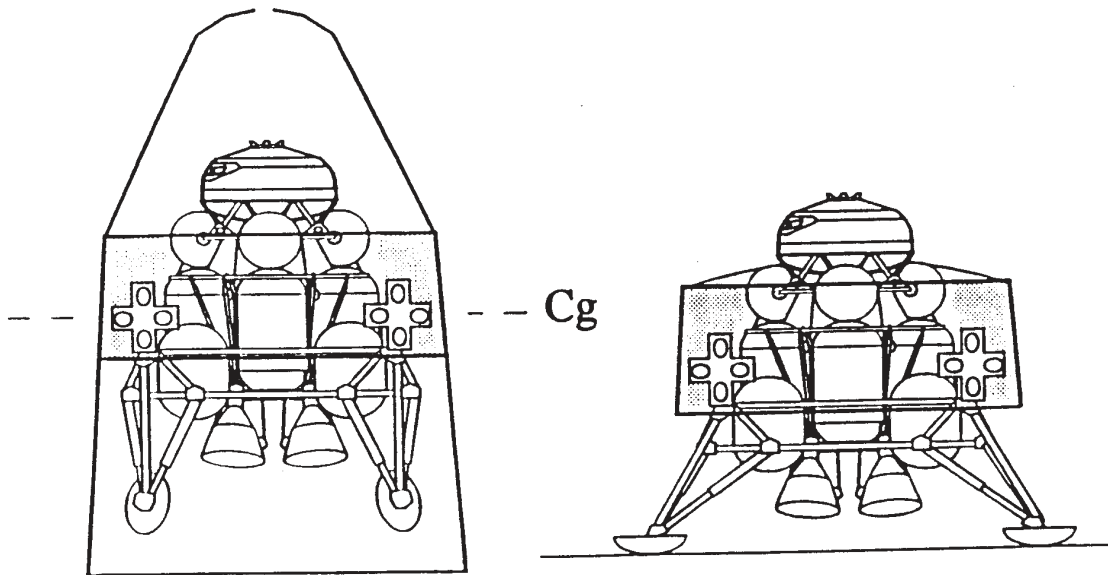
Figure 3-29 Mars surface lander and biconic aeroshell.

Figure 3-30 Crew ascent capsule just after launch from Mars surface.

9 (m)

4 (m)

One center (core)
3.6 (m) dia spherical
LO2 tanks

One center (core)
3.3 (m) dia spherical
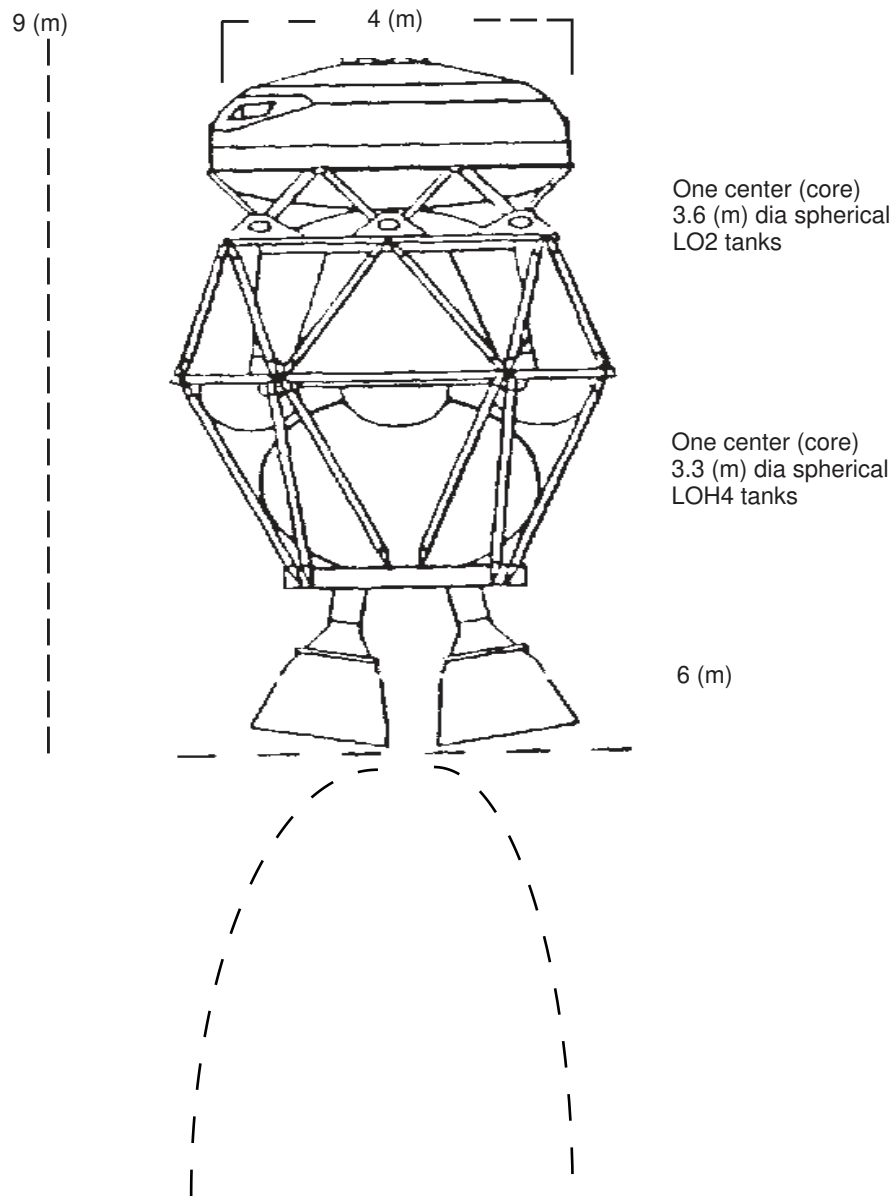LOH4 tanks

6 (m)

Figure 3-31 Methane/LOX ascent stage configuration.

to Earth. For the return to Earth, the crew will jettison the MAV and wait for the appropriate departure time to leave the parking orbit. During the 180-day return trip, the crew will recondition themselves as much as possible for the return to an Earth gravity environment, train for those procedures they will use during the entry phase, perform science experiments and maintenance tasks, and prepare reports. As they approach Earth, the crew will transfer to the ECCV, along with the samples they are returning, and separate from the remainder of the ERV. The TEI stage and the transit habitat will fly by Earth and continue on into deep space. The crew in the ECCV will deflect their trajectory slightly so that they reenter the Earth's atmosphere and land on the surface.

The propulsion system for the ERV is sized for the velocity change needed to move the Earth return habitat and the ECCV from the highly elliptical parking orbit at Mars to the fast-transit return trajectory to Earth. As with the TMI stage, the energetically demanding 2011 return trajectory was used to size this system for a 180-day return; less energetically demanding returns could be accomplished faster or with larger return payloads.

Several propellant and engine combinations were considered by the Mars Study Team for the TEI propulsion system. The two options given the most consideration were liquid hydrogen with a NERVA derivative engine comparable to the TMI

stage, and liquid oxygen/liquid methane with the same engine used by the lander and the MAV. With the 4-year loiter time in Mars orbit, propellant boiloff was the major design consideration. Liquid hydrogen would require active refrigeration for this extended period in orbit to avoid excessive boiloff losses. Liquid oxygen/liquid methane boiloff losses could be held to acceptable levels using passive insulation and appropriate orientation of the vehicle while in Mars orbit (to minimize radiative heat input from Mars, the largest source). The 30 kWe solar power system (used primarily for powering the ERV on the return to Earth) is also on board and could be used for active cooling of these propellants. Based primarily on this trade-off, liquid oxygen and liquid methane were chosen as the TEI stage propellants.

With this selection, the TEI propulsion system uses two RL10-class engines modified to burn LOX/CH$_4$. Again, these are the same engines developed for the ascent and descent stages, thereby reducing engine development costs and improving maintainability. To achieve the velocity change for the 2011 fast-transit return requires approximately 52 tonnes of liquid oxygen and liquid methane. The remainder of the TEI propulsion system, including tanks, structure, engines, and reaction control systems, has a dry mass of approximately 5.2 tonnes.

The return habitat is a duplicate of the outbound transit/surface habitat used to go to Mars but without the stores of consumables

in the surface habitat. As with the surface habitats, the primary structure of this habitat consists of a cylinder 7.5 meters in diameter and 4.6 meters long with two elliptical end caps (overall length of 7.5 meters). The internal volume will be divided into two levels, oriented so that each "floor" will be a cylinder 7.5 meters in diameter and approximately 3 meters in height. The primary and secondary structure, windows, hatches, docking mechanisms, power distribution systems, life support, environmental control, safety features, stowage, waste management, communications, airlock function and crew egress routes will be identical to the other habitation elements. Table 3-14 details the mass estimate for this habitat module.

The ECCV is similar in concept to the Apollo Command Module and is eventually used by the crew to enter the Earth's atmosphere and deliver the crew to a safe landing on land. The ECCV will have the necessary heat shield for Earth reentry and will be heavier than the ascent capsule specialized only for that portion of the mission. This vehicle has all of the life support, guidance and navigation, and propulsion systems to keep the crew alive for several days and to maneuver the vehicle into the proper entry trajectory. Once the reentry phase has been completed, the ECCV will use a steerable parafoil to land at a designated location on the surface (Figure 3-32). The ECCV has an estimated mass of 5.5 tonnes.

3.6.3.7 Interplanetary Transportation Power Systems

A source of power will be required for all of the interplanetary transportation systems during the flight times to and, in the case of the ERV, from Mars. While several alternatives are available as a primary source of power for these vehicles, solar energy is readily available throughout these transit phases and photovoltaic energy is a known technology. Thus, a basic photovoltaic power capability is assumed for those vehicles that are operating in interplanetary space. A source of stored power will also be needed for the interplanetary vehicles during periods of eclipse and of array retraction prior to capture into Mars orbit, and for vehicles not typically operating in interplanetary space (such as the Mars surface lander, the MAV, and the ECCV). During the eclipse periods and for the other vehicles, a regenerative fuel cell (RFC) system will be used to provide necessary power.

The most significant power requirements for the interplanetary transportation system come from the transit/surface habitat and the ERV. Table 3-15 shows the estimated power requirements to support the six-person crew for both nominal and powerdown emergency mode. The life support system is a major constituent of the almost 30 kWe needed for these two vehicles under nominal conditions. The life support system is based on a partially closed air and water system design that performs CO_2 reduction, O_2 and N_2 generation, urine processing, and water processing (potable and hygiene). The emergency mode

Figure 3-32 ECCV returning to Earth on a steerable parafoil.

Table 3-14 Earth-Return Habitat Element Mass Breakdown

Subsystem	Subsystem Mass (tonnes)	Consumables Subtotal (tonnes)	Dry Mass Subtotal (tonnes)
Physical/chemical life support	6.00	3.00	3.00
Plant growth	0.00	0.00	0.00
Crew accommodations	22.50	17.50	5.00
Health care	2.50	0.50	2.00
Structures	10.00	0.00	10.00
EVA	4.00	3.00	1.00
Electrical power distribution	0.50	0.00	0.50
Communications and information management	1.50	0.00	1.50
Thermal control	2.00	0.00	2.00
Power generation	0.00	0.00	0.00
Attitude control	0.00	0.00	0.00
Spares/growth/margin	3.50	0.00	3.50
Radiation shielding	0.00	0.00	0.00
Science	0.90	0.00	0.90
Crew	0.50	0.50	0.00
Total estimate	**53.90**	**24.50**	**29.40**

value is based on the life support system operating in an open loop mode with reductions in noncritical operations.

The solar array as it would appear on the ERV (Figure 3-33) is designed to produce the required 30 kWe in Mars orbit at the worst-case distance from the Sun, 1.67 AU. The energy storage system is sized to provide power before and after Mars orbit capture as well as during attitude control, array retraction, orbit capture, array extension maneuvers, and orbit eclipse. A nominal power profile for these activities is shown in Figure 3-34. It is currently assumed that the outbound transit/surface habitat can be safely powered down to 20 kWe during these mission phases to save RFC mass and volume, and that the RFC and solar array will remain with the transit/surface habitat to be used on the surface as a backup system.

Based on the size of the energy storage system, eclipse power requirement, and available power from the array, it will take seven orbits of Mars to fully charge the RFC. The RFC delivers power when the solar array is retracted during entry, descent, and landing of the transit/surface habitat. The RFC can also deliver 20 kWe for 24 hours after landing,

Table 3-15 Estimated Power Profile for Outbound and Return Transits

Element	Mode		Notes
	Nominal	**Emergency**	
Life Support System (LSS)	12.00	8.00	Open Loop in Emergency
Thermal Contract System (TCS)	2.20	2.20	Mode
Galley	1.00	0.50	Emergency values
Logistic Module	1.80	1.80	Derated from nominal where
Airlock	0.60	0.10	appropriate
Communications	0.50	0.50	
Personal Quarters	0.40	0.00	
Command Center	0.50	0.50	Values adapted from NAS8-
Health Maintenance Facility (HMF)	1.70	0.00	37126, "Manned Mars System
Data Management System	1.90	0.80	Study
Audio/Video	0.40	0.10	
Lab	0.70	0.00	
Hygiene	0.70	0.00	
SC/Utility Power	5.00	5.00	
Total	**29.40**	**19.50**	

and it will be the prime power source for the transit/surface habitat and crew until the habitat is moved to its final location and connected to the main power grid. The RFC could also provide power for moving the habitat from the landing site to its final emplacement location, assuming no solar array deployment.

A duplicate of the solar array and RFC system will be used on the ERV, saving development costs for a unique system. All other spacecraft discussed will use a subset of the RFC system (assumed to be modular or at least manufactured in smaller units) used in the transit/surface habitat. The base power load for vehicle avionics, communications, and the propulsion system (noted as "S/C

Utility Power" in Table 3-15) is estimated at 5 kWe. This value is assumed as the power requirement for the unmanned cargo-only vehicles during the outbound transit.

Tables 3-16 and 3-17 show the mass estimates for the two power systems discussed: the 30 kWe system used for the habitats and the 5 kWe system used for the cargo flights. Both tables show the resulting system characteristics if the RFCs must be recharged over the course of one orbit versus recharging them over seven orbits. The savings in mass, volume, and array area are obvious and support the choice to stay in orbit for a longer period of time.

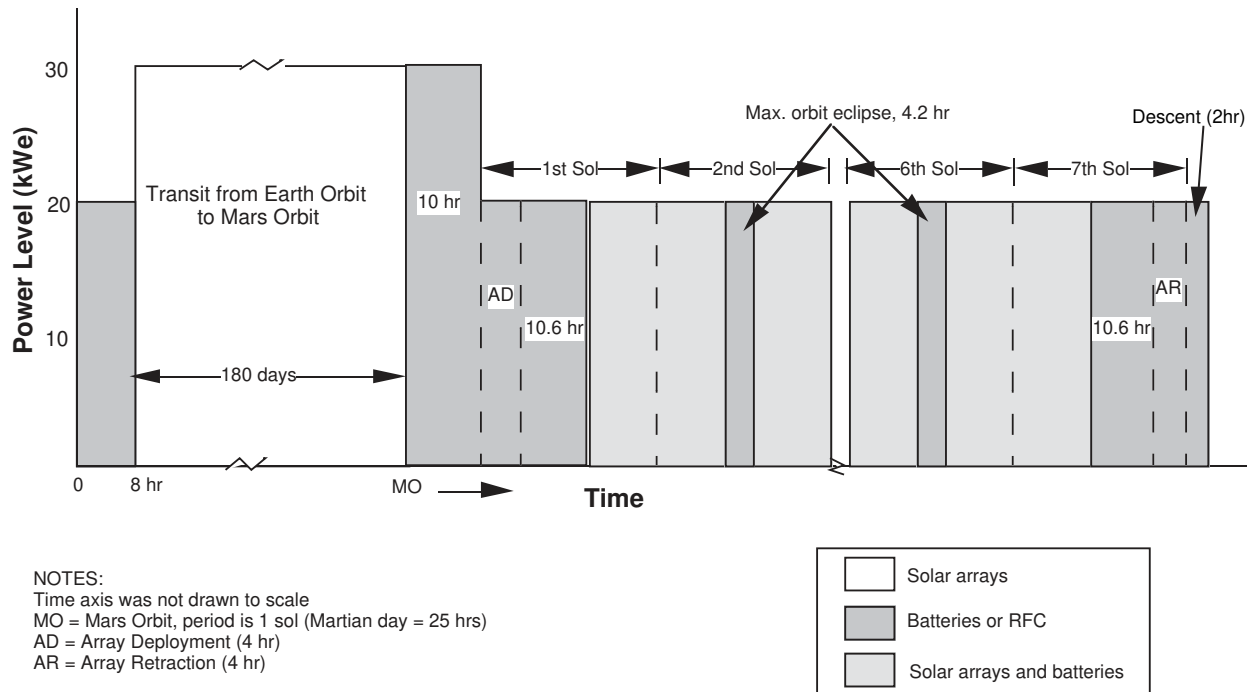*Figure 3-33 Solar array power source for interplanetary spacecraft.*

Figure 3-34 Nominal power profile for the transit/surface habitat.

3.6.4   Surface Systems

The surface systems assembled to support the long-duration science and exploration activities of the Reference Mission consist of six major systems: a surface laboratory and habitat module, a bioregenerative life support system, ISRU equipment, surface mobility systems (rovers), extravehicular mobility systems (EVA suits or space suits), and power systems. All of these systems, with the possible exception of the EVA suits, are sent to Mars, landed on the surface, deployed, and determined to be functioning before departure of the flight crew. This requires that each system be developed with a high degree of built-in

autonomy and require support from the flight crew or Earth-based supervisors only in extreme situations where built-in capabilities cannot cope.

3.6.4.1 Surface Habitat/Laboratory

The primary function of the Mars surface habitat/laboratory is to support the scientific and research activities of the surface crews. The same structural cylinder (7.5 meters in diameter, bi-level, and vertically oriented) used for the other habitat elements was used here, but it is more specialized for the research activities. It will operate only in 3/8 gravity.

Table 3-16 30 kWe Power System With Fuel Cells and Solar Arrays

Power System Type	1-Orbit Recharge			7-Orbit Recharge		
	Mass (kg)	Volume (m³)	Array Area (m²)	Mass (kg)	Volume (m³)	Array Area (m²)
Fuel Cell	1481	0.194	N/A	1102	3.83	N/A
Radiator	259	3.260	47	190	1.5	35
Array	2971	N/A	918	1682	N/A	520
Total	**4711**	**3.454**	**965**	**2974**	**5.38**	**555**

Table 3-17 5 kWe Power System With Fuel Cells and Solar Arrays

Power System Type	1-Orbit Recharge			7-Orbit Recharge		
	Mass (kg)	Volume (m³)	Array Area (m²)	Mass (kg)	Volume (m³)	Array Area (m²)
Fuel Cell	398	9.498	N/A	347	0.456	N/A
Radiator	76	0.971	14	49	0.653	9
Array	795	N/A	246	431	N/A	138
Total	**1269**	**1.469**	**260**	**827**	**1.109**	**147**

This surface habitat/laboratory will be one of the first elements landed on the surface of Mars. Once moved to a suitable location (should the actual landing site prove unsuitable or to accommodate other operational needs), this facility will be connected to the surface power systems and all internal subsystems will be activated. Only after these internal subsystems and other landed surface systems have been verified to be operating satisfactorily will the first crew be launched from Earth.

The surface habitat/laboratory contains a large stowage area on the first level and the second level is devoted entirely to the primary science and research laboratory. The stowage area will initially contain nonperishable consumables that can be sent to the surface prior to the arrival of the first crew. As these consumables are used, this space will become available for other uses—likely to be plant growth and greenhouse-type experiments. The other subsystems of this module, such as the primary and secondary structure, windows, hatches, docking mechanisms, power distribution systems, life support, environmental control, safety features, stowage, waste management, communications, airlock function, and crew egress routes, will be identical to the other habitats with a few exceptions. No crew quarters or accommodations will be included in this module except for a minimal galley and minimal waste management facility. However, the life support subsystem will be capable of supporting the entire crew should it become necessary for the crew to spend

extended periods of time in the habitat/ laboratory. The primary airlock for EVA activities will be located in this module (with backup capability in one of the other habitat modules) with an EVA suit maintenance and charging station located near the airlock. Table 3-18 details the estimated mass for this module.

3.6.4.2 Life Support System

An important reason for sending humans to live on and explore Mars is to determine whether human life is capable of surviving and working productively there. The life support system (LSS) for a Mars surface mission will be an integral part of the mission architecture, and must be viewed in terms of its requirements to maintain the health and safety of the crew and its capability to minimize the dependence of a Mars outpost on materials supplied from Earth. Proving that human, and by extension animal and plant, life can inhabit another world and become self-sufficient and productive will be a major objective of this LSS.

Four options were examined for use as the LSS for the Mars surface facilities: open loop, physical/chemical, bioregenerative, and cached stocks of consumable materials.

•The open loop option is the simplest to implement but typically the most expensive in terms of the mass required. For this option, life support materials are constantly replenished from stored supplies as they are used (for example, as air is breathed by the crew, it is dumped overboard and replaced

Table 3-18 Mars Surface Habitat/Laboratory Mass Breakdown

Subsystem	Subsystem Mass (tonnes)	Consumables Subtotal (tonnes)	Dry Mass Subtotal (tonnes)
Physical/chemical life support	4.00	2.00	2.00
Plant growth	3.00	1.00	2.00
Crew accommodations	7.50	7.50	0.00
Health care	0.00	0.00	0.00
Structures	10.00	0.00	10.00
EVA	1.50	1.00	0.50
Electrical power distribution	0.50	0.00	0.50
Communications and information management	1.50	0.00	1.50
Thermal control	2.00	0.00	2.00
Power generation	0.00	0.00	0.00
Attitude control	0.00	0.00	0.00
Spares/growth/margin	5.50	0.00	5.00
Radiation shielding	0.00	0.00	0.00
Science	3.00	Uncertain	3.00
Crew	0.00	0.00	0.00
Total estimate	**38.50**	**11.50**	**27.00**

with "new" air). While not seriously considered, this option was carried for comparison purposes.

- The physical/chemical option is typical of the systems used in current spacecraft and relies on a combination of physical processes and chemical reactions to scrub impurities from the air and water.

- The bioregenerative option uses higher plant life species to provide food, revitalize air, and purify water. This type of approach is technically embodied in the concept of a Controlled Ecological Life Support System, although it is often described colloquially as a "greenhouse system."

- The cached stocks option makes use of the ISRU equipment already in place for manufacturing propellants to also make usable air and water for the crew. Trace amounts of the constituents of usable air and water will be by-products (in fact impurities that must be removed) of the propellant manufacturing process. Capturing and storing these impurities as well as oversizing some of the

production processes can allow the crew to at least augment other elements of the LSS.

Combinations and hybrids of these options are also possible and were also examined for this report. Using a combination of systems or a hybrid system would provide more levels of functional redundancy and thus provide an attractive option for enhancing the viability of the Mars surface facilities as a safe haven. Figure 3-35 illustrates a hybrid system using physical/chemical and bioregenerative elements.

In this example, certain life support functions, such as CO_2 reduction and water purification, can be shared by both elements, while other functions, such as fresh food production, can only come from the greenhouse. As an integrated system, neither element needs to provide 100 percent of the full life support demand on a continuous basis. Both elements however, should be capable of being periodically throttled to satisfy from 0 percent to 100 percent of the LSS load.

The Reference Mission adopted the philosophy that life-critical systems (those systems absolutely essential to ensure the crew's survival) should have two backup levels of functional redundancy. That is, if the first two levels fail, the crew will not be in jeopardy, but will not be able to complete all mission objectives. As previously discussed, each habitat is equipped with a physical/chemical LSS capable of providing for the entire crew for the duration of their surface

stay. A physical/chemical system was chosen due to the mature nature of the technology. Thus, the first habitat and the surface laboratory constitute the primary and first backup (although not strictly a functional but rather a redundant backup) for the crew life support.

It is highly desirable for the second backup to use indigenous resources so that the backup life support objective and the live off the land objective are both met. Table 3-19 compares the various options for the combined LSSs with an open system. Each of these options was sized for a crew of six spending 600 days on the martian surface.

Because of the life-critical nature of the propellant manufacturing facility and the high level of reliability that must be designed into this system, the cached stocks option was chosen as the second backup. However, demonstrating the capability to produce foodstuffs and revitalize air and water using bioregenerative processes is considered a mission-critical objective for the Reference Mission. For that reason, an experimental bioregenerative life support system capable of producing a small amount of food is included as a science payload to be delivered for use by the second crew.

Several options exist for the location of the experimental bioregenerative LSS. One is to use the storage space in the surface habitat/laboratory that will become available as consumables are used. This is the simplest to implement but would require artificial lighting and would be restricted to the
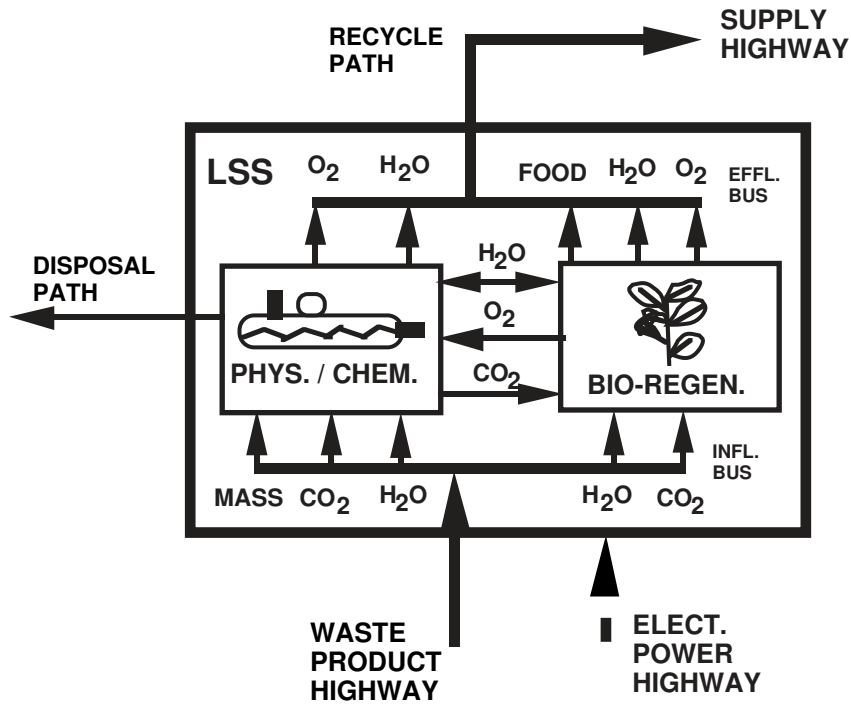
Figure 3-35 Hybrid LSS process distribution.

Table 3-19 LSS Mass, Volume, Power Comparison.

Architecture	Functional Redundant Levels	Mass (mt)	Volume (m^3)	Maximum Δ Power Over Open Loop (kW)
Open Loop	1	180	290	0
Physical/Chemical with Cached Stocks	2	60	470	7
Bioregenerative with Cached Stocks	2	60	410	60
Hybrid Physical/Chemical and Bioregenerative with Cached Stocks	3	80	600	60

volume available in the storage area. Two other options involve attaching an external pressurized structure to one of the habitat modules. One external option would use a hard opaque structure for the external shell and would also require artificial lighting. The other external option would use an inflatable transparent structure for the external shell. Natural sunlight would be used to illuminate the plants which would reduce the power needed by the system; however, the potential risk of a puncture due to natural or human-derived events would be increased.

In either external scheme, the greenhouse atmospheric volumes would normally communicate directly with the atmospheric volume of the habitat without further processing, but could be sealed off in contingencies. The greenhouse(s) could be erected or inflated at the convenience of the crew. The loss of a greenhouse module for any reason, such as puncture, mechanical or electrical failure, or loss of shielding integrity, would not seriously impact overall mission success.

3.6.4.3 In Situ Resource Utilization

ISRU for the Reference Mission provides two basic resources: propellants for the MAV and cached reserves for the LSSs. Using indigenous resources to satisfy these needs instead of transporting resources from Earth reduces launch mass and thus mission cost. ISRU production for the Reference Mission includes two virtually redundant ISRU plants, the first delivered before the initial piloted mission and the second delivered prior to the

first follow-up mission. Each ISRU plant will produce propellants for at least two MAV missions. However, only the first plant is required to produce life support caches.

For each MAV mission, a plant is required to produce 20 tonnes of oxygen and methane propellants at a 3.5 to 1 ratio: Each plant must produce 5.8 tonnes of methane and 20.2 tonnes of oxygen. Further, the first ISRU system is required to produce 23.2 tonnes of water, 4.5 tonnes of breathing oxygen, and 3.9 tonnes of nitrogen/argon inert buffer gasses for use by any of the three Mars crews. The system liquefies and stores all of these materials as redundant life support reserves or for later use by the MAV.

The approach to ISRU production uses the martian atmosphere for feedstock and imports hydrogen from Earth. The main processes used are common to both ISRU plants. The significant difference between the two is that the second plant is smaller and excludes equipment for buffer gas extraction. Should sources of indigenous and readily available water be found, this system could be simplified.

3.6.4.3.1   *Processes*

The Mars atmosphere, which is used as a feedstock resource, is composed primarily of carbon dioxide with just over 3 percent nitrogen and argon. The ISRU plants must be capable of converting the carbon dioxide to methane, oxygen, and water. Since hydrogen is not substantially present in the atmosphere in gaseous form and indigenous sources of

water are uncertain, hydrogen must be imported from Earth. The first plant must also be capable of extracting the nitrogen and argon for buffer gas reserves. The reference ISRU system uses Sabatier, water electrolysis, carbon dioxide electrolysis, and buffer gas absorption processes to achieve these ends.

• Methane production - The Sabatier reaction was discovered by French chemist P. Sabatier in the nineteenth century and is one of the most often cited for ISRU on Mars (Sullivan, et al., 1995). The reaction converts carbon to methane and water by reacting it with imported hydrogen at elevated temperatures. This process is also commonly used in closed physical/chemical LSSs for reduction of metabolic carbon dioxide. It results in a water to methane mass ratio of 2.25:1 and requires 0.5 tonnes of hydrogen for each tonne of methane produced. The resultant methane is stored cryogenically as fuel. The water can either be used directly as cached life support reserves or can be broken down into oxygen and hydrogen to be recycled.

• Oxygen production - Oxygen production is accomplished with two different processes. The Reference Mission uses both water electrolysis to produce oxygen from water produced in the plant and carbon dioxide electrolysis to directly convert the Mars atmosphere to oxygen.

Water electrolysis is well known and has been used for numerous terrestrial applications for many years. The combined Sabatier and electrolysis processes generate oxygen and methane for use as propellants at a mass ratio of 2:1. In this combined process case, the hydrogen is recycled into the Sabatier process so that 0.25 tonnes of hydrogen are needed for each tonne of methane. The engines selected for the Reference Mission use oxygen and methane at a mass ratio of 3.5 to 1. Therefore, an additional source of oxygen is needed to avoid overproduction of methane.

The carbon dioxide electrolysis process is used in the Reference Mission to provide the needed additional oxygen. The process converts the atmospheric carbon dioxide directly into oxygen and carbon monoxide using zirconia cells at high temperature. The zirconia cell system is not as well developed as the Sabatier process but is under development (Sridhar, et al., 1991; Ramohalli, et al., 1989; and Colvin, et al., 1991). This process eliminates the overproduction of methane during propellant production except during the first mission when the Sabatier-produced water is also needed.

The two strong alternatives to carbon dioxide electrolysis—methane pyrolysis and reverse water gas shift—were not studied in-depth for the Reference Mission report, but they should be considered seriously in further studies of manned Mars missions.

- Buffer gas extraction - The buffer gas extraction process has not been examined in detail during this study. It will most likely be a nitrogen and argon absorption process in which compressed atmosphere is passed over a bed of material which absorbs the nitrogen and argon. The gases are then released by heating the bed and the products are passed on to the cooling and storage system. Parallel chambers are used so that one bed is absorbing in the presence of atmosphere while the other is releasing its captured gases.

- Ancillary Systems - Systems for atmosphere intake, product liquefaction, and product storage and transfer will be needed. These systems have not been detailed for the Reference Mission at this stage of study but their necessary functions can be described. The filter and compressor equipment cleans the martian atmosphere of dust and compresses it to a pressure usable by the rest of the ISRU plant. Product liquefaction must include cryogenic liquefaction of oxygen, methane and nitrogen as well as condensation of the water stored as cached reserves. Storage systems will include cryogenic tanks for cached oxygen and buffer gasses. An expandable bladder-type tank is anticipated for cached water. Propellant storage will be accomplished in the MAV tanks and so is not considered part of the ISRU system.

3.6.4.3.2 *Initial ISRU Plant*

The first ISRU plant is delivered to Mars over a year prior to the first departure of humans from Earth, and during that year the plant produces all the propellants and life support caches that will be needed. Thus, humans do not even leave Earth until reserves and return propellants are available. This plant also produces propellants for the MAV mission of the third crew in the overall Reference Mission scenario.

A schematic of this initial plant is shown in Figure 3-36. The plant integrates all the processes needed for both propellant and life support products. The water electrolyzer is not used in the plant during the first period of operation. Because of the total mass of the water cache, all of the water produced by the Sabatier reactor is stored and the carbon dioxide electrolysis reactor is responsible for producing all the oxygen needed. In addition, over 10 tonnes of excess methane are produced as a by-product of the water production process for the LSS cache.

When the plant is operated for the third MAV launch propellants, the water electrolyzer is brought on-line. Instead of being condensed, the water from the Sabatier reactor is split by the electrolyzer into hydrogen (which is recycled to the Sabatier reactor) and oxygen (which is liquefied and sent to the MAV tanks). For this operation of the plant, no methane overproduction is needed.
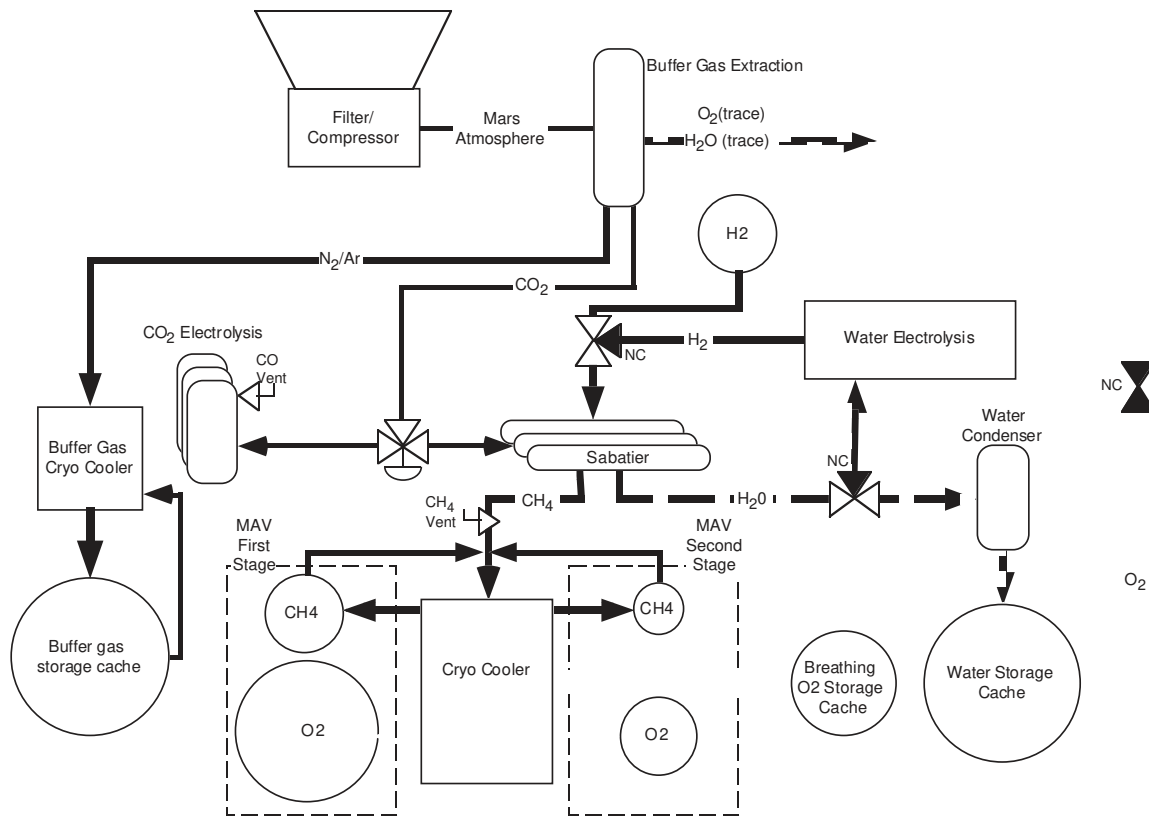
Figure 3-36 Schematic of the first ISRU plant.

The size of the ISRU plant has only been estimated parametrically. These estimates are based on some previous work on the options for ISRU and on the rates needed to produce requisite materials over a 15-month period. The mass and power requirements for this plant are given in Table 3-20. The power requirements represent those of the plant's initial period of operation.

3.6.4.3.3   Second ISRU Plant

The second ISRU plant is delivered at essentially the same time as the arrival of the first crew on Mars. This allows time for propellant production prior to the Earth departure of the second crew. The second plant is only charged with production of propellants since, the life support reserves are presumably still present.

Table 3-20 Mass and Power Estimates for the First ISRU Plant

Plant Component	Production Rate (per day)	Component Mass (kg)	Component Power (kWe)
Compressor	269.7 kg	716	4.09
CO_2 Electrolysis	53.2 kg	2128	63.31
Sabatier	22.9 kg	504	1.15
H_2O Electrolysis	27.8 kg	778	0.00
Buffer Gas Extraction	8.7 kg	23	0.13
Cryogenic Coolers	84.8 kg	653	3.59

The plant schematic is essentially the same as that shown in Figure 3-36. The second plant does not include the buffer gas extraction, liquefaction, and storage equipment or the water condensation and storage equipment. Further, the size of the reactors is reduced because of the lower production rates needed. Table 3-21 shows the estimated mass and power requirements for this plant. Plant operations are the same as those of the first plant during its second period: All Sabatier-produced water is electrolyzed, and the extra oxygen needed is produced by the carbon dioxide electrolyzer.

3.6.4.4 Surface Mobility

Mobility on a local scale and regional scale will be required during all phases of the surface exploration of the Reference Mission. The basic objectives for the Reference Mission require that a variety of mobility systems be provided for basic maintenance and operations activities as well as for exploration of the surface. Prior to the first crew's arrival and during all subsequent periods whether a crew is present or not, exploration at short and long ranges will be performed by automated rovers. Surface facility setup activities will require rovers acting under the supervision of Earth-based operators. Maintenance and operations by the surface crews can be more productive with the availability of mobile utility systems. And finally, long-range, long-duration exploration by the surface crews will be possible only with the use of pressurized, autonomous rovers.

The Reference Mission identifies three classes of mobility systems, based on the time and distance to be spent away from the surface habitats.

Table 3-21 Mass and Power Estimates for the Second ISRU Plant

Plant Component	Production Rate (per day)	Component Mass (kg)	Component Power (kWe)
Compressor	87.8 kg atm	233	1.33
CO_2 Electrolysis	18.5 kg O_2	740	22.00
Sabatier	12.4 kg CH_4	272	0.62
H_2O Electrolysis	27.8 kg H_2O	778	5.79
Cryogenic Coolers	30.8 kg	238	2.3

• Immediate vicinity of the surface base facilities: hundreds of meters and the 6- to 8-hour limit of the EVA portable LSS

• Local vicinity of the surface base facility: several kilometers and the 6- to 8-hour limit of the EVA portable LSS

• Regional distances: a radius of up to 500 km in exploration sorties that allow 10 workdays to be spent at a particular remote site, and with a transit speed such that less than half of the excursion time is used for travel (for example, for 10 workdays, no more than 5 days to reach the site and 5 days to return).

These divisions resulted in three basic rover types and a number of other mobility systems to support the kinds of activities at these ranges and for these amounts of time.

On the local scale, any time the crew is outside of the habitat(s) they will be in EVA suits and will be able to operate at some distance from the habitat. The maximum distance will be determined by their capability to walk back to the outpost within the time set by the recharge limits of the portable LSS. During these activities, the EVA crew will have a variety of tools, including rovers, carts, and wagons, available for use.

For distances perhaps beyond a kilometer from the habitats but less than 10 kilometers distant, exploration will be assisted by unpressurized self-propelled rovers. This rover is functionally the same as the Lunar Rover Vehicle used in the Apollo Program and is meant to assist the EVA crews by transporting them and their equipment over relatively short distances. Figure 3-37 illustrates one concept for this rover (partially hidden behind one of the teleoperated long-range rovers) with a gabled radiator above the aft end. This rover is driven by six cone-shaped wheels and has an estimated mass of 4.4 tonnes. Three of these vehicles will be part of the cargo carried to the surface for use in and around the surface facilities.

On the regional scale, beyond the safe range for exploration on foot or in unpressurized rovers, crews will explore in pressurized rovers, allowing them to operate for the most part in a shirtsleeve environment. Figure 3-38 illustrates one possible concept for this rover. The rover is assumed to have a nominal crew of two people, but can carry four in an emergency. Normally, the rover would be maneuvered and EVAs would be conducted only during daylight hours, but sufficient power will be available to conduct selected investigations at night. Crew accommodations inside the rover will be relatively simple: a drive station, a work station, hygiene facilities, a galley, and sleep facilities. An airlock on this rover will be capable of allowing not only surface access for an EVA crew, but also direct connection to the habitat, thus precluding the need for an EVA to transfer either to or from the rover. Each day on an excursion away from the main surface facilities, the rover has the capability of supporting up to 16 person-hours of EVAs. Facilities for recharging the portable LSSs and for making minor repairs to the EVA suits are also included. The work station will be used, in part, to operate two mechanical arms that can be used to manipulate objects outside the rover without leaving the pressurized environment. These arms, along with other mobility subsystems, can also be operated remotely by Earth-based personnel. This feature is required to allow many of the deployment, setup, and monitoring activities to be carried out prior to the arrival of the first crew. A final feature of

this rover is the power system. The choice of the specific power system is discussed in a later section. However, this system will be mounted on a separate trailer to be towed by the rover whenever it is in operation. At times when the rover is dormant, the power trailer can be used for other purposes, including its use as a backup power source for any of the surface facilities. Two pressurized rovers will be carried to the surface. This allows for redundancy in this function, including the possibility of rescuing the crew from a disabled rover located at a distance from the habitats. Each rover is driven by four cone-shaped wheels and is estimated to have a mass of 16.5 tonnes.

Exploration at a regional scale will also be undertaken by small teleoperated rovers. The foreground of Figure 3-38 illustrates one possible concept for this rover. The main purpose for these rovers is to explore the martian surface at long distances, hundreds to thousands of kilometers, from the habitats. The activities carried out by this type of rover will be to conduct scientific investigations, collect and return samples to the habitats, and scout possible locations for human crews to investigate in more detail. Three of these rovers will be delivered as part of the first cargo mission and will be supervised from Earth during the time between landing and the arrival of the first crew. Determining sites for the crews to investigate and safe routes to the sites will be the primary activity before the first crew arrives and during those periods when no crew is at the surface base. When a crew is on the martian surface, these

Figure 3-37 Concepts for the unpressurized and automated surface rovers.

Figure 3-38 Concept for the large pressurized surface rover.

rovers will be available for teleoperation by the crews. Focused exploration, sample collection, and scientific measurements will be the main tasks for these rovers while under the control of the surface crew, who will be able to operate these rovers from the shirtsleeve environment of the surface habitat/laboratory. Each rover is estimated to have a mass of 440 kilograms.

This range of mobility systems will allow exploration activities to be carried out continuously once the first cargo mission has delivered its payload to the martian surface. The variety of range requirements and surface activities leads to a suite of mobility systems that have overlapping capabilities.

3.6.4.5 EVA Systems

The ability for individual crew members to move around and conduct useful tasks outside the pressurized habitats will be a necessary capability for the Reference Mission. EVA tasks will consist of constructing and maintaining the surface facilities, and conducting a scientific exploration program encompassing geologic field work, sample collection, and deployment, operation, and maintenance of instruments. EVA systems provide a primary operational element and a critical component of the crew safety system and must be integrated into the design of a habitation system during the very early stages. Two systems will make EVA possible for the crews: an EVA suit designed for use in the martian environment and an airlock system that will

allow the crew to safely exit and enter the pressurized habitats.

The EVA system will have the critical functional elements of a pressure shell, atmospheric and thermal control, communications, monitoring and display, and nourishment and hygiene. Balancing the desire for high mobility and dexterity against accumulated risk to the explorer will be a major design requirement on a Mars EVA system. Lightweight and ease of maintenance will also contribute to the design. Specific concepts for an EVA suit that will satisfy these requirements were not investigated in this study. Further effort will be required to translate these general needs into specific requirements and an actual implementation.

The airlock system, although integral with the habitation system, was developed as an independent element capable of being "plugged" or relocated as the mission requires. Because EVA will be a substantial element of any planetary surface mission, the design and location of the associated airlock facilities will have a major impact on the internal architecture of each pressurized element.

A conceptual airlock configuration was prepared (Figure 3-39). In the foreground of this conceptual design is an airlock sized for two suited crew members. In the rear of the illustration is a facility for EVA suit maintenance and consumables servicing. Each habitat will have an airlock located within it. The maintenance and consumables
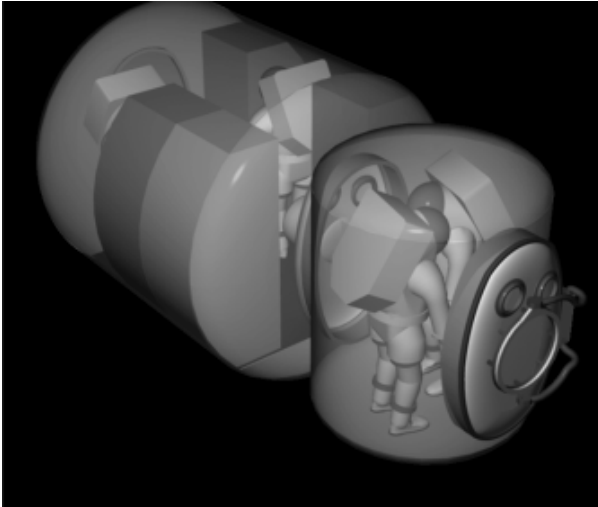
Figure 3-39 Conceptual airlock and EVA suit maintenance facility.

servicing facility will be located in the surface habitat/laboratory.

3.6.4.6 Surface Power Systems

A source of power will be required for a number of diverse systems operating on the surface of Mars. A large fixed power source is required to support the propellant manufacturing facility and the surface habitats. A mobile source of power is required to support the three categories of rovers that will move crew and scientific instruments across the martian surface. Various power system options were reviewed for their appropriateness to meet mission requirements and guidelines for these surface systems. Contending power system technologies include solar, nuclear, isotopic, electrochemical, and chemical for both the fixed and mobile power source.

While all surface element power system requirements were assessed for application synergies that would suggest common hardware (duplicates of the same or similar design) or multiuse (reuse system in a different application or location) wherever prudent, the specific requirements for the fixed and mobile power sources were examined individually.

3.6.4.6.1   *Fixed Surface Power Systems*

To best determine the type and design of the fixed power system, an estimated power profile was developed and is shown in Figure 3-40.

The power system must be one of the first elements deployed because it provides power to produce the life support cache and ascent vehicle propellants prior to the launch of the first crew. Approximately 370 days will be available to produce the required life support cache and ascent propellant. However, this will be reduced by the time to deploy the power system. With an estimated power system deployment time of 30 to 60 days, about 320 days remain for producing these products. An initial 60 kWe power level was determined by this required deployment time and the energy required to produce the life support cache and ascent vehicle propellants during the time remaining. As the outpost reaches full maturity, power levels approach 160 kWe due to increased habitation volumes and life support capability.

Significant design requirements are also placed on all the surface equipment delivered on the initial cargo flights. Each system must be deployed to its respective locations and
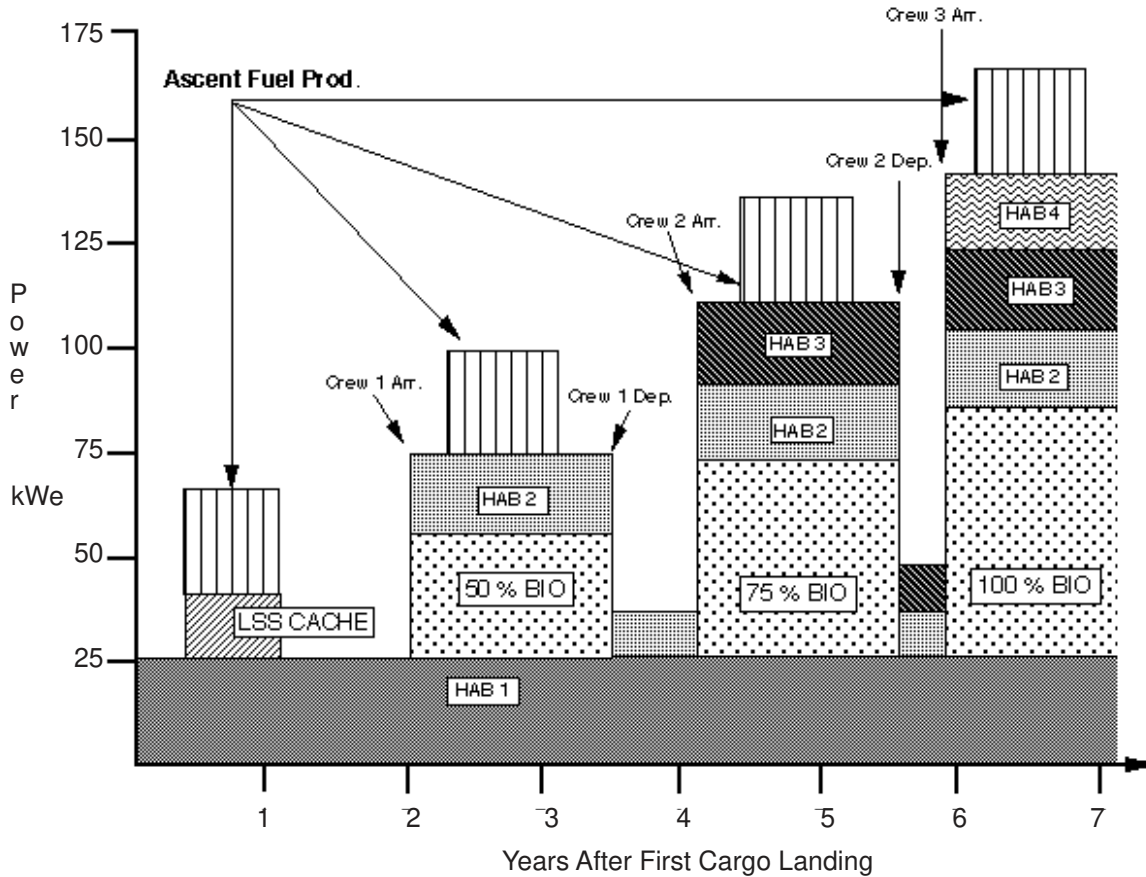
Figure 3-40   Mars surface power profile.

function autonomously for almost 2 years. Crew safety and well-being demands reliability and robustness in all surface elements. (Part of this risk is mitigated by backup and redundant systems or systems that can perform multiple functions.) These requirements all impact the design and selection of the power system for the central base.

To meet the evolutionary power requirements of the base, two types of power systems were evaluated: nuclear and solar. Table 3-22 shows estimated mass, volume, and area for each of these options.

The power management, transmission, and distribution system masses (at 95 percent efficiency) have been included in each of the system sizing estimates. Transmission cable masses were calculated using 500 volts due to the Paschen breakdown limit associated with Mars' atmospheric pressure. (For a wide range of conditions, exposed conductors at an electrical potential greater than 500 volts could experience large power drains due to atmospheric discharges.)

Due to the potential radiation hazard of a nuclear power source, the nuclear power system is configured with a completely

Table 3-22 Characteristics for Fixed Surface Power System Options

Main Power System (kWe)	Type	Mass (MT)	Volume (m³)	Area (m²)
160	NUCLEAR- SP-100 type, low-temp, stainless steel, dynamic conversion, 4-Pi shielding	14	42	321 radiator area
120	SOLAR - tracking, O.D. = 0.4	19.6	341	6,400 array area 45,000 field area
	SOLAR - nontracking, O.D. = 0.4	33.5	686	13,000 array area 39,000 field area
Backup 40	SOLAR - tracking, O.D. = 6.0	14	390	7,600 array area 53,000 field area
	SOLAR - nontracking, O.D. = 6.0	26	816	16,000 array area 48,000 field area
Emergency	Use Pressurized Rover Power System (See Table 3-21)			

O.D. - optical depth

enveloping shield for remote deployment and is integrated with a mobile platform. The entire system is deployed from the landing site (trailing distribution cables) to a site at least 1 kilometer from the base. It is planned to use one of the rovers for this task. Power from the rover will be used to start up the power system, deploy radiators, and obtain operating conditions. All of these activities will be supervised remotely by personnel on Earth and will be performed in a manner that will minimize the risk to this critical piece of equipment. The first nuclear power system will be capable of delivering the full base needs of 160 kWe. A second system is delivered during the first opportunity and is deployed to satisfy the fail-operational

mission requirement, but it will not be turned on unless required.

The second option, a solar power system, requires array panels to supply the main base load and recharge the energy storage for nighttime operations. The primary 120 kWe system was sized to produce required power during winter diurnal cycles at the equator. The backup habitat power system was designed to operate at worst-case global dust storm conditions, characterized by an optical depth (O.D.) equal to 6.0, since these conditions could be present at the base when an emergency power situation arose. Under nominal conditions, these two systems were assumed to be operating in unison to provide the maximum 160 kWe required for the

mature base. The ISRU plant was not considered a life-critical function so the power system was designed to produce full power at an O.D. of 0.4 or a clear Mars sky. Both sun tracking and nontracking arrays were evaluated. The solar tracking array total land area is greater that the nontracking because of the required panel spacing needed to eliminate shadows from one panel upon the other.

O.D., or the intensity of the solar radiation reaching the surface of Mars, has a significant impact on system size and mass. For example, if the entire 160 kWe were solar generated, the array field would encompass about 11 (O.D. = 0.4) to 40 (O.D. = 6.0) football fields. In addition, the need for prompt telerobotic emplacement of the array panels and interconnecting cables would present a significant challenge. Dust erosion, dust accumulation, and wind stresses on the array panels raise power system lifetime issues. For these reasons, nuclear power was deemed the most appropriate primary power source for the fixed surface power system. However, use of the "in-space" solar array and fuel cell power system is assumed as the habitat emergency/backup power systems, which could be stowed until needed. The MAVs will also be provided with this same solar array backup system to ensure that the manufactured propellants are maintained in their cryogenic state should power from the nuclear system be lost (Withraw, et al., 1993).

3.6.4.6.2   *Mobile Surface Power Systems*

The other major category of surface systems needing a power source will be the rovers. The three types of rovers identified, long-range pressurized, local unpressurized, and long-range robotics, each have power requirements driven by their range and the systems they must support. Several power source options were evaluated for the rovers, including solar arrays/RFCs, combustion engines, and isotopes. Solar array systems were not considered due to the large size of the array needed to support each vehicle.

The long-range pressurized rover must be able to support a crew of 2 to 4, with a 500-km range sortie (5 days out, 10 days at site, 5 days back). The power estimate for this rover is 10 kWe continuous. It is anticipated that the pressurized, regional rover or its power system would be used to assist in the deployment of the main power system, situate future habitat modules, and serve as backup emergency power when required. A desirable feature for the rover power system is that it be mounted on its own cart. This would add considerable versatility to its use when the rover is not on a sortie.

The local unpressurized rover is conceptually the same as the Apollo lunar rover. It would function to transport the crew 10's of kilometers, 3 hours out and back, and 4 hours at the site.

Table 3-23 shows the estimated mass, volume, and array or radiator area for the four power system options listed.

The Dynamic Isotope Power System (DIPS) was considered primarily for its low mass and significantly lower radiator size compared to the photovoltaic array (PVA) area. The ^{238}Pu isotope has a half life of 88 years and can be the same design as the flight proven radioisotope thermoelectric generator (RTG). The isotope fuel would be reloadable into other power units in the event of a failure, thus preserving its utility. Another feature of isotope fuel is that it does not need to be recharged and is always ready as a backup, emergency power source independent of solar availability or atmospheric conditions. However, the ^{238}Pu isotope availability, quantity, and cost are issues to be addressed.

The PV/RFC power option seems impractical for the regional rover due to the large array area. The arrays would have to be sized to provide required power output during a local dust storm, the worst-case scenario, anticipating suspended operations during potential global dust storm season.

Methane is a possible fuel for the rover since the propellant plant could produce additional fuel, given that extra hydrogen is brought from Earth. Methane could be used in an appropriately designed fuel cell. The reactant water would be returned and fed through an electrolyzer to capture the hydrogen. However, once the water has been electrolyzed into H_2 and O_2, which the fuel cell actually uses to operate, it is not prudent from an energy utilization standpoint to make methane again. Storing and maintaining reactants on the rover also needs further study.

A methane-burning internal combustion engine could be used to operate either rover. However, combustion materials would need to be collected to reclaim the H_2.

Table 3-23 Rover Power System Characteristics

Power System	Mass (MT)	Volume (m³)	Area (m²)	Mass (MT)	Volume (m³)	Area (m²)
	Regional Rover			*Local Rover*		
Dynamic isotope	1.1	10	33	0.5	4	16
Photovoltaic (PV) RFC	2.8	66 (RFC-4) PV-62)	1,275	recharge by fueling		
Primary Fuel Cell	6.5	29	13	0.160	1	6
Methane/Oxygen Internal Combustion Engine	12	36	n/a	0.160	0.4	n/a

Given these system characteristics, the DIPS system was selected for the long-range pressurized rover, and the primary fuel cell was selected for the local rover. The DIPS system can be another level of functional redundancy for the base systems, and the small amounts of radiation emitted can be mitigated by a small shield and distance to the rover crew. The primary fuel cell would meet the local rover requirements at less mass than other options. However, this power system design assumes refueling after every sortie. The power system for the long-range robotic rover was not specifically addressed in this analysis. However, the long range over rugged terrain and long duration of this rover's missions will likely drive the selection to an RTG- or DIPS-type system.

3.7   Robotic Precursors

Robotic precursor missions will play a significant role in two important facets of the Reference Mission. The first will be to gather information about Mars that will be used to determine specific activities the crew will perform and where they will perform them. The second will be to land, deploy, operate, and maintain a significant portion of the surface systems prior to the arrival of the crew.

3.7.1   Current Robotic Program Plans

In November and December 1996, NASA launched two missions to Mars: the Mars Global Surveyor (MGS) and the Mars Pathfinder lander. MGS will monitor global weather and provide global maps of martian surface topography and mineral distribution. The Mars Pathfinder will validate entry, descent, and landing technologies and will also deploy a microrover on the surface to analyze the elemental composition of martian rocks and soil.

NASA's Mars Surveyor Program will continue the robotic exploration of Mars with two spacecraft launches planned during each of the 1998, 2001, and 2003 opportunities. A Mars sample return mission is scheduled for 2005. The goals of the Mars Surveyor Program are to expand our knowledge of the geology and resources on Mars, to understand the meteorology and climate history, and to continue the search for evidence of past life.

3.7.2   Mars Sample Return With ISRU

Detailed laboratory analyses of martian rock, soil, and atmosphere samples at Earth will provide essential information needed before sending humans to Mars. In addition to an understanding of the martian environment, a sample return mission will afford the opportunity to validate the technology of ISRU for propellant production. As discussed in Section 3.6.4.3, ISRU is a critical technology for the Reference Mission. To ensure that this technology is available for the human missions, it should be demonstrated on the Mars sample return in 2005.

3.7.3　Human Exploration Precursor Needs

Robotic precursor missions offer the capability to demonstrate and validate the performance of key technologies that are essential to the Reference Mission (such as ISRU, aerobraking and aerocapture at Mars) and to provide information needed for site selection.

Critical to selection of the landing site for the humans will be the availability of indigenous resources, and of paramount importance is water. Precursor missions which can identify the location and accessibility of water will be invaluable in the Mars exploration program. To satisfy the human habitation objectives in particular, it would be highly desirable to locate an outpost site where water can be readily extracted from minerals or from subsurface deposits. Such a determination may only be possible from data collected by a surface mission.

With the three human missions all landing at the same site, selection of that landing site is very important. The location chosen must permit the objectives of the Reference Mission to be achieved. Consequently, the site will be chosen on the basis of proximity to a region of high science yield, availability of water or other indigenous resources, and operations considerations such as a hazard-free terrain for safe landing and surface mobility. Final site selection may require several robotic site reconnaissance landers to be sent to survey

various candidate sites. Detailed maps of candidate landing sites built from data gathered by these precursor missions will define the safety and operational hazards of the sites, as well as confirm access to scientifically interesting locations and resources.

In summary, then, the Reference Mission assumes a set of robotic precursor missions which includes:

- The Mars Surveyor Program

- A Mars sample return mission in 2005 which also demonstrates in situ propellant production

- Other sample return missions to various interesting regions

- A demonstration of aerobraking/ aerocapture

- Mission(s) to search for resources, particularly water

- Site reconnaissance landers to aid in the selection of the human landing site

The last two mission types may have their objectives incorporated into the Mars Surveyor Program or the Mars sample return mission; or a separate set of missions may be required.

3.7.4　Autonomous Deployment of Surface and Orbital Elements

As described in Section 3.5.3.2, a key strategy of the Reference Mission is to use a split mission concept that will allow

unmanned cargo to be sent to Mars on low energy, longer-transit-time trajectories. These unmanned elements must arrive at Mars and be verified to be operating properly before the human crew is launched from Earth. The arrival, precision landing, deployment, and operation of these surface or orbital elements will be performed using robotic systems. The detailed nature of these robotic systems was not examined as part of this study; however, the discussion of the surface facilities and the nature of the operations involved to set up, maintain, and, if necessary, repair these facilities can well be imagined. This area of technology development will be a very active one to meet the needs of the Reference Mission.

3.8 Ground Support and Facilities Operations

The overall goal of mission operations is to provide a framework for planning, managing, and conducting activities which achieve mission objectives. (In general, mission objectives can be considered all activities which maintain and support human presence and support scientific research during the mission.) Achieving this operational goal requires successful accomplishment of the following functions.

- Safe and efficient operation of all resources (includes, but is not limited to, vehicles, support facilities, training facilities, scientific and systems data, and personnel knowledge and experience bases).

- Provision of the facilities and an environment which allow users (such as scientists, payload specialists, and to an extent crew members) to conduct activities that will enhance the mission objectives.

- Successful management and operation of the overall program and supporting organizations. This requires defining roles and responsibilities and establishing a path of authority. Program and mission goals and objectives must be outlined so that management responsibilities are clear and direct. Confusing or conflicting objectives can result in loss of resources, the most important of which are time and money. In addition, minimizing layers of authority will help avoid prolonged operational decision-making activities. This is key when considering large, complex programs such as the Reference Mission.

As with the discussion of crew operations (Section 3.4), specific hardware, software, and system recommendations will not be made in this section. Guidelines for the organization and management of operations are put forward as foundation on which an actual operations philosophy and detailed plan should be built.

The organization of supporting facilities must follow the lower costing and innovative approaches being taken by other areas of the Reference Mission. One way of achieving this

is to use the related expertise and functionality of existing facilities to keep to a minimum the layers of authority and overhead in the program and take advantage of the existing knowledge bases at each facility. Proper and efficient organization of mission operations and support facilities is required for any program to be successful.

The Reference Mission has the added complication of being a program with phases that cannot be supported with near real-time operations. Planetary surface operations pose unique operational considerations on the organization of ground support and facilities. Near real-time ground support, as provided for current manned space programs, is not possible. A move toward autonomy in vehicle operations, failure recognition and resolution, and mission planning is needed; and ground support must be structured to support these needs. Some of the specific criteria required for allocating functions between ground support and the Mars surface base will be the available resources at the remote site versus on Earth, criticality of functions for crew safety and mission success, and desired time and resources available for achieving scientific mission objectives.

In general, due to the uniqueness of planetary surface operations, Earth-based support should manage and monitor operations planning and execution, and crew members should be responsible for operations planning and execution. Crew members will be told what tasks to do or what objectives to accomplish, but not how to do it. This has the benefit of involving system and payloads experts in the overall planning, yet giving crews the flexibility to execute the tasks. This approach differs from current Space Shuttle operations where detailed plans are prepared by ground personnel, crew members execute the plans, and ground personnel monitor in near real-time. The crew members are fully involved in execution but do little in terms of planning. The proposed method for the Reference Mission would take advantage of the unique perspective of crew members in a new environment but would not restrict their activities because of the mission's remote nature. Additionally, it places the responsibility of mission success with the crew, while the overall responsibility for prioritizing activities in support of mission objectives resides with Earth-based support.

After dividing functional responsibilities between Earth-based support and crew, the support may be structured to manage the appropriate functions. To accomplish mission objectives while maintaining the first operational objective of safe and efficient operation of all resources, Earth-based support can be organizationally separated into systems operations and science operations, provided a well-defined interface exists between the two. The systems operations team would be responsible for conducting the safe and efficient operation of all resources, while the science operations team would be responsible for conducting activities which support scientific research. Such an organizational structure would

dictate two separate operations teams with distinct priorities and responsibilities yet the same operational goal.

Crew and vehicle safety are always of primary concern. When those are ensured, science activities become the highest priority. To accommodate this hierarchy of priorities within the operations management structure, the overall operations manager should reside within systems operations. A science operations manager, who heads the science operations team, should organizationally be in support of the operations manager. Various levels of interfaces between systems engineers and science team members must exist to maximize the amount of science and mission objectives that can be accomplished. For example, a proposed science activity may need systems information for its planning and feasibility studies, and such information, including providing access to the systems' experts, must be made available. There may be a few overlapping areas of responsibility between the systems and science teams. (In the area of crew health and safety, for example, scientific investigators doing biomedical research on the crews will have to interface with the systems medical team responsible for maintaining crew health.) Avenues for such interaction and exchange must be provided to ensure mission success.

3.8.1 Systems Operations

Systems operations are those tasks which keep elements of the program in operational condition and support productive utilization of program resources. Thus, the systems operations team has the responsibility for conducting the safe and efficient operation of all such resources and consists of representatives from each of the primary systems (power, propulsion, environmental, electrical, etc.) used throughout the various mission phases. This organizational structure is similar to current flight vehicle operations where representatives for each system are responsible for verifying the system's operational functionality. Each system representative will have an appropriate support team of personnel familiar with the hardware and software of that system.

Real-time operational support will be applicable only during launch, Earth orbit (for vehicle and crew checkout), and Earth entry phases. As a result, the systems operations team will function in a response, tracking, and planning mode throughout most of the other mission phases. Thus, Earth-based operations will be a checks and balances function analogous to the mission engineering functions executed during Space Shuttle missions. Hardware and software documentation will be available to the crew on board for real-time systems operations and failure response. However, Earth-based support must be provided for instances where documentation is limited or does not cover a particular situation.

Except for the above mentioned near real-time mission phases, data monitoring by Earth-based personnel must be limited to periodic evaluations. Data and

communication constraints will make real-time system monitoring by Earth-based personnel impractical and unfeasible. Failures and other systems issues will be worked by Earth-based personnel on an as needed basis and in support of long-term trend analysis. Vehicle and system maintenance and checkout will be evaluated by the Earth-based systems experts to assist in crew monitoring and verification. Consumables management such as usage planning and tracking will be done by the crew (with some degree of automation) with Earth-based personnel doing verification only.

3.8.2 *Science Operations*

The science operations team's sole function is to recommend, organize, and aid in conducting all activities which support scientific research within the guidelines of the mission objectives. The team will consist of representatives from the various science disciplines (biology, medicine, astronomy, geology, atmospherics, etc.) which support the science and mission objectives. Each scientific discipline will have an appropriate support team of personnel from government, industry, and academia who have expertise in that field. The science operations team will act as the decision-making body for all science activities from determining which activities have highest priority to handling and disseminating scientific data. The science operations team will be coordinated and managed by the science operations manager, who will be the ultimate decision maker and

the primary interface between the science team and the operations manager.

As science activities (such as initial investigations, clarification of previous research, and follow-up investigations) are proposed by various principle investigators, the science team will evaluate the proposed research, determine feasibility and appropriateness of the study, and select appropriate crew activities based on available time and personnel. This process is similar to the process used by the National Science Foundation for the U.S. Antarctic Program which has successfully operated remote scientific bases in Antarctica since 1970 (Buoni, 1990). Selected science proposals will be presented to the systems operations team for evaluation of feasibility and resources. For example, appropriate members of the systems operations team will determine if there are enough consumables to support the required activities and if all of the desired activity is operationally feasible from a systems standpoint. Upon verification, the proposed research activity will be submitted to the crew for execution.

An initial set of science activities will be planned before each crew departs Earth. This is especially true of the scientific investigations which support not only crew health and safety but also the primary mission objectives. As new discoveries are made and new avenues for research are opened, an iterative science planning process will become essential for the success and effectiveness of all scientific activities.

Successful scientific operations will also require, when needed, crew access to the principal investigators for a given research avenue. Such access must be made feasible within the structure of mission operations.

3.9   Programmatic Issues

Three significant programmatic issues must be considered in an undertaking of this magnitude, if the undertaking is to be successfully achieved: cost, management, and technology development. Each of these factors was examined to determine how they should be incorporated into this and further studies of the Reference Mission or comparable endeavors.

3.9.1   Cost Analysis

Cost analysis is an important element in assessing the value of a program such as this and should be used from the very beginning. But at the beginning of a program and, in many cases, up to the time that specifications are written and contracts are let, it is not possible to analytically determine the cost of a program. If new systems need to be developed for programs, it is not possible to know at the outset what the total cost will be because hardware is not on the shelf. For these reasons, cost models are used that are typically based on historical data for similar programs.

- The total program cost will be important to the beneficiaries and resource providers, who will be interested in whether to invest current and future

resources in this program or some alternative program. As many of the benefits of an exploration program are intangible and long term, reducing the program costs to an understandable and supportable level is of prime importance.

- Whatever the total cost, the program will not be undertaken if resources are not available. Thus, cost estimates can be the basis for apportionment of resource requirements between participants, phasing of resource provisions, or phasing of mission elements to avoid peak-year funding issues that could stymie the program. Little has been done in the Reference Mission costing to address this question; however, the database is available to analyze cost-phasing strategies.

- The cost of mission elements and capabilities needs to be understood in order to prioritize early investments in technology and initiate other cost-reduction strategies. The estimated cost of each element (for example, ETO launch) is related to the program risk, with higher relative costs associated with larger perceived risks of development or operation. Thus, understanding the cost can be a first step in designing program risk-reduction strategies. As part of this process, estimates were also made of the cost uncertainty for each of the technical elements of the mission, which are also

useful in understanding the appropriate capability development strategies. In the past, technology development efforts have focused primarily on improving performance. Now, it is important to address reduction of cost as a goal of the technology development program.

The cost of a program such as the Reference Mission is a function of two major variables: the manner in which it is organized and managed and the technical content of the program.

3.9.1.1 Organizational Culture and Cost

Management systems and the organization under which programs are conducted are a major factor in the cost of a program. Basing costs simply on historical data implies that the management system under which the historical programs were carried out will be assumed for the new program. This is a particularly serious problem in estimating the Reference Mission costs, as the environment in which future space exploration will be carried out will be much more cost-conscious than in the past. Changes in management, for which no comparative costs are available, will have to occur. Because management style and culture are introduced at each level of design and production, the leverage of management changes in making cost reductions can be quite high. However, such changes are difficult to estimate. This is a major reason why cost analysis should be considered a design tool to be used at all stages of a

program. It is also a major reason to seek examples or benchmarks in other programs to determine the best possible management approaches to design and development, or to conduct specific programs under new management rules as prototypes for the approach that will be used in the actual program.

The cost of doing space missions lies at the extreme edge of costliness in comparison to other high technology systems. The technical reasons for this appear to be that space missions:

- Are usually one of a kind or are projects with small numbers of production units

- Are typically aimed at expanding capability and technology, so are designed with small margins of mass, power, volume, etc.

- Have high transportation costs, so high reliability in the spacecraft is important

- Are expected to operate for extended periods of time in difficult environments and, in the case of crewed vehicles, they must meet high standards of safety

The engineering and management culture that has been built up around these characteristics has stressed excellence of performance, safety, and high reliability. Cost has typically been a secondary criterion. It is not clear that high quality performance and high reliability always require the corresponding costly culture.

To illustrate the effect of culture on cost, consider Figure 3-41 which shows the relative cost of programs developed using different management approaches. Point 0 is the relative cost for human spacecraft, point 1 is for robotic spacecraft, point 2 for missiles, and point 3 for military aircraft. Differences in management styles develop as a result of the different environments in which programs are carried out.

Table 3-24 depicts the differences between a "Skunk Works" management environment, such as might be used on a military aircraft development program (point 2 in Figure 3-41) and the environment for NASA's human programs. Some of these differences will have to be addressed if the cost of human space exploration is to be reduced. To further illustrate differences, Table 3-25 compares the parameters of the development culture for commercial aircraft and NASA human programs. These are starting points that indicate the changes that will be necessary.

The cost model used for the Reference Mission (see next section) takes these variables into account in a "culture" variable, which can be characterized in more detail by such attributes as organizational structure, procurement approach, and the degree of program office involvement in production.

3.9.1.2 The Cost Model

The cost model used for the technical content of the Reference Mission is the Advanced Missions Cost Model (AMCM)

(Cyr, 1988). This model considers the scale (particularly mass), the scope (number of production and test articles) of the development of each of the systems required to undertake the program, the complexity or technical readiness for each of the systems and their subsystems, the schedule under which the program will be carried out, and the production generation in which the item is produced. To the extent that experience exists or off-the-shelf hardware can be procured, more precise numbers can be estimated. The newer or more untried a technology is, the greater will be its cost in the model.

Input for the AMCM model was derived from previous experience and information provided by members of the Study Team. Included in the estimate were the development and production costs for all of the systems needed to support three human crews as they explore Mars. In addition, ground rules and assumptions were adopted that incorporated some new management paradigms, as discussed later in the Program Management and Organization section. The management costs captured program level management, integration, and a Level II function. Typical pre-production costs, such as Phase A and B studies, were also included.

Not included in the cost estimate were selected hardware elements, operations, and management reserve. Hardware costs not estimated include science equipment and EVA systems, for which data were not available at the time estimates were prepared; however,
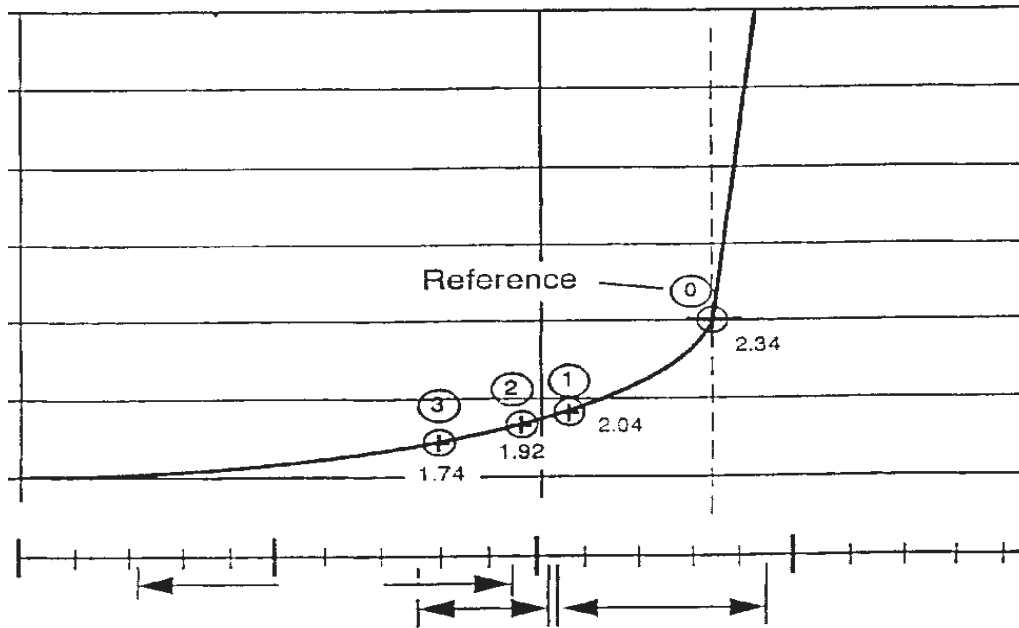
Figure 3-41   The relative cost of programs using different management approaches.

these are not expected to add significantly to the total. No robotic precursor missions are included in the cost estimate although their need is acknowledged as part of the overall approach to the Reference Mission. Operations costs have historically been as high as 20 percent of the development cost. However, due to the extended operational period of the Reference Mission and the recognized need for new approaches to managing and running this type of program, estimating the cost for this phase of the progam was deferred until an approach is better defined. Similarly, the issue of management reserve was not addressed until a better understanding of the management approach and controls has been developed.

When compared to earlier estimates of a similar scale (NASA, 1989), the cost for the Reference Mission is approximately an order of magnitude lower. A distribution of these costs is shown in Figure 3-42. It can be seen from this figure that the major cost drivers are those associated with the transportation elements: the ETO launch vehicles, the TMI stages, and the Earth-return systems. In addition, the organization mechanisms chosen have significantly reduced the cost for these elements of cost, when compared to traditional programs of this type, creating a significant challenge for those who would manage this program.

The Mars Study Team recognizes that, even with a significant reduction in the program cost achieved by this team, the

Table 3-24 Program Environment Effects on Program Management Style

Environment Factor	"Skunk Works" Management	NASA Human Program Management
Political Environment	- Major threat perceived by all involved	- Non-urgent - Threat not perceived as critical
Cost of Failure	- Hidden	- Public - Potentially catastrophic to Agency
Products	- High technology - Prototypes - Experimental	- High technology - High quality "mature" designs
Risk to Life	- Acceptable, but - Worthy of spending major resources to avoid	- Unacceptable - Worthy of spending major resources to avoid
Public Perception	- Secret - Defense - Urgent - Unaware of existence until after deployment	- Public - Science, exploration - Discretionary - Every detail open to public scrutiny and criticism
Schedule	- Typically 2 years	- Typically 8 to 10 years
Quantities	- Small to moderate	- Small to moderate
Management Teams • Contractor • Government	- Very small (under 10) - Very small (3 to 10 typically)	- Moderate to large (dozens) - Large (hundreds)
Political Support	- High	- High
Cost	- Small portion of parent agency budget - Low specific cost (e.g., $/1b)	- High percentage of parent agency budget - High specific cost

Table 3-25 A Comparison of Development Culture Parameters for Commercial Aircraft and NASA Manned Programs

Parameter	Commercial Aircraft Program	NASA Human Program Management
Customer Role	Requirements definition, arms length	Highly interactive
Type of Requirements	Performance of the product	Detailed build specifications, some to piece part level
Program Office Size and Type of Interactions	Small (tens or less) Interaction for clarification of details	Large (hundreds) Interaction to lowest WBS levels
Proximity of Program Office Relative to Customer	Geographic separation, frequent travel by very small groups	Geographic separation, with frequent travel for face-to-face meetings by large numbers of project people
Competition Through	Commitment to fixed price by supplier	Three phases: end of preliminary design, program definition, start of detailed design and development
Technology Status at Full Scale Development Start	Totally demonstrated flight systems	Proof of concept
Management Systems	Supplier's systems only: occasional tailored reports to the customer	Customer imposed, often duplicative with contractor systems
Length of Full Scale Development	2 to 3 years	6 to 15 years
Budget Strategy	Full commitment with guarantees by both parties	Annual, incremental, high risk
Changes	None to very few	Thousands per year
Fee Type	Included in fixed price	Fixed, and/or award, based on supplier performance
Contract Type	Fixed price with incentives	Cost plus fixed, award fee
SR&QA	Industry and supplier standards	Customer specified

magnitude is probably still too high in today's fiscal environment. More work to further reduce these costs is needed.

The largest cost element of the Reference Mission is the ETO transportation system which makes up approximately 32 percent of the total program cost. This element was assumed to be a new HLLV capable of lifting 220 tonnes of payload to LEO. Although this is a launch vehicle larger than any previously developed, its design was assumed to be based on the Saturn V technology, and engines were selected from existing designs. The costs of development were approximately 20 percent of the total ETO Line Item, and production costs (assuming that 12 HLLVs would be produced to support the program, using 3 HLLVs for the first opportunity and 3 HLLV launches at each of the remaining 3 launch opportunities) were 80 percent of the ETO Line Item.

To reduce the cost of the HLLV component, several possible strategies could be used.

- Reduce the mass of systems, infrastructure, and payloads that need to be launched into Earth orbit for transport to Mars to support the surface mission (assume that mission capability is not going to be reduced, which is also possible but not desirable). This could reduce the total number of HLLV launches and the assumed production cost. For example, Robert Zubrin believes that the program could be

carried out using two HLLV launches per opportunity (requires some reduction of capability) (Zubrin, et al., 1991). Reducing the number of launches from 12 to 8 would reduce the production costs by one-third and would reduce total costs of this element by 26 percent. Developments in new materials, which are rapidly occurring, could improve systems performance and reduce the mass of the protective shells and vehicle systems.

- Reduce the size of the HLLV (also proposed by Zubrin). This might or might not reduce total costs, because additional costs for on-orbit operations might be required. Reducing the cost of launch to LEO using reusable vehicles currently under consideration in the reusable launch vehicle program would require very large investments in LEO assembly. The trade-off might be favorable, but may or may not make a significant reduction in total cost. The availability and use of an in-orbit assembly capability like the International Space Station could make this an effective strategy.

- Improve the production efficiency for HLLVs. The AMCM model includes a learning curve assumption that each time the number of items produced doubles, the cost per item is 78 percent of the previous production cost. More production learning could be very
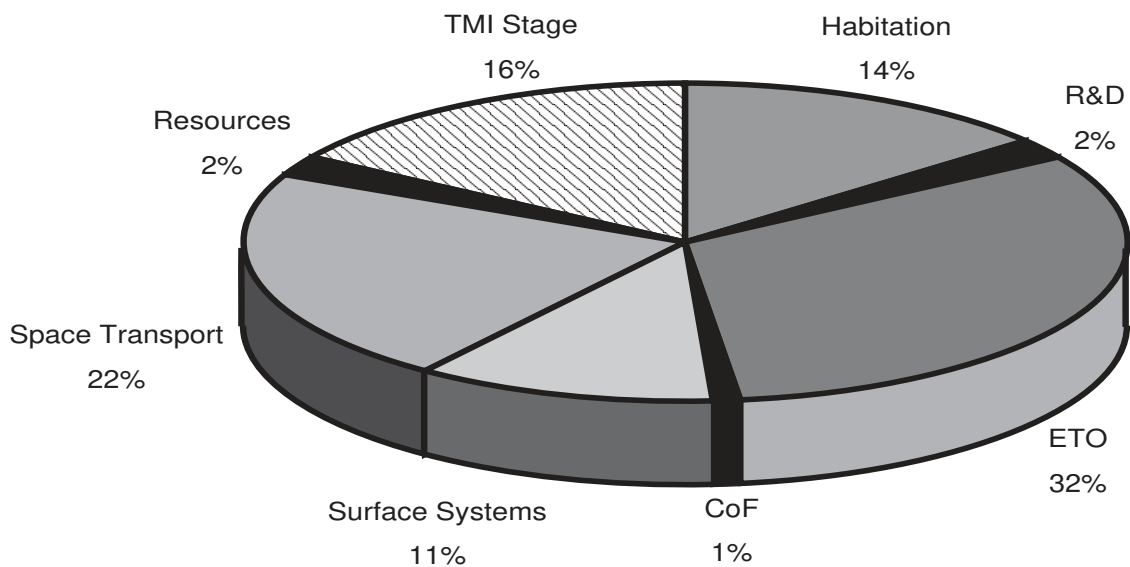
Figure 3-42   A comparison of the relative costs for Reference Mission elements.

significant. For example, if 12 HLLVs of equal capability had been produced for another program, the cost of HLLVs for the Mars program could be cut by 22 percent. To achieve these cost reductions would require that no special modifications be necessary for the ETO vehicles used by the Mars program.

- A significant reduction in HLLV cost might be designed in at the start if new techniques for manufacturing and testing were introduced. However, the learning curve benefits of mass production might be less.

- The HLLV development was assumed to be purchased by the government in a

conventional manner; however, some procurement aspects were assumed to be new, and credit was taken in the estimates for these new ways of doing business. The HLLV might be developed by industry at lower cost, to meet performance specifications rather than government technical specifications. The assured sale of 12 vehicles may be large enough to achieve some amount of cost reduction to LEO, but is not likely to lead to major cost reductions. However, industry might be able to consider the government an "anchor tenant" for HLLV production, develop additional markets for their technology, and amortize the investment over a larger

number of vehicles. This would imply an assumption that the space frontier is expanding significantly.

- The HLLV could be supplied by the Russians or as a joint effort by multiple international partners. This might be a contribution to an international program where it would be an example of cost-sharing between partners. At the present time, this does not appear to be a feasible solution; however, it may be reasonable in 15 years. If the U. S. or other partners were expected to pay the Russians for their participation, it would require the appropriate political rationale. If the Russians were to contribute the HLLV without payment, it would be the equivalent of one-fourth of the total program cost, though it might not cost the Russians as much as it would cost the U. S. in absolute dollars.

- Finally, innovative advances in propulsion could result in the development of new propulsion techniques; for example, electromagnetic propulsion for ETO could substantially decrease the transportation cost for some materials (propellant).

The Earth-Mars vehicle (the TMI stage) and the Mars-Earth vehicle (the ERV) elements provide for the delivery of humans and payloads to Mars and the return of humans to Earth. The costs are for the transportation elements alone (the interplanetary habitat elements are not

included). The TMI stage was costed separately because it was assumed to require separate development of a nuclear thermal propulsion system. The TMI stage was assumed to be jettisoned before reaching Mars. Conventional space storable chemical propellants were assumed to be used in the ERV stage to return to Earth. The nuclear thermal stage assumed considerable inheritance from the U. S. nuclear propulsion program that produced the NERVA engines in the 1960s; development costs for the TMI stage were projected to be 16 percent of the total cost. The space transportation vehicles are all new and include several vehicles (ascent vehicle, crew capsule, and the TEI stage). The cost of the space transportation vehicles comprises 22 percent of the total.

The ratio of development cost to production cost for these vehicles is rather high, partly because of the smaller number of vehicles produced for the return home. Various ways of reducing the costs of these elements might be considered.

- Development of nuclear electric or solar electric propulsion vehicles that are more efficient could lower transportation costs for cargo but might not reduce costs of human flights and might increase costs if parallel development of two transportation systems was necessary. If a single technology with higher efficiency than chemical rockets could be used to go to Mars and return, much of the cost associated with developing the space transportation stages might be

saved because the number of separate developments would be minimized.

- Systematic application of new techniques of automated design to the development process and use of concurrent engineering could reduce life cycle costs of the systems.

- General improvements in methods of procurement and program management could have significant returns in these areas. Reduction of integration costs can be accomplished by centrally locating design and development teams and keeping simple interfaces between systems manufactured by different providers.

- Several vehicle elements could be provided by international partners. Each of the vehicles provided without cost to the program could reduce total program costs by several percent.

Habitats are an essential part of the Reference Mission scenario. They represent 14 percent of total mission cost and are assumed to have inheritance from the International Space Station program. The Reference Mission has made the assumption that all habitats required by the program are essentially identical, which is probably an oversimplification. To the extent the design of space habitats and surface habitats diverges, the cost could rise. Eight production habitats are required. Modest learning curve cost reductions are assumed for the production line. About one-third of the estimated cost of habitats is development, production is the remaining two-thirds. Thus, cost reductions involving the improvement of design and procurement processes are potentially the most important objectives. Note, however, that the habitats are also a significant mass element; therefore, technology that reduces their mass will also have a significant effect on the transportation system.

Surface systems, including mobility systems and resource utilization systems, surface power, and other nonhabitat systems, constitute about 11 percent of the total mission cost. Because these surface systems are rather complex, critically determine mission productivity, and are a small fraction of the total, this area does not appear to be a high-priority source of major additional cost reductions. However, mass reductions in the hardware will have high leverage in the space transportation cost elements, if the size of the transportation vehicles or the number of launches can be reduced. Surface systems costs are probably underestimated in the current model, because no data for a closed LSS, EVA hardware, and science hardware were included in this estimate. Development of a suitable EVA suit will be a significant technology challenge and potentially expensive. The closed environment LSS hardware probably is not extraordinarily expensive. However, testing and demonstrating it will only partially occur in the International Space Station program, so additional cost and risk are involved in its development. Science equipment is not a

major cost item, in comparison with the large costs ascribed to the transportation system.

Operations was not included as part of the cost analysis, but has been previously estimated as a proportion (historically as high as 20 percent) of the total development costs. The operations costs are incurred primarily in the 11 years of the operational missions. The allocation of budget that would be associated with this estimate is equivalent to approximately 20,000 people per year for that period of time. This is definitely an old way of doing business which must change for the Mars missions. A reasonable target would be an operational team of approximately 1,000 persons. This is likely to be attainable in part because automation and autonomy will be a necessary characteristic of the Mars missions. A principal mechanism for reducing these costs may be a directed program to reduce the operational costs of the International Space Station as an analog to Mars missions.

The number and type of systems represented in the Reference Mission is near minimal considering the desired surface mission capability. It is always possible to reduce costs by reducing the required performance. For example, using the same assumptions used for this model if only a single landing were carried out, the total program costs would be reduced by about 30 percent in comparison to the full three piloted mission program. Reducing the scope of the surface activity will not have a big effect on cost, as it is already a relatively small proportion of total mission costs, confirming

the expectation that optimizing the surface mission for its benefit is also the way to improve the benefit/cost ratio for the human exploration of Mars.

The question of management style must now be addressed. Particular attention needs to be paid to the process by which the production elements are procured. The current estimates probably are still influenced by current ways of doing business. If total Reference Mission costs are to be reduced, it is at this level of effort that the most effective changes can be made. Focusing on the wrap factors may not accomplish significant additional reductions, although reducing the production costs will also reduce the amount that must be spent in these areas.

3.9.2 *Management and Organizational Structure*

Organization and management is one of the principal determinants of program cost. This is a rather wide-ranging topic, which is not entirely divisible from the technical content of the program, because it includes program level decision making that is intimately tied to the system engineering decision-making process.

The magnitude of the Reference Mission, once it has been initiated, is enormous. Many good examples exist of smaller programs that have failed or have not performed well due to management deficiencies. Thus, as the Reference Mission is examined and improved, continued consideration should be given to streamlining its management; assigning

authority, responsibility, and accountability at the right levels; and developing processes that are simple, with clear-cut interfaces and measurable performance standards.

The relationship between cost and management style and organizational culture is rather well-known in a general manner, through a large number of lessons learned analyses made postprogram. The list of key elements of lower-cost programs is shown in Table 3-26. These have been pointed out in a series of analyses, but have not commonly been applied at the critical stage of developing program organization and management approaches. Rather, the organizational and management style has been determined rather late in the program, generally because the program content and final design were typically delayed through redesign, changing requirements, and funding irregularities.

To manage a Mars program to a lowest possible cost, a number of considerations have been identified.

- The design of the organization and management system should be an area of investigation in subsequent studies of the Reference Mission. The relationship between program cost and program culture is illustrated in Figure 3-46. Although several factors are involved, this figure indicates that significant cost impacts are tied to the organizational culture and the management system.

- The human exploration of Mars will be highly visible to the world, will be a tool of international policy in many countries, will be complex and expensive, and will take several years to develop. Under these conditions, it is essential that a philosophical and budgetary agreement be reached prior to initiating development. A formal agreement should be reached between all parties as to the objectives and requirements that are imposed on the mission before development is initiated, and an agreement to fund the project to its completion should be reached prior to development. In the U. S., this would include multiyear budgetary authority. This should be accompanied by a management process that would protect against program overruns through appropriate incentives.

- The human exploration of Mars will have quite different risks than any space mission which will have been undertaken at its time. These include risks to the safety of the crew and accomplishment of the mission (primarily technical risks) and risks of meeting cost and schedule objectives. Maintaining launch schedule is exceedingly important, due to the dependency on several successful launches for mission success and the high cost of missed launch windows (missed launch windows imply 2-year program delays at potentially high

Table 3-26 Key Elements of Lower-Cost Programs

- Use government to define only requirements
- Keep requirements fixed; once requirements are stated, only relax them; never add new ones
- Place product responsibility in a competitive private sector
- Specify end results (performance) of products, not how to achieve the results
- Minimize government involvement (small program office)
- Ensure that all technologies are proven prior to the end of competition
- Use the private sector reporting reporting system: reduce or eliminate specific government reports
- Don't start a program until cost estimate and budget availability match
- Reduce development time: any program development can be accomplished in 3 to 4 years once uncertainties are resolved
- Force people off development programs when development is complete
- Incentivize the contractor to keep costs low (as opposed to CPAF, CPFF, or NASA)
- Use goegraphic proximity of contractor organizations when possible
- Use the major prime contractor as the integrating contractor

program cost). Thus a risk management plan can help identify the risks and formulate a mitigation strategy.

• The Reference Mission requires a number of elements, many of which are technically alike but serve somewhat different functions over the duration of the program. For example, the surface habitat may be the basis for the transit habitat, and each habitat delivered to the surface will have a different complement of equipment and supplies, according to its position in the delivery sequence. The elements will be developed over a period of several years, and there will be a temptation to improve the equipment and supply manifest. It will be important for requirements to be fixed at the time of initial development to maintain cost

control for the program. To accomplish this:

-There should be a clear demarcation between the design phase and the development/production phase of the project, and development should not begin before the design phase is ended.

-All technologies should be proved prior to initiation of production of program elements.

-Once the requirements have been established, they should not be changed unless they can be relaxed.

-A system should be developed that documents the relationship and interaction of all requirements and should be available for use prior to the beginning of production.

• The design phase of the program is critical to successful cost control. The design should be based on a set of functional requirements established by a Program Office, which may well be a multinational activity. The Program Office should be in place to manage technical requirements, provide decisions that require consultation and trade-offs (technical and political), and manage development contracts. The Program Office should also establish functional requirements for the design phase and conduct a competitive procurement for the design phase with the selection of a prime contractor. To accomplish this:

- Requirements should be provided for the design phase, describing the performance expected, and a clear set of criteria for completeness of design as a function of resources expended in design.

- A significant design cost margin should be used to manage the design resources.

- The successful prime contractor should be selected as integration contractor for the development phase.

• Once committed to development, the development time should be strictly limited if costs are to be contained. This will be difficult in the Mars program, where it probably will be effective to produce common elements sequentially rather than all at one time, although there may be a high enough production rate that costs will drop as experience is gained. A new approach will be needed to ensure that the development time for each individual element is strictly limited.

• The program will require two levels of integration, similar to that of the International Space Station program: a program level which ensures that overall mission requirements will be met at each stage of the mission, and a launch package level integration in which all required elements of each launch to Mars are packaged and their performance ensured. To accomplish this, both aspects of integration should be the responsibility of a single organization, a prime contractor to the Program Office.

• The operational phase of the Mars program must be represented in the design and development phase. This will require a concurrent engineering approach which considers the operational costs as well as the development costs in a life cycle cost approach to the program. To accomplish this, operational considerations must be included in the design and development phases of the program, and life cycle costs should be used as the determinant for program design and development decisions.

• Finally, at all stages of design, development, production, and operations, all program office officials and contractor organizations must be incentivized to maintain program costs within approved levels, and positive incentives must be put into place to reduce costs of each phase of the program.

3.9.3 Technology Development

The Reference Mission was developed with advances assumed in certain technology areas known to be necessary to send people to Mars for a reasonable investment in time and resources. The same objective could be satisfied using other technologies in some cases, making it necessary to identify selection criteria for the set of technologies the Reference Mission should favor. A reasonable investment also implies that there must be some reliance on technologies developed for other uses or simply discovered during some other development activity.

Dual-use technologies are those which are deliberately developed with more than one application in mind and which carry requirements for these various uses through the development period. Spin off or spin in technologies are those which are developed with a specific application in mind but which find other uses with little or no additional development work. Spill over technologies are those which grow to include entirely new, unplanned technologies as a by-product of

the effort to bring the original technology to its desired state.

At this particular stage in developing human exploration missions to Mars, it is difficult to do more than speculate about spin off and spill over technologies that could result from, or be useful to, this endeavor. However, identifying dual uses for some of the assumed technologies can be started now and, to a certain degree, will be required for such a program to progress. In the current political environment, investment in technology is seen as a means of improving the general quality of life, and multiple use of technologies is emphasized to obtain the best return on the resources invested in their development. Space programs are not spared this requirement. A program strategy that emphasizes dual-use technologies, besides being consistent with this current trend could:

• More easily generate funds through increased cooperation and joint ventures with other U.S. federal agencies, international partners, and commercial concerns

• Provide smaller projects which could be more easily funded

• Provide a step-by-step approach to the Reference Mission

• Provide a stimulus to local and national economies

• Foster an increase in advocacy for space programs

To this end, the Reference Mission study identified and worked with 10 Mars mission-related technology categories: propulsion, communications and information systems, ISRU, surface mobility - suits, surface mobility - vehicles, human support, power, structures and materials, science and science equipment, and operations and maintenance. These categories were then associated with a total of 54 technology areas along with their applications. Tables 3-27 through 3-36 document these various technology applications. In addition, the tables indicate where these technologies may spin off into other applications and where developments in other areas may, in fact, benefit or spin into the Mars program.

Not all of the advantageous technology for the Reference Mission must be developed by the program organization. International cooperation can benefit from the technology advancements needed for this class of space mission. Two obvious examples include heavy lift launch technology and space-based nuclear power. The relatively heavy lift launch capabilities either developed or nearing completion for the Russian Energia and the European Ariane V could form the basis for at least part of a cooperative technology development program. The former Soviet Union had also developed a relatively sophisticated operational space-based nuclear power capability.

U.S. federal agencies can also cooperate to develop mutually beneficial technologies. The long-standing cooperation between

NASA and the Department of Energy to develop small nuclear power sources for robotic spacecraft could be expanded to include the development of larger power sources (perhaps as part of a cooperative endeavor with the Russian government) or for the propulsion system technologies assumed for the Reference Mission. The Department of Defense is currently studying an integrated propulsion and electrical power system driven by the heat of the Sun (Reference: Anon., 1995). This could be a technology useful to the Reference Mission as an alternative to the nuclear system assumed and form the basis for a cooperative development program.

Several specific examples may help illustrate how technology development for the Reference Mission will benefit from spill over, spin off, and dual-usage.

One of the precursor activities to the Reference Mission that has a high priority will be the characterization of the martian surface in great detail by orbiting robotic spacecraft. Data collected by this vehicle or vehicles will be needed in many areas to prepare for this Reference Mission. One of the most significant areas will be the choice of a landing site at which the outpost will be established. This selection will be based in part on information ranging from hazards in the proposed landing zone to the proximity of the site to a variety of surface features, the investigation of which will contribute to meeting the overall Reference Mission objectives. Technology to obtain this remote

sensing data could be available from the U.S., Russia, Japan, and the Europeans, based on their previous Earth-orbiting, remote-sensing missions and other planetary explorations. But due to the high cost of transporting these sensors to the vicinity of Mars, further development or enhancement of these technologies could reduce their size, mass, and need for supporting resources (power, communications band width, etc.). Advancements in other areas, such as the Ka band utilization, data compression, and information processing technologies mentioned in the Communication and Information Systems category or from technology developed as part of the explosive growth in the PC marketplace, can also serve to improve performance and reduce costs for these systems and the data they return. Any technology enhancement developed to support the Reference Mission will then be available for use in Earth-orbiting applications.

The single largest cost of a human Mars exploration program may be the cost of ETO transportation. The development of a new HLLV solely for the Mars program could require up to 30 percent of the total resources for the program. However, approaches that can launch the appropriate payloads to Mars using smaller launch vehicles have not appeared to be viable in the past. This is a conundrum which has and may still stymie human exploration of Mars. Other avenues exist:

- The Russian Energia heavy lift launch system can be maintained and upgraded until human missions to Mars can begin. A variation of this would be to evolve a higher capacity launch vehicle using technologies developed for Energia, Ariane V, and the Space Shuttle. Either of these options would offer an opportunity for international cooperation that would not only benefit the Reference Mission but also allow for heavier, more sophisticated payloads to be launched into Earth orbit or used for lunar missions.

- The mass of hardware required to support humans in Mars journeys can be reduced. Few concepts now exist for this, but advancements in the technology options mentioned in most, if not all, of the 10 categories identified by the Mars Study Team will lead to a reduction in the hardware mass that must be sent to Mars. Each of the 10 categories also identified Earth-bound applications that may also benefit from these advancements.

A third example involves the significant level of automation assumed for the Reference Mission. The program assumes infrastructure elements (including a system to produce propellant and life support consumables, the first of two habitats, power systems, and surface transportation elements) will robotically land on the surface at a designated location. All of these systems will be delivered, set up, and checked out using

Table 3-27 Dual-Use Technologies: Propulsion

Terrestrial Application	Technology	Space Application
• Nuclear Reactors • Weapons and Nuclear Waste Disposal • High-Efficiency Heat Engines (Turbines, Thermostructural Integrity)	• High-Temp Materials	• NTR • Aerobraking
• Clean-Burning Engines (H_2/O_2)	• High Efficiency Cryo-Refrigeration	• Propellant Maintenance
• Higher Performance Commercial Launches	• Methane/O_2 Rocket Engines	• ISRU-Based Space Transportation

Table 3-28 Dual-Use Technologies: Communications/Information Systems

Terrestrial Application	Technology	Space Application
• Communications High-Definition TV Broadcast	• Ka Band or Higher	• Telepresence: Vision and Video Data • Interferometers: Raw Data Transmission
• Entertainment Industry • Commercial Aviation	• Machine-Human Interface	• Control Stations • System Management
• Communications • Archiving	• Data Compression Information Processing • Large Scale Data Management Systems	• Interferometers: Raw Data Transmission Information Processing • System Management, Expert Data • Archiving/Neural Nets

spin-in →

spin-off ←

Both ↔

Table 3-29 Dual-Use Technologies: In Situ Resource Utilization

Terrestrial Application	Technology	Space Application
• Mineral Analysis, Yield Estimation-Deep Mine Vein Location and Tracking • Wall and Ceiling Integrity	• Advanced Sensors	• Mineral Analysis, Yield Estimation Surface Mineral Analysis, and Resource Location

• Deep Mine Robotic Operations
  • Mining
  • Beneficiating
  • Removal
	• Advanced Robotic Mining	• Surface Mining Operations
		  • Mining
		  • Beneficiating
		  • Removal

• Improved Automated Processing; Increased efficiency	• Automated Processing: Advanced FDIR	• Remote, Low-Maintenance, Processing

• Reliable, Low-Pollution Personal Transmission
• Regenerable Energy Economies
• Small, Decentralized Power Systems for Remote or Third World Applications
	• Alternative, Regenerable Energy Economies
	  • Methane/O_2
	  • H_2/O_2
		• ISRU-Based Engines
		• Regenerable Energies
		• High-Density Energy Storage

• Environmentally Safe Energy Production	• Space-Based Energy Generation and Transmission	• Surface Power Generation and Beaming

spin-in →
spin-off ←
Both ↔

Table 3-30 Dual-Use Technologies: Surface Mobility - Suits

Terrestrial Application	Technology	Space Application
• Hazardous Materials Cleanup • Fire Fighting Protection and Underwater Equipment	• Lightweight, Superinsulation Materials	• Surface Suits: Thermal Protection
• Robotic Assisted Systems • Orthopedic Devices for Mobility Impaired Persons	• Robotics • Mobility Enhancement Devices and Manipulators	•Robotic Assisted Suit Systems
• Hazardous Materials Cleanup • Fire Fighting Protection and Underwater Equipment	• Dust Protection, Seals, Abrasive Resistant Materials	• Surface Suits: Outer Garment
• Hazardous Materials Cleanup, Underwater Breathing Gear	• Lightweight Hi-Rel, Life Support	• Portable Life Support for Surface Suits
• Remote Health Monitoring	• Portable Biomedical Sensors and Health Evaluation Systems	• Surface EVA Crew Member Health Monitoring
• Hypo-Hyper Thermal Treatments • Fire Fighting Protection and Underwater Equipment • Artic/Antartic Undergarments	• Small, Efficient, Portable, Cooling/Heating Systems	• Surface Suits: Thermal Control Systems

Table 3-31 Dual-Use Technologies: Surface Mobility - Vehicles

Terrestrial Application	Technology	Space Application

• All-Terrain Vehicles
  • Research (Volcanoes)
  • Oil Exploration
	• Mobility	• Surface Transportation
		  • Humans
		  • Science Equipment
		  • Maintenance and Inspection

• Reactor Servicing/Hazardous Applications	• Robotics and Vision Systems	• Teleoperated Robotic Systems
• Earth Observation, Weather, Research	• Super-Pressure Balloons (110,000 ft - Earth Equiv)	• Mars Global Explorations

• Efficient, Long-Term Operations Low-Maintenance
• Machines in Artic/Antaric Environments
	• Tribology	• Surface Vehicles
		  • Drive Mechanisms
		  • Robotic Arms
		  • Mechanisms

• Helicopers, Autos	• Variable Speed Transmissions	• Surface Vehicles
• Automated, Efficient Construction Equipment	• Multipurpose Construction Vehicle Systems and Mechanisms	• Robotic Construction and Set-up Equipment

spin-in ⟶

spin-off ⟵

Both ⟷

Table 3-32 Dual-Use Technologies: Human Support

Terrestrial Application	Technology	Space Application
• Stored Food • US Army • NSF Polar Programs	• Long-Life Food Systems • With High Nutrition • Efficient Packaging	• Efficient Logistics • Planetary Bases • Long Spaceflights • Space Stations
• Improved Health Care • Sports Medicine - Cardiovascular • Osteoporesis - Immune Systems • Isolated Confined Environments/Polar Operations • Noninvasive Health Assessments	• Physiological Understanding of the Human/Chronobiology • Understanding of Psychosocial Issues • Instrumentation Miniaturization	• Countermeasures for Long-Duration and/or Micro-g Space Missions • Health Management and Care
• Health Care • Disaster Response • US Army	• Long-Term Blood Storage	• Health Care for Long-Duration Space Missions
• Office Buildings ("Sick Building" Syndrome) • Manufacturing Plants	• Environmental Monitoring and Management	• Environmental Control for • Spacecraft Cabins • Planetary Habitats • Pressurized Rovers
• Contamination Cleanup • Waste Processing	• Waste Processing/SCWO • Water Purification	• Closed Water Cycles for • Spacecraft Cabins • Planetary Habitats • Pressurized Rovers
• Long-Life Clothes • Work Clothes in Hazardous Environments • US Army	• Advanced Materials/Fabrics	• Reduced Logistics Through Long-Life, Easy-Care Clothes, Wipes, Etc. • Fire Proof/Low-Out-gassing Clothes
• Efficient Food Production	• Advanced Understanding of Food Production/Hydroponics	• Reduced Logistics Through Local Food Production for • Spacecraft Cabins • Planetary Habitats

Table 3-33 Dual-Use Technologies: Power

Terrestrial Application	Technology	Space Application

• Batteries/RFCs for
 • Autos
 • Remote Operations
  • DOD
  • NSF Polar Programs
	• High-Density Energy Storage
	• Alternate Energy Storage (Flywheels)
		• Reduced Logistics for Planetary Bases
		• High-Rel, Low-Maintenance Power Systems

• Clean Energy From Space	• Beamed Power Transmission	• Orbital Power to Surface Base • Surface Power Transmission to Remote Assets
• Remote Operations • DOD • NSF Polar Programs	• Small Nuclear Power Systems	• Surface Base Power •Pressurized Surface Rover • Interplanetary Transfer Vehicle
• Remote Operations • DOD • NSF Poloar Programs • High-Efficiency Auto Engines	• High-Efficiency, High-Rel, Low-Maintenance Heat-to-Electric Conversion Engines	• Energy Conversion for Planetary Bases • Low Servicing Hours • Little or no Logistics

spin-in   →

spin-off   ←

Both   ↔

3-142

Table 3-34 Dual-Use Technologies: Structures and Materials

Terrestrial Application	Technology	Space Application

• Vehicles
• Fuel-Efficient Aircraft
• Modular Construction (Homes, etc.)
	• Composite Materials
	  • Hard
	  • Soft
	• Advanced Alloys, High-Temperature
		• Cryo Tanks
		• Habitat Enclosures
		• Pressurized Rover Enclosures
		• Space Transit Vehicle Structures

TBD	• Superinsulation • Coatings	• Cryo Tanks • Habitable Volumes

• Large Structures, High-Rises, Bridges
• Commercial Aircraft
  • Improved Safety
  • Lower Maintenance
	• Smart Structures
	• Imbedded Sensors
		• Space Transit Vehicle Structures
		• Planetary Habitat Enclosures
		• Surface Power Systems
		• Rover Suspensions

Table 3-35 Dual-Use Technologies: Science and Science Equipment

Terrestrial Application	Technology	Space Application

• Energy Resource Exploration
• Environmental Monitoring, Policing
	• Spectroscopy
	  • Gamma Ray
	  • Laser
	  • Other
		• Geo-chem Mapping
		• Resource Yield Estimating
		• Planetary Mining Operation Planning

• Undersea Exploration • Hazardous Environment Assessments, Remediation	• Telescience	• Remote Planetary Exploration

• Environmental Monitoring
• Medicine
	• Image Processing
	  • Compression Technique
	  • Storage
	  • Transmission
	  • Image Enhancements
		• Communication of Science Data
		• Correlation of Interferometer Data

• Improved Health Care • Sports Medicine - Cardiovascular • Osteoporesis - Immune Systems • Isolated Confined Environments/Polar Operations • Noninvasive Health Assessments	• Physiological Understanding of the Human • Instrumentation Miniaturization	• Countermeasures for Long-Duration and/or Micro-g Space Missions • Health Management and Care

spin-in →

spin-off ←

Both ↔

Table 3-36 Dual-Use Technologies: Operations and Maintenance

Terrestrial Application	Technology	Space Application
	• Task Partitioning • R & QA in Long-Term, Hazardous Environments • System Health Management and Failure Prevention Through A1 and Expert Systems, Neural Nets ←	
We mentioned this area as important, but did not complete. Recommend that we work with Jon Ericson and bob Savely to get ir right.		
	←	
	←	

spin-in →

spin-off ←

Both ↔

robotic systems perhaps operated from or, more likely, merely supervised from Earth. Due to the communications time delay and the absence of any local human operator or repair personnel, these systems must be capable of performing normal operations, sense system failures or imminent failures, and, if necessary, safely shut down or repair failed items. Chemical processing plants and manufacturing plants on Earth are approaching this level of sophistication and it may be possible to adapt some of the technologies from these plants, as well as from technology that will exist in the future, to the Reference Mission. But as with the remote sensing example, the Reference Mission will enhance the automation and maintenance technologies used which will then be available to Earth-bound users for a variety of applications.

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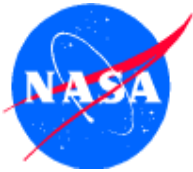
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