

# 3. Mission and System Overview

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### **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**

<p><b>Conduct Human Missions to Mars</b></p> <ul style="list-style-type: none"><li>a. Land people on Mars and return them safely to Earth.</li><li>b. Effectively perform useful work on the surface of Mars.</li><li>c. Support people on Mars for 2 years or more without resupply.</li><li>d. Support people away from Earth for periods of time consistent with Mars mission durations (2 to 3 years)</li><li>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.</li><li>f. Identify the characteristics of space transportation and surface operations systems consistent with sustaining a long-term program at affordable cost.</li></ul> <p><b>Conduct Applied Science Research to Use Mars Resources to Augment Life-Sustaining Systems</b></p> <ul style="list-style-type: none"><li>a. Catalog the global distribution of life support, propellant, and construction materials (hydrogen, oxygen, nitrogen, phosphorous, potassium, magnesium, iron, etc.) on Mars.</li><li>b. Develop effective system designs and processes for using in situ materials to replace products that otherwise would have to be provided from Earth.</li></ul> <p><b>Conduct Basic Science Research to Gain New Knowledge About the Solar System's Origin and History</b></p> <ul style="list-style-type: none"><li>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.</li><li>b. Identify suitable venues at Mars, in the martian system, and during Earth-Mars transits for other science measurements.</li></ul>
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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.

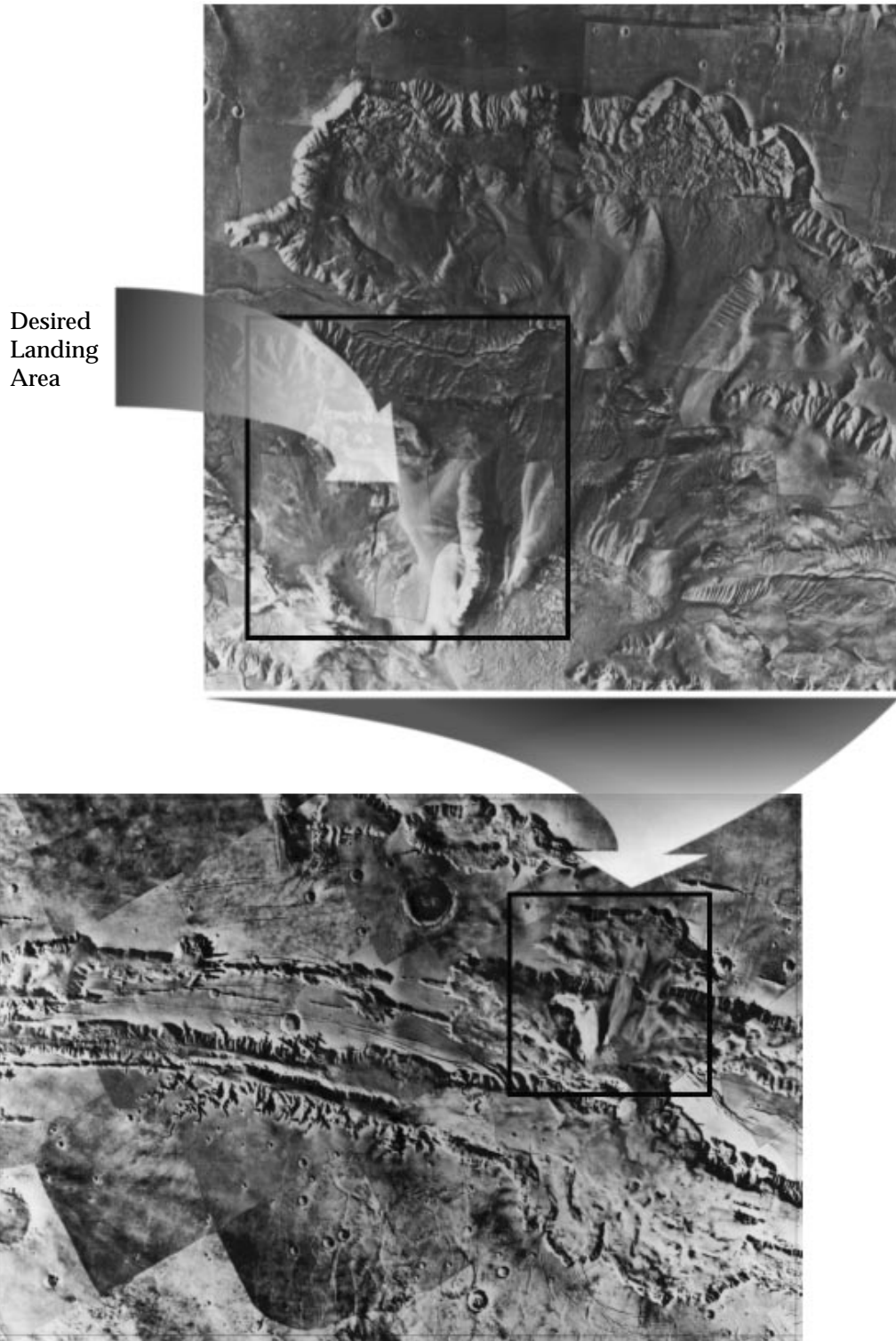
#### 3.1.2.4 Surface Operations Philosophy

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





*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 bottom-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  Food Preparation <ul style="list-style-type: none"> <li>• routine greenhouse operations</li> <li>• plants to ingredients</li> <li>• ingredients to food</li> </ul> Vehicle Control Navigation Teleoperated Rover Control  Journalism Housekeeping
Electrical Systems Operations, Maintenance and Repair Electronics Systems Operations, Maintenance and Repair	Biology Botany Ecology Agronomy Social Science	
General Practice Medicine Surgery Psychology	Biomedicine Psychology	

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



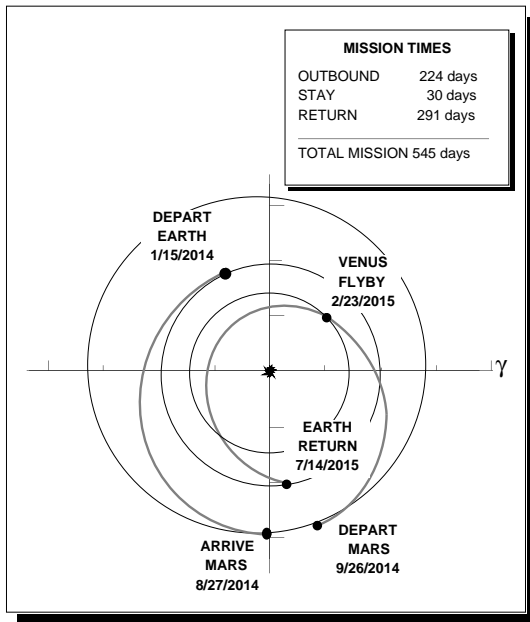


Figure 3-2 Typical short-stay mission profile.

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

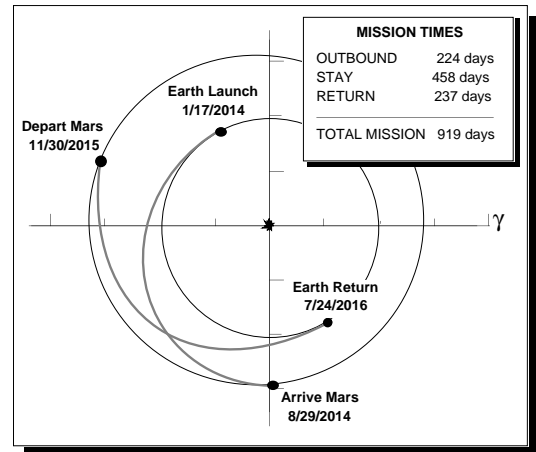


Figure 3-3 Typical long-stay mission profile.

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.



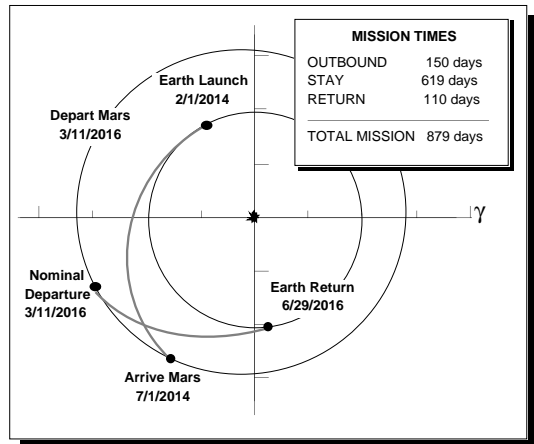


Figure 3-4 Fast-transit mission profile.

### 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 opportunities 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

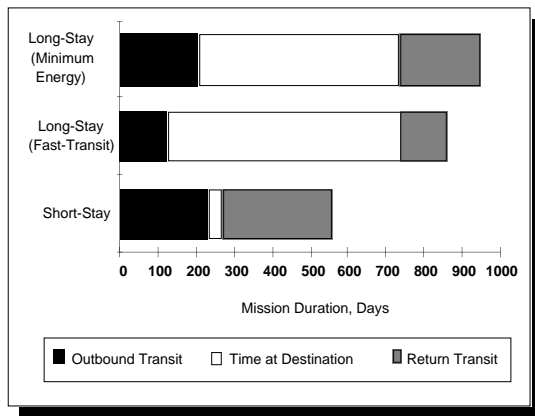
The applicability of each of the previously discussed mission types to the human exploration of Mars has been the subject of much debate. The general opinion is that the initial flights should be short-stay missions performed as fast as possible (so-called “sprint” missions) to minimize crew exposure 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 health effects exceeding acceptable risk levels. At present, acceptable risk levels are based on not

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



**Figure 3-5 Round-trip mission comparisons.**



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

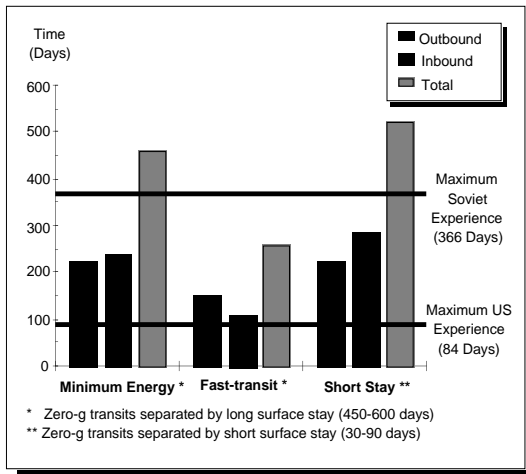
long surface stays associated with the minimum-energy, fast-transit missions.

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<sup>2</sup>/sec<sup>2</sup> 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<sup>2</sup>/sec<sup>2</sup> 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





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
<b>Surface Payload</b>		
<ul style="list-style-type: none"> <li>• None</li> </ul>	<ul style="list-style-type: none"> <li>• Ascent Capsule</li> <li>• Empty Ascent Stage</li> <li>• LOX/CH<sub>4</sub> Production Plant</li> <li>• LH<sub>2</sub> Propellant Seed</li> <li>• Power Supply (nuclear-160 kW)</li> <li>• Utility Truck</li> <li>• Pressurized Rover</li> <li>• Additional Payload</li> </ul>	<ul style="list-style-type: none"> <li>• Surface Habitat/Laboratory</li> <li>• Nonperishable Consumables</li> <li>• Power Supply (nuclear-160 kW)</li> <li>• Utility Truck</li> <li>• Spares</li> <li>• Teleoperable Science Rover</li> </ul>
<b>Mars Orbit Payload</b>		
<ul style="list-style-type: none"> <li>• Earth-Return Vehicle               <ul style="list-style-type: none"> <li>• Fueled (LOX/CH<sub>4</sub>) TEI Stage</li> <li>• Transit Habitat</li> <li>• Earth-Return Capsule</li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>• None</li> </ul>	<ul style="list-style-type: none"> <li>• None</li> </ul>
<b>Space Transportation Vehicles</b>		
<ul style="list-style-type: none"> <li>• NTR Transfer Stage</li> <li>• LOX/CH<sub>4</sub> TEI Stage w/Mars Aerobrake</li> </ul>	<ul style="list-style-type: none"> <li>• NTR Transfer Stage</li> <li>• LOX/CH<sub>4</sub> Descent Stage w/Mars Aerobrake</li> </ul>	<ul style="list-style-type: none"> <li>• NTR Transfer Stage</li> <li>• LOX/CH<sub>4</sub> Descent Stage w/Mars Aerobrake</li> </ul>

TEI: Trans Earth Injection  
 NTR: Nuclear Thermal Rocket

LOX: liquid oxygen  
 CH<sub>4</sub>: methane

LH<sub>2</sub>: liquid hydrogen

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



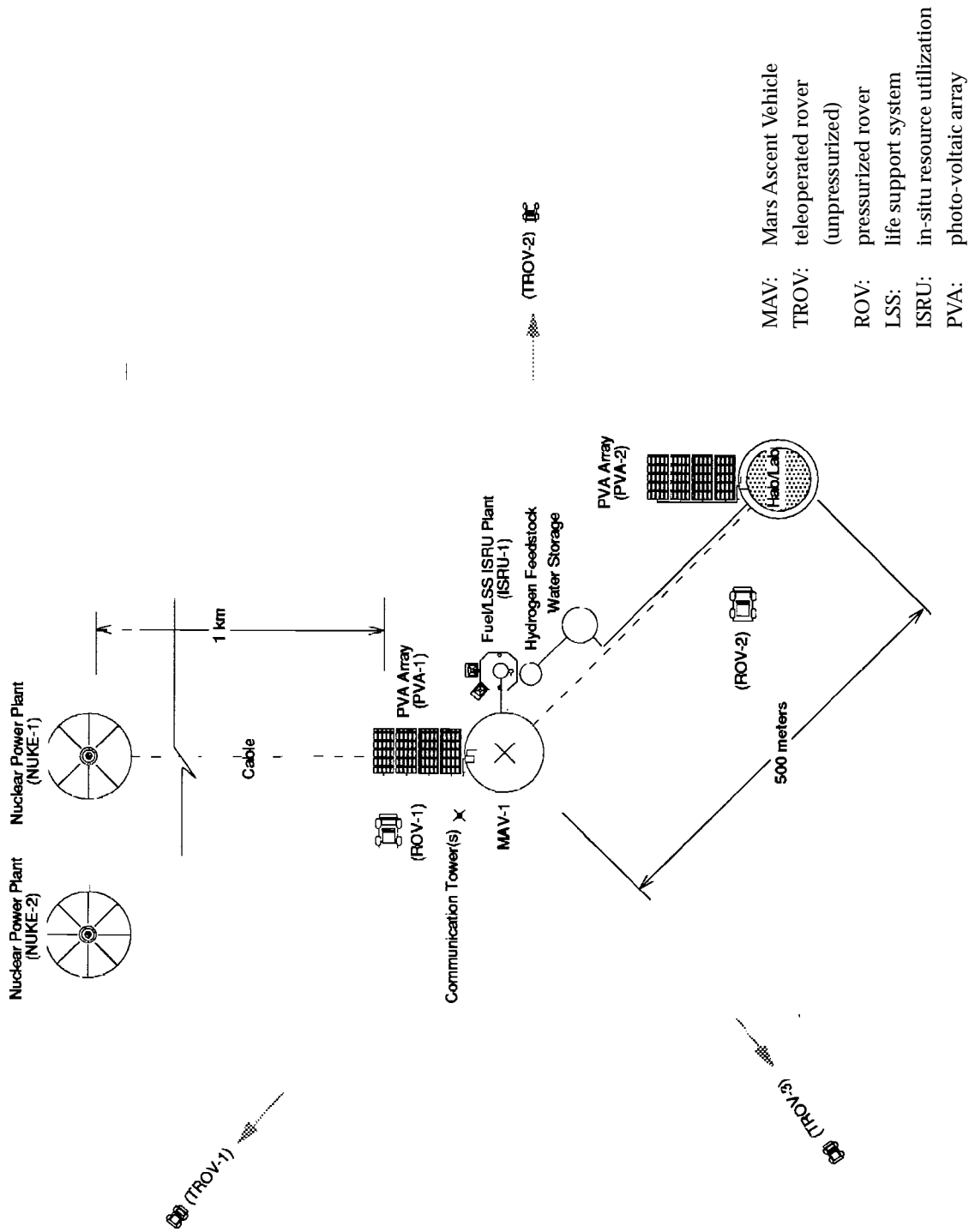


Figure 3-8 Mars surface outpost after deployment of payloads from first two cargo landers.

**Table 3-4 General Launch Manifest: 2009 Launch Opportunity**

Flight 4: Cargo	Flight 5: Cargo	Flight 6: First Crew
<b>Surface Payload</b>		
<ul style="list-style-type: none"> <li>• None</li> </ul>	<ul style="list-style-type: none"> <li>• Ascent Capsule</li> <li>• Empty Ascent Stage</li> <li>• LOX/CH<sub>4</sub> Production Plant</li> <li>• LH<sub>2</sub> Propellant Seed</li> <li>• Bioregenerative Life Support Outfitting Equipment</li> <li>• Science: 1 km drill</li> <li>• Science Equipment</li> <li>• Additional Payload /Spares</li> </ul>	<ul style="list-style-type: none"> <li>• Crew</li> <li>• Surface Habitat</li> <li>• Consumables</li> <li>• Spares</li> <li>• EVA Equipment</li> <li>• Science Equipment</li> </ul>
<b>Mars Orbit Payload</b>		
<ul style="list-style-type: none"> <li>• Earth-Return Vehicle               <ul style="list-style-type: none"> <li>• Fueled (LOX/CH<sub>4</sub>) TEI Stage</li> <li>• Transit Habitat</li> <li>• Earth-Return Capsule</li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>• None</li> </ul>	<ul style="list-style-type: none"> <li>• None</li> </ul>
<b>Space Transportation Vehicles</b>		
<ul style="list-style-type: none"> <li>• NTR Transfer Stage</li> <li>• LOX/CH<sub>4</sub> TEI Stage w/Mars Aerobrake</li> </ul>	<ul style="list-style-type: none"> <li>• NTR Transfer Stage</li> <li>• LOX/CH<sub>4</sub> Descent Stage w/Mars Aerobrake</li> </ul>	<ul style="list-style-type: none"> <li>• NTR Transfer Stage</li> <li>• LOX/CH<sub>4</sub> Descent Stage w/Mars Aerobrake</li> </ul>

TEI: Trans Earth Injection  
 NTR: Nuclear Thermal Rocket

LOX: liquid oxygen  
 CH<sub>4</sub>: methane

LH<sub>2</sub>: liquid hydrogen

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



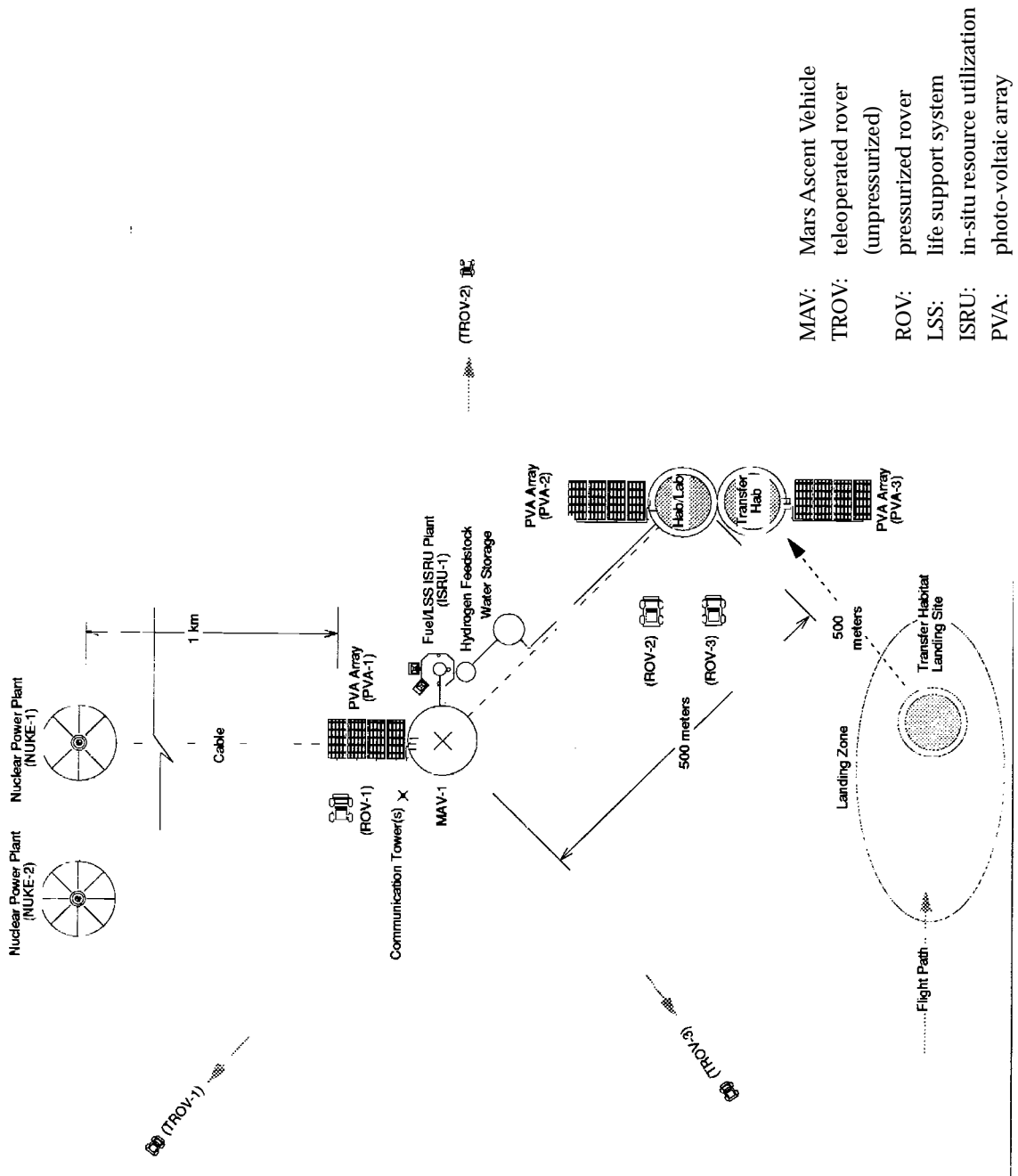


Figure 3-9 Mars surface outpost at the end of first flight crew's stay.

**Table 3-5 Surface Science Payload for First Flight Crew**

<b>Payload Description</b>	<b>Payload Mass (kg)</b>
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
<b>Total</b>	<b>2370</b>

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)

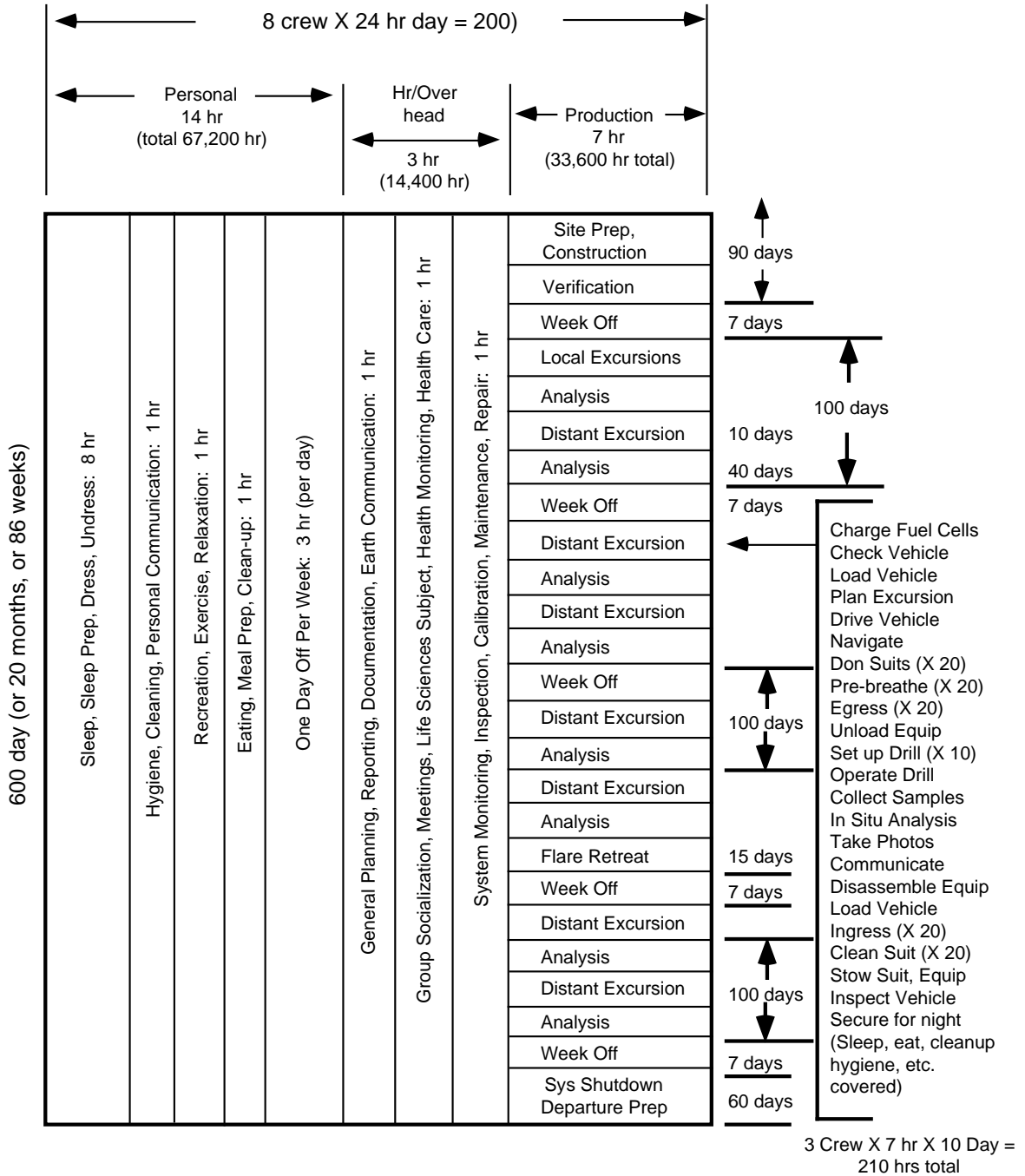


Figure 3-10 Possible surface mission time line.



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 measurements, 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
<b>Surface Payload</b>		
<ul style="list-style-type: none"> <li>• None</li> </ul>	<ul style="list-style-type: none"> <li>• Ascent Capsule</li> <li>• Empty Ascent Stage</li> <li>• LOX/CH<sub>4</sub> Production Plant</li> <li>• LH<sub>2</sub> Propellant Seed</li> <li>• Pressurized Rover</li> <li>• Science Equipment</li> <li>• Additional Payload/Spares</li> </ul>	<ul style="list-style-type: none"> <li>• Crew</li> <li>• Surface Habitat</li> <li>• Consumables</li> <li>• Spares</li> <li>• EVA Equipment</li> <li>• Science Equipment</li> </ul>
<b>Mars Orbit Payload</b>		
<ul style="list-style-type: none"> <li>• Earth-Return Vehicle                             <ul style="list-style-type: none"> <li>• Fueled (LOX/CH<sub>4</sub>) TEI Stage</li> <li>• Transit Habitat</li> <li>• Earth-Return Capsule</li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>• None</li> </ul>	<ul style="list-style-type: none"> <li>• None</li> </ul>
<b>Space Transportation Vehicles</b>		
<ul style="list-style-type: none"> <li>• NTR Transfer Stage</li> <li>• LOX/CH<sub>4</sub> TEI Stage w/Mars Aerobrake</li> </ul>	<ul style="list-style-type: none"> <li>• NTR Transfer Stage</li> <li>• LOX/CH<sub>4</sub> Descent Stage w/Mars Aerobrake</li> </ul>	<ul style="list-style-type: none"> <li>• NTR Transfer Stage</li> <li>• LOX/CH<sub>4</sub> Descent Stage w/Mars Aerobrake</li> </ul>

TEI: Trans Earth Injection  
 NTR: Nuclear Thermal Rocket

LOX: liquid oxygen  
 CH<sub>4</sub>: methane

LH<sub>2</sub>: liquid hydrogen

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



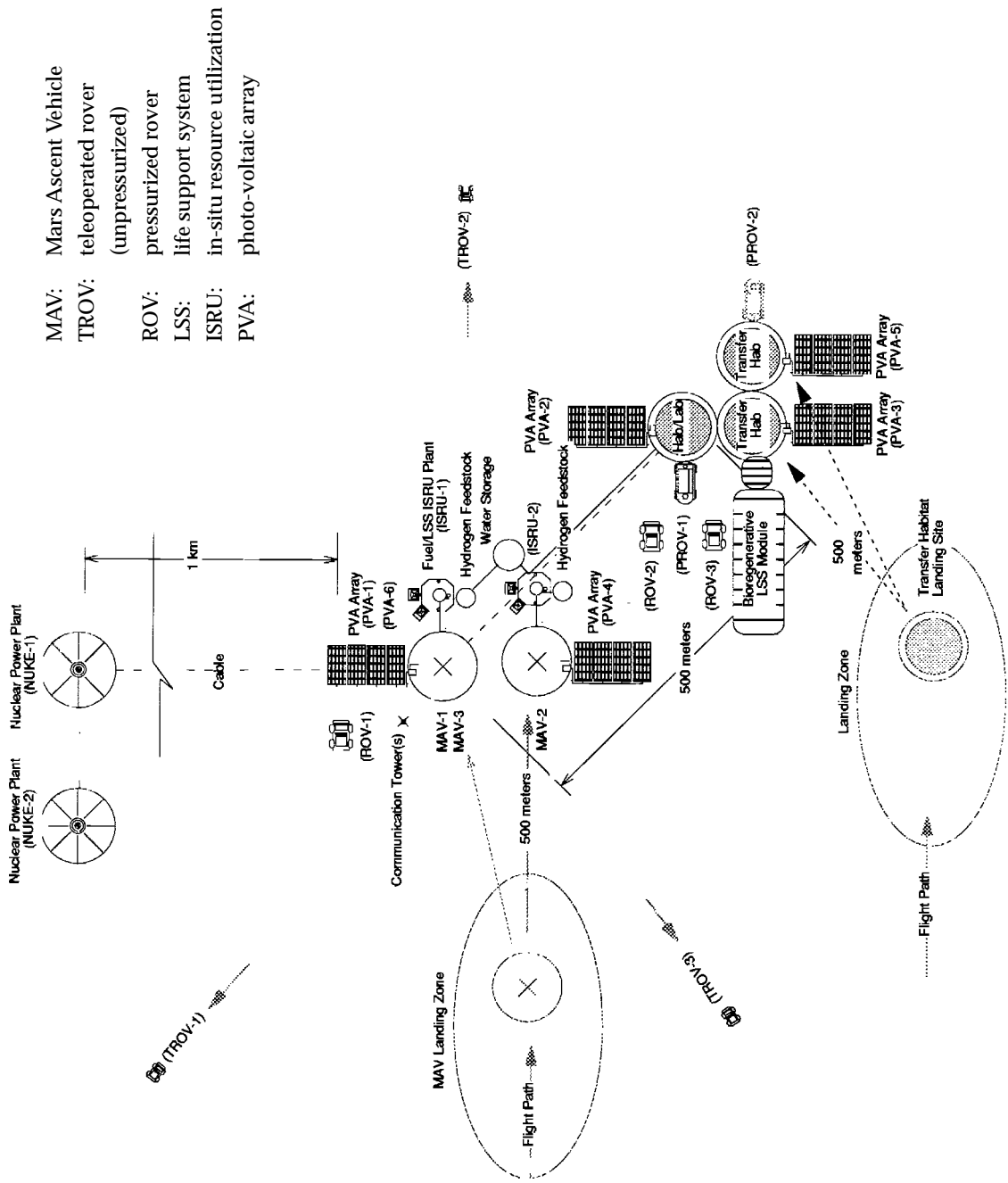


Figure 3-11 Mars surface outpost at the end of second flight crew's stay.

**Table 3-7 Surface Science Payload for Second Flight Crew**

<b>Payload Description</b>	<b>Payload Mass (kg)</b>
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
<b>Total</b>	<b>23,000</b>

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





**Table 3-8 General Launch Manifest: 2014 Launch Opportunity**

Flight 10: Cargo	Flight 11: Cargo	Flight 12: Third Crew
<b>Surface Payload</b>		
<ul style="list-style-type: none"> <li>• None</li> </ul>	<ul style="list-style-type: none"> <li>• Ascent Capsule</li> <li>• Empty Ascent Stage</li> <li>• LOX/CH<sub>4</sub> Production Plant</li> <li>• LH<sub>2</sub> Propellant Seed</li> <li>• Science Equipment</li> <li>• Additional Payload/ Spares</li> </ul>	<ul style="list-style-type: none"> <li>• Crew</li> <li>• Surface Habitat</li> <li>• Consumables</li> <li>• Spares</li> <li>• EVA Equipment</li> <li>• Science Equipment</li> </ul>
<b>Mars Orbit Payload</b>		
<ul style="list-style-type: none"> <li>• Earth-Return Vehicle                             <ul style="list-style-type: none"> <li>• Fueled (LOX/CH<sub>4</sub>) TEI Stage</li> </ul> </li> <li>• Transit Habitat</li> <li>• Earth-Return Capsule</li> </ul>	<ul style="list-style-type: none"> <li>• None</li> </ul>	<ul style="list-style-type: none"> <li>• None</li> </ul>
<b>Space Transportation Vehicles</b>		
<ul style="list-style-type: none"> <li>• NTR Transfer Stage</li> <li>• LOX/CH<sub>4</sub> TEI Stage w/Mars Aerobrake</li> </ul>	<ul style="list-style-type: none"> <li>• NTR Transfer Stage</li> <li>• LOX/CH<sub>4</sub> Descent Stage w/Mars Aerobrake</li> </ul>	<ul style="list-style-type: none"> <li>• NTR Transfer Stage</li> <li>• LOX/CH<sub>4</sub> Descent Stage w/Mars Aerobrake</li> </ul>

TEI: Trans Earth Injection  
 NTR: Nuclear Thermal Rocket

LOX: liquid oxygen  
 CH<sub>4</sub>: methane

LH<sub>2</sub>: liquid hydrogen

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**

<b>Payload Description</b>	<b>Payload Mass (kg)</b>
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
<b>Total</b>	<b>4070</b>

- 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.



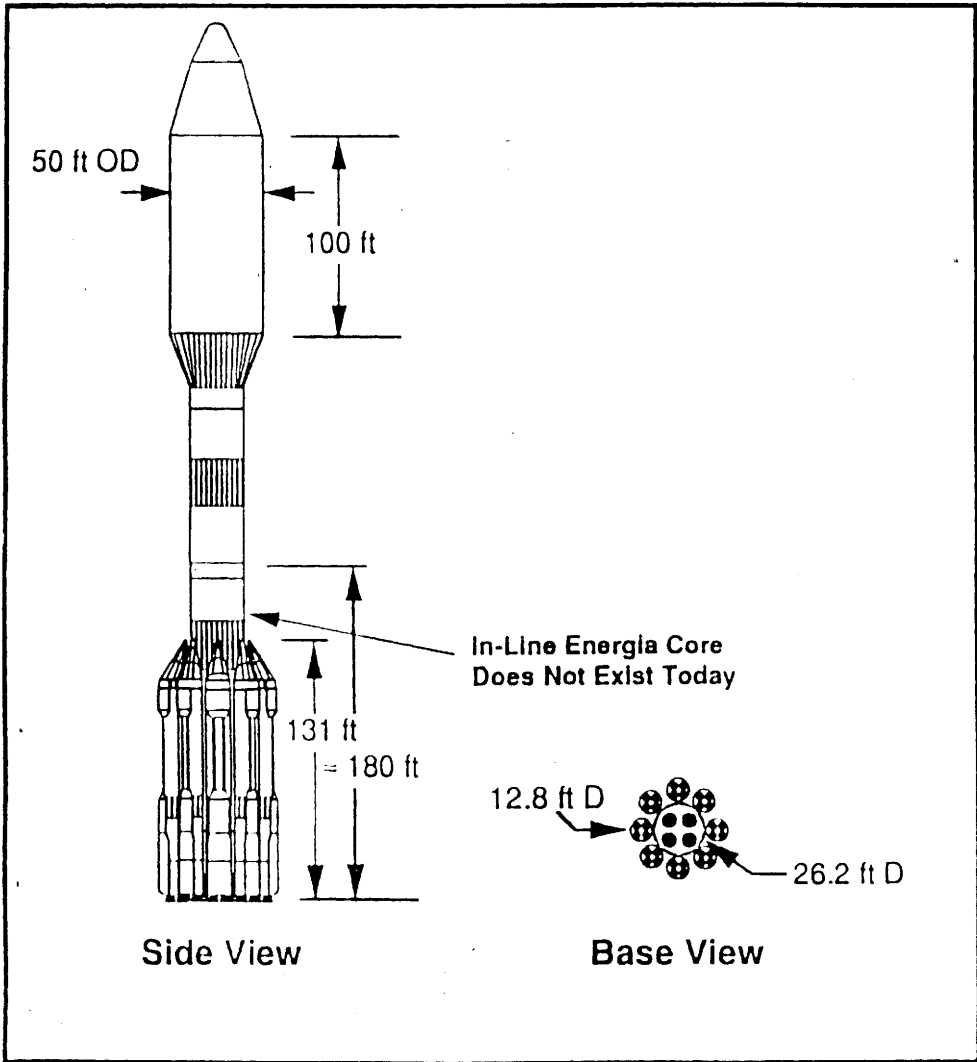


Figure 3-13 Mars Energia-derived HLLV with eight Zenit-type boosters.



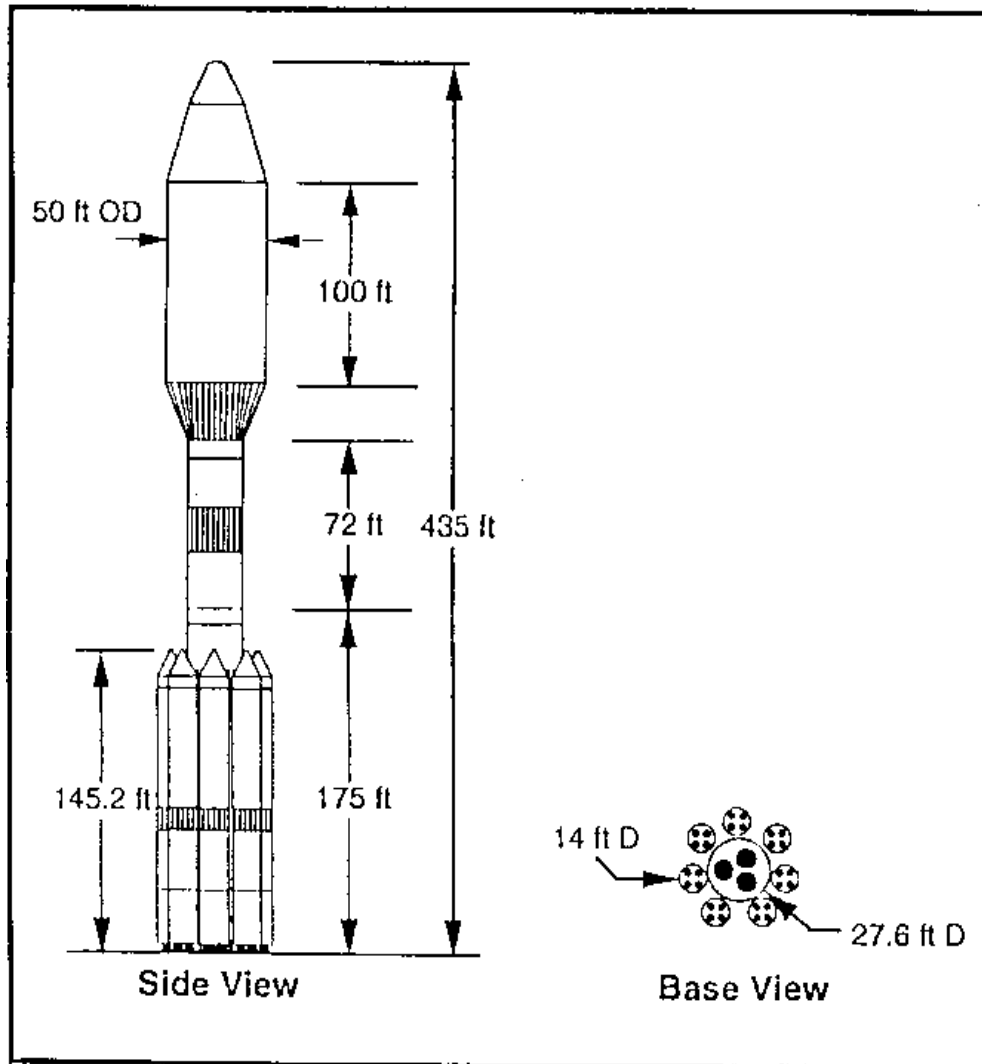


Figure 3-14 STS External Tank-derived HLLV with seven LOX/RP boosters.



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



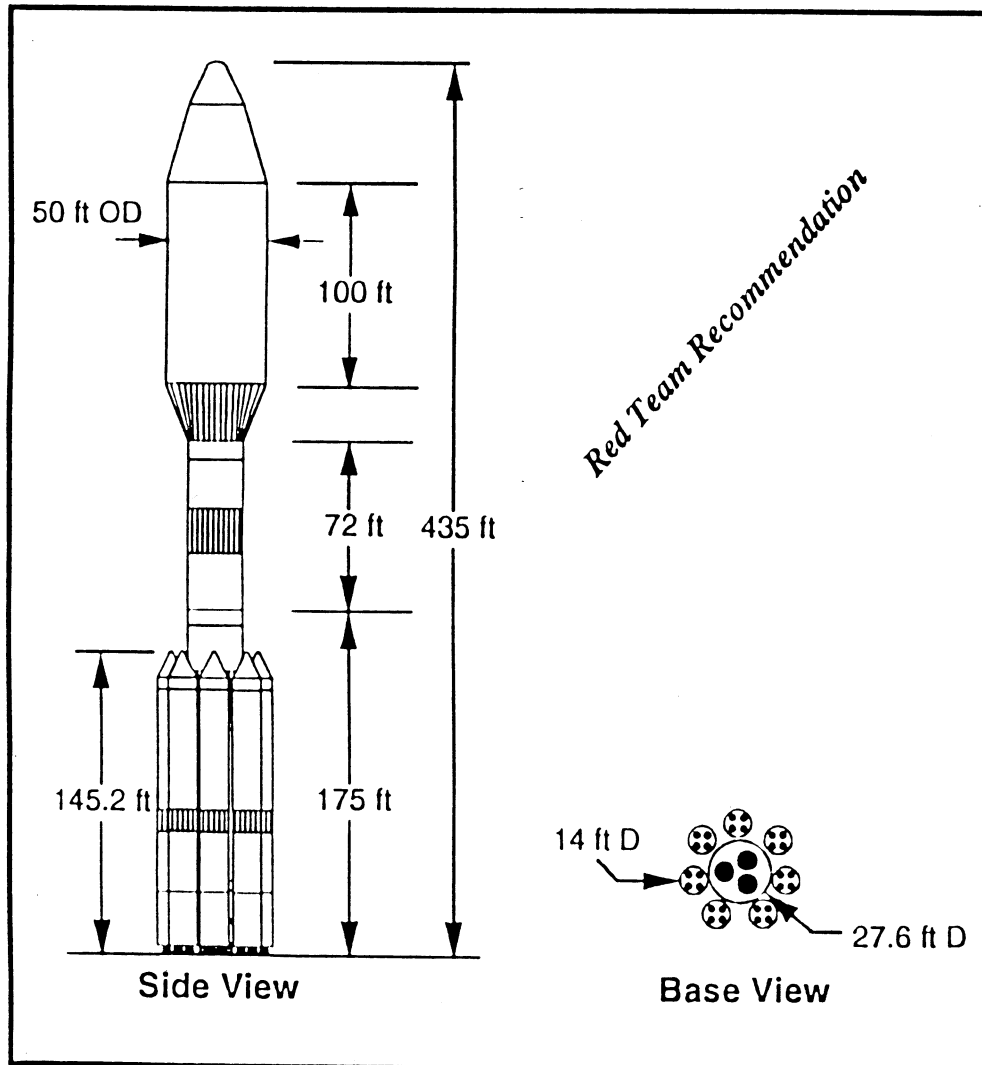


Figure 3-15 STS External Tank-derived HLLV with four strap-on boosters, each having two F-1 engines.



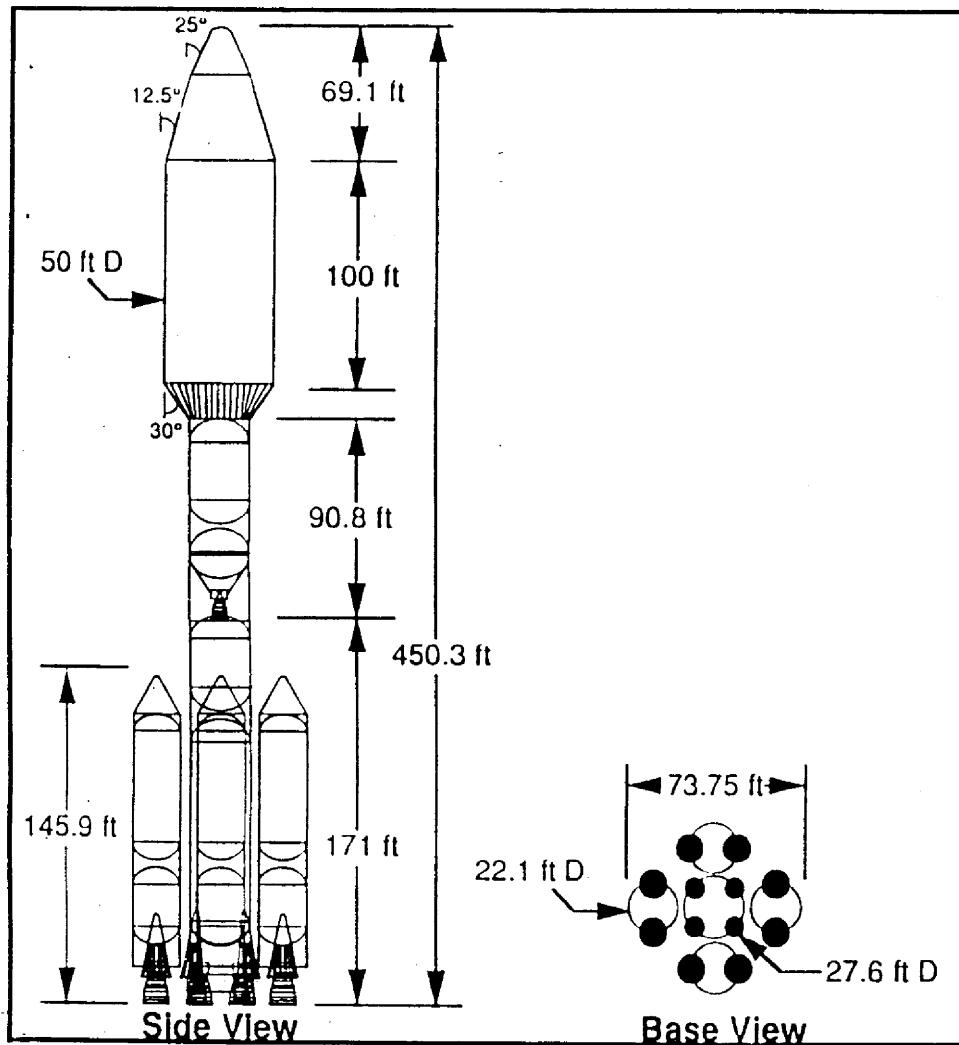


Figure 3-16 Saturn V-derived Mars HLLV with F-1A/J-2S propulsion.



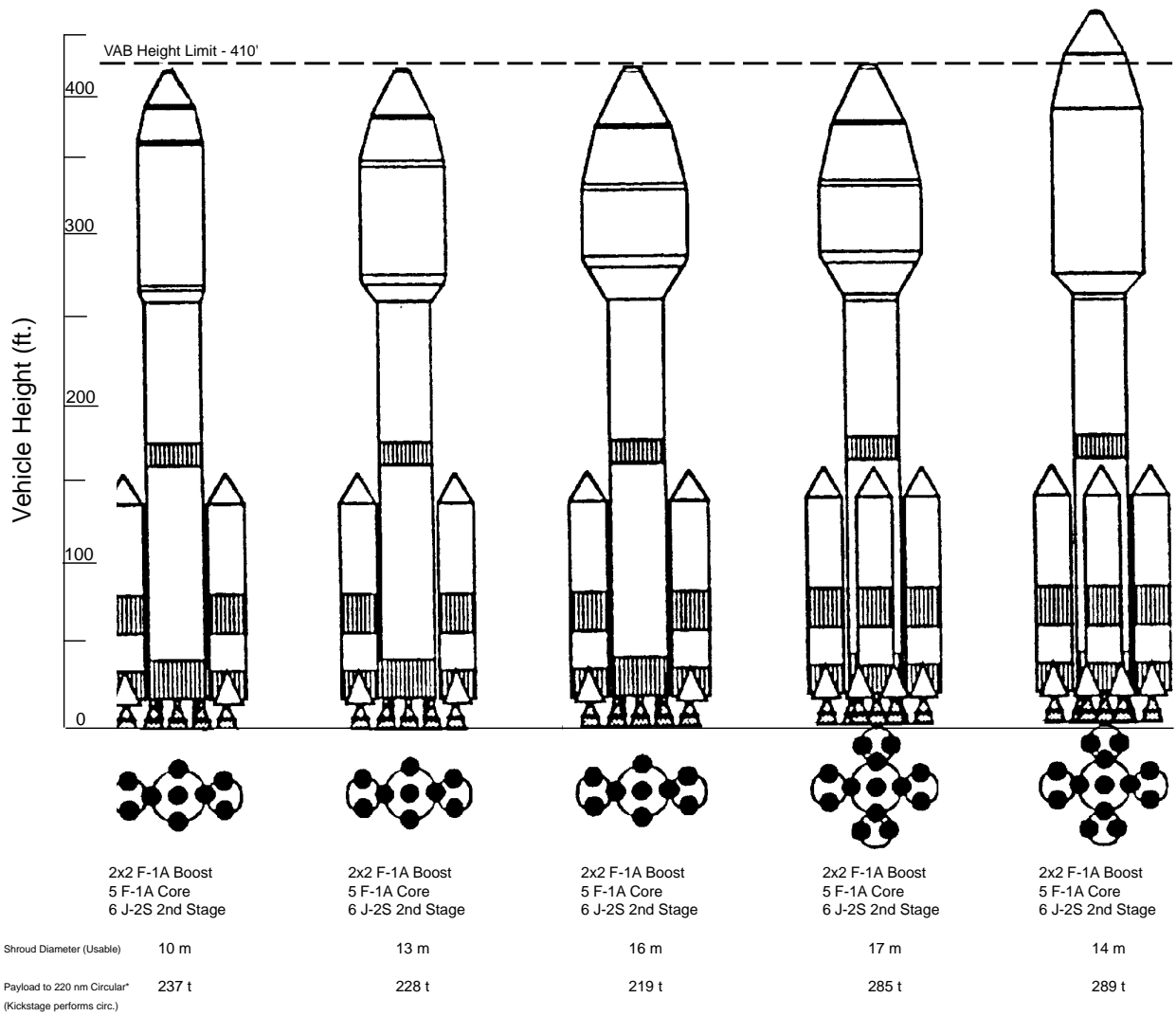


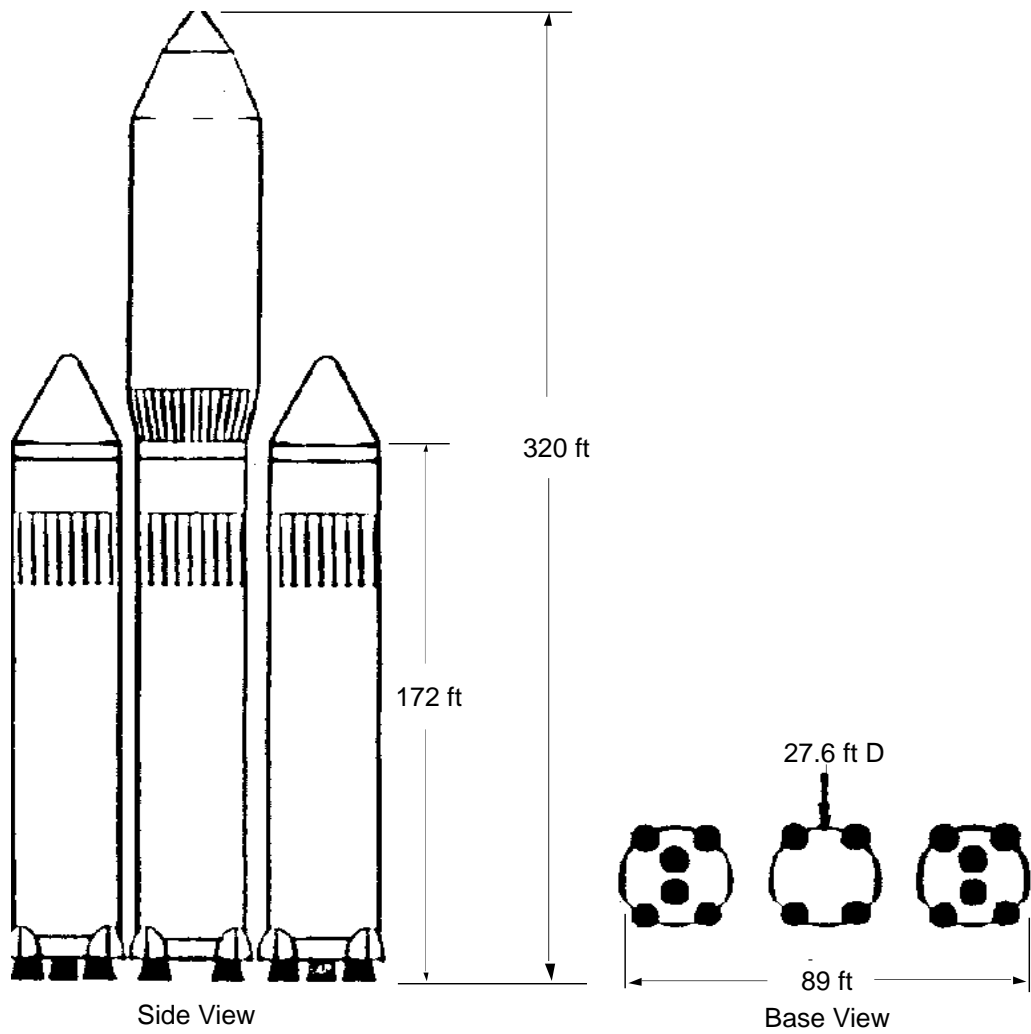
Figure 3-17 Saturn V-based Mars HLLV concepts.





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





*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<sub>2</sub> 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

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.

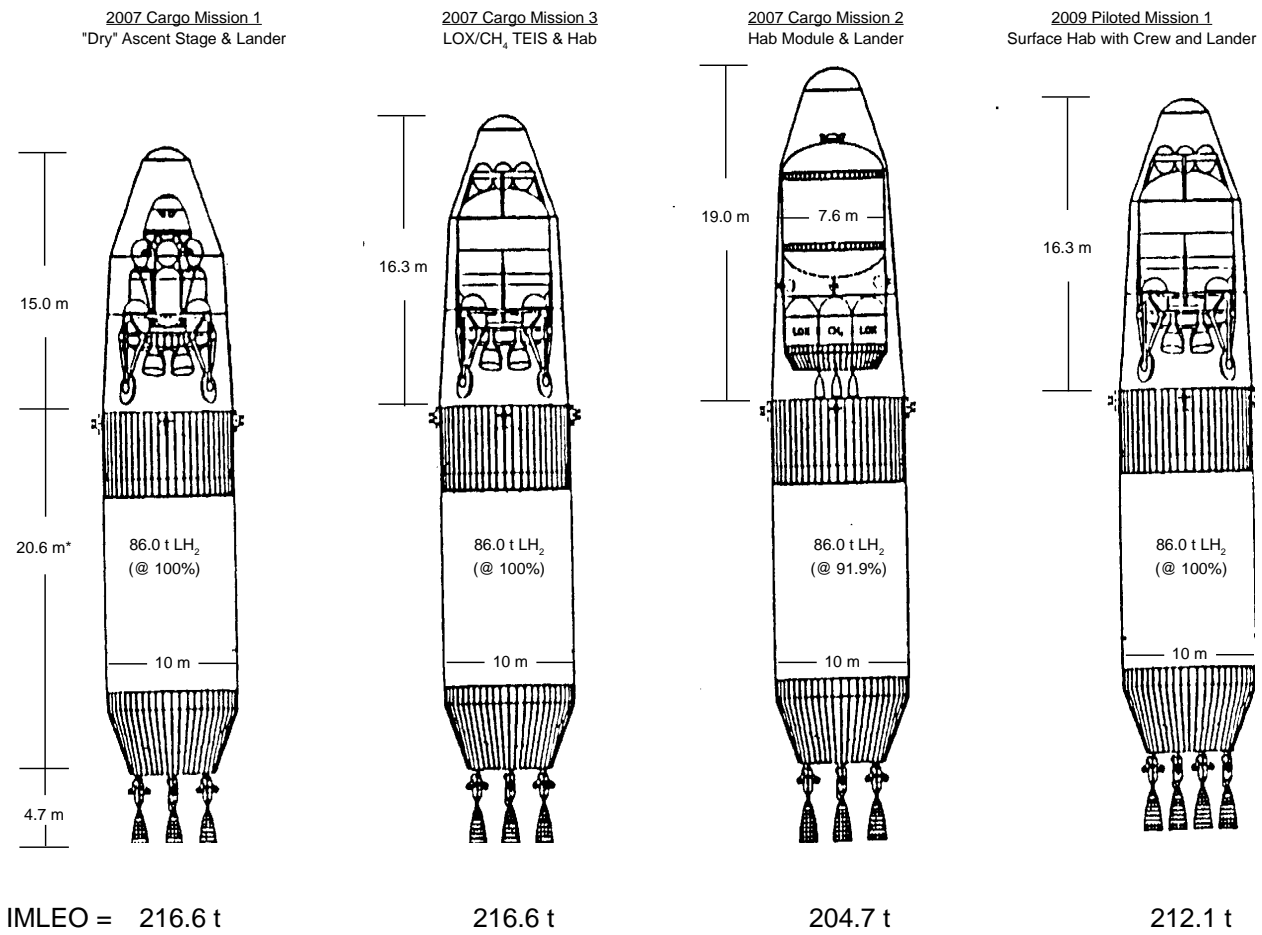
### 3.6.3.2 Biconic Aeroshell

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

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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 LH<sub>2</sub> as both a reactor coolant and propellant was convincingly demonstrated.





\* 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**

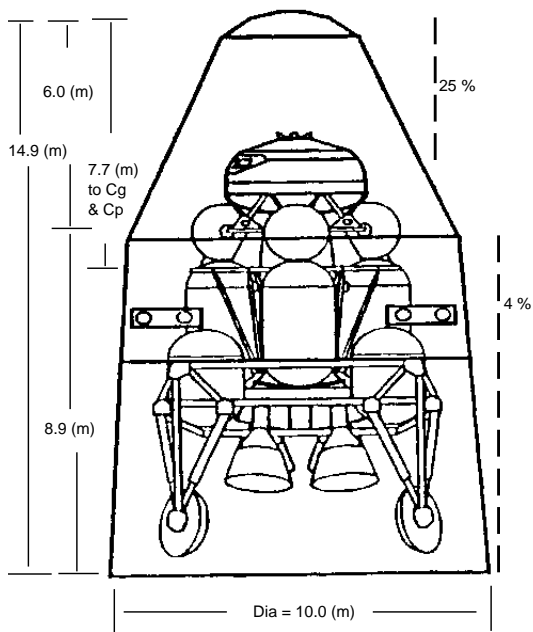
TMI Stage Element	Piloted Version	Cargo Version
ND Engines (4 for piloted, 3 for cargo)	9.8	7.4
Radiation Shield	0.9	0.0
Tankage and Structure	18.4	18.4
LH <sub>2</sub> Propellant (maximum)	86.0	86.0
Control System Tankage and Propellant	3.1	3.0
<b>Total (tonnes)</b>	<b>118.2</b>	<b>114.8</b>

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

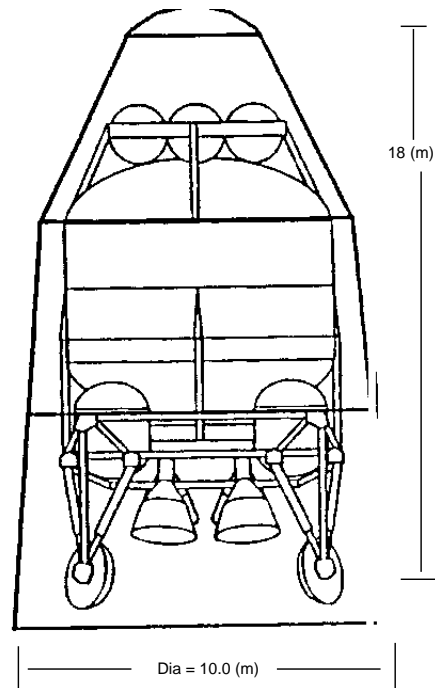
biconic aeroshells that can be used for both Mars orbit capture and descent maneuvers. Given the demands on a descent aeroshell of the Mars entry and landing requirements, the additional capability to permit aerocapture is considered modest.

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**

<b>Aeroshell Payload</b>	<b>Mass Estimate (tonnes)</b>	<b>Overall Length (meters)</b>
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



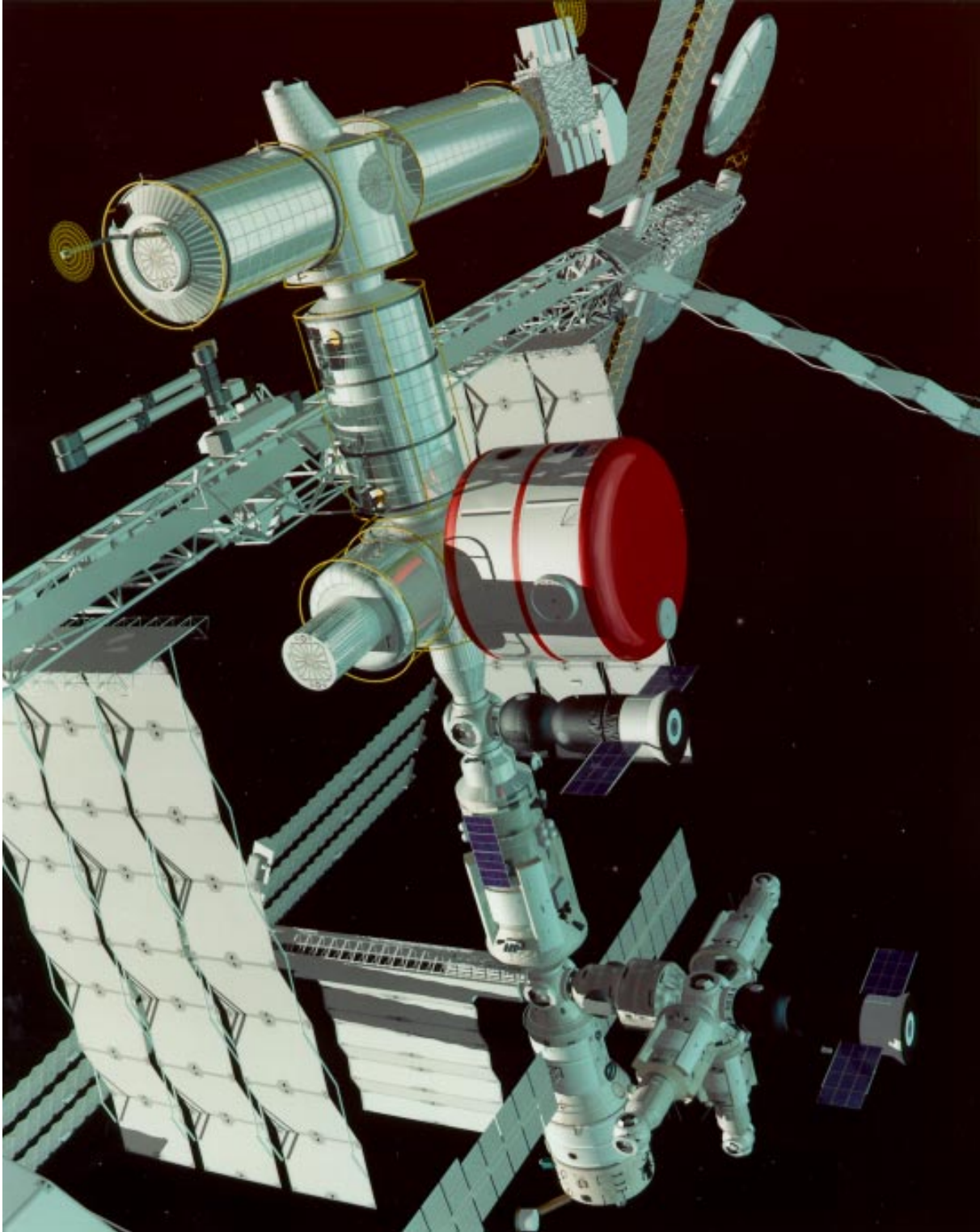


Figure 3-22 Transit habitat attached to International Space Station.



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.

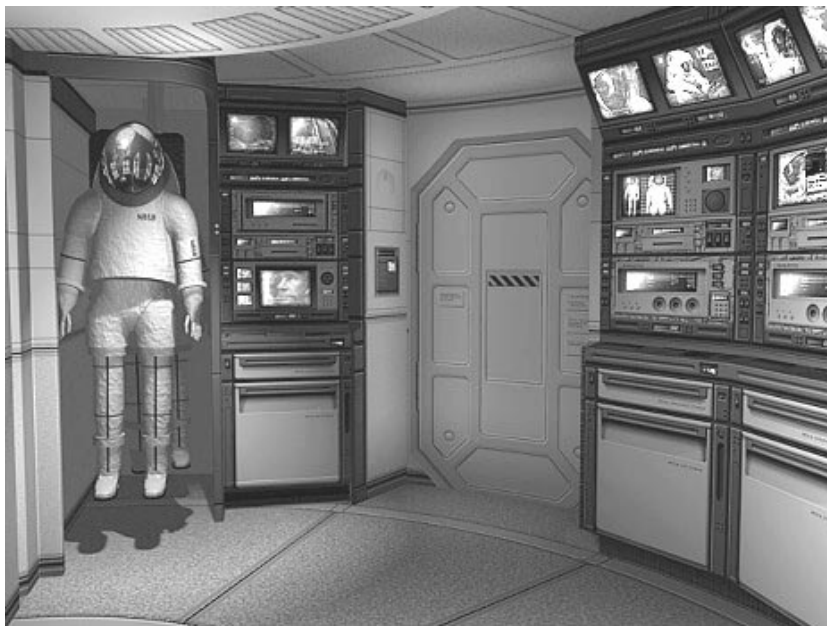
The descent stage consists of four subsystems: a basic structure to which all other elements (including payload) are attached, a parachute system to assist in slowing the stage, a propulsion system to slow the stage prior to landing, and a surface mobility system.

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
<b>Total estimate</b>	<b>53.90</b>	<b>24.50</b>	<b>29.40</b>

The propulsion system employs four RL10-class engines modified to burn LOX/CH<sub>4</sub> 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



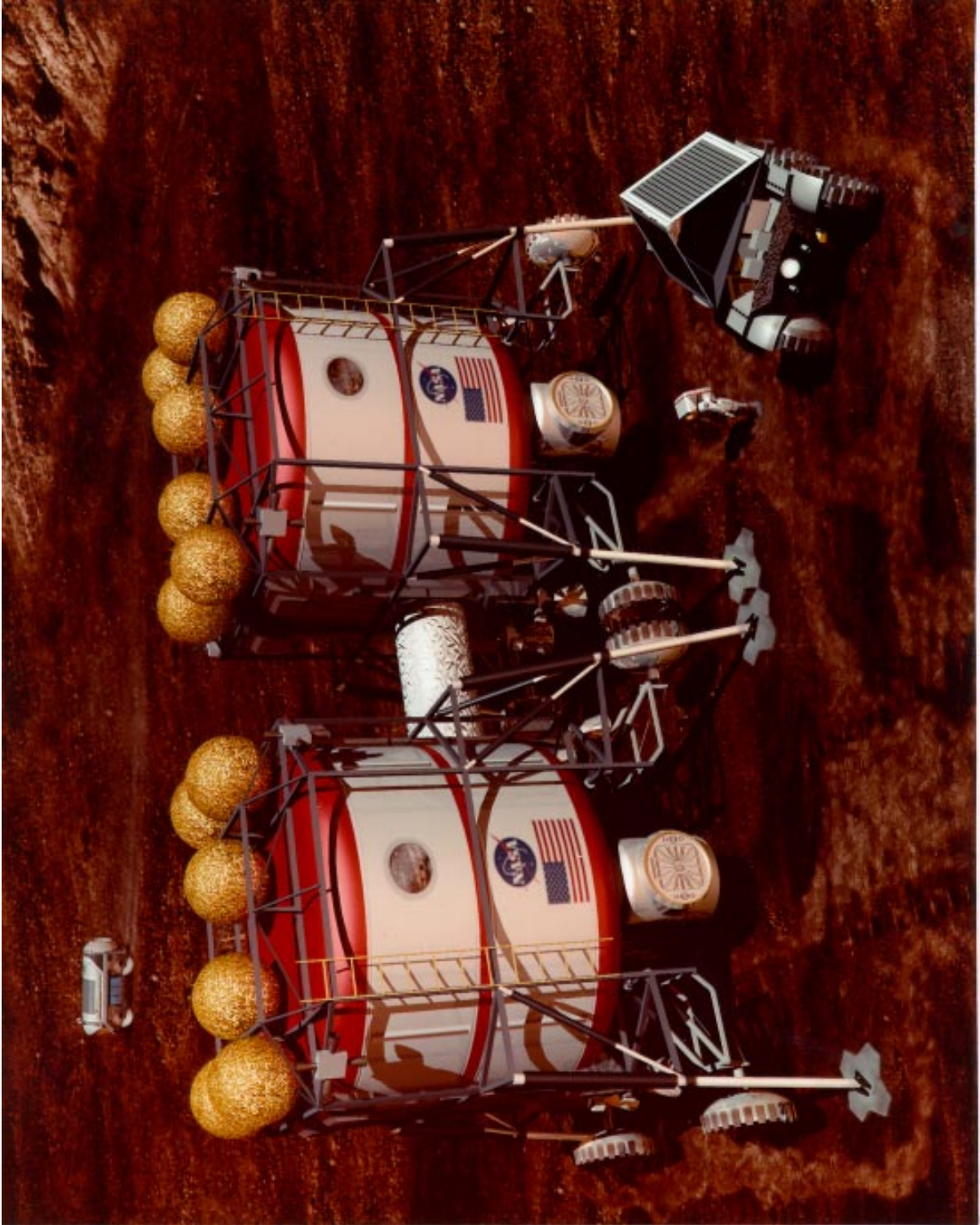


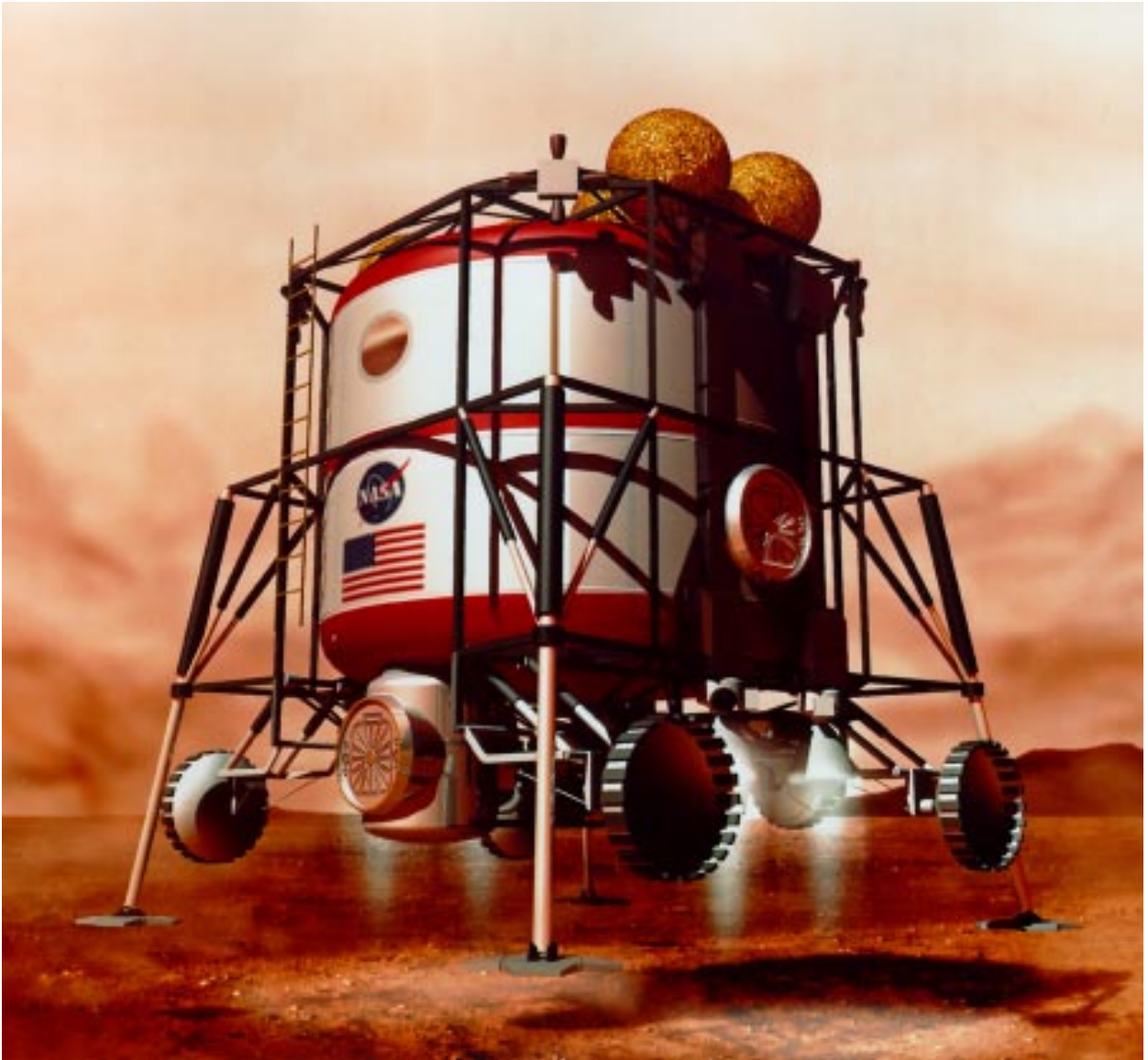
Figure 3-26 Habitat and surface laboratory joined on Mars surface.





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<sub>4</sub>. 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



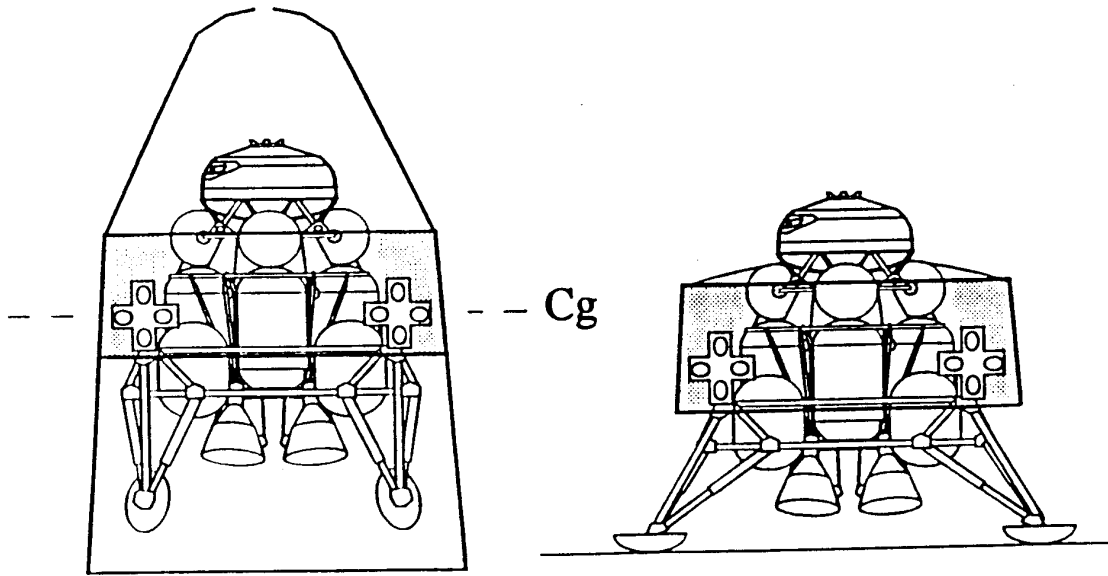
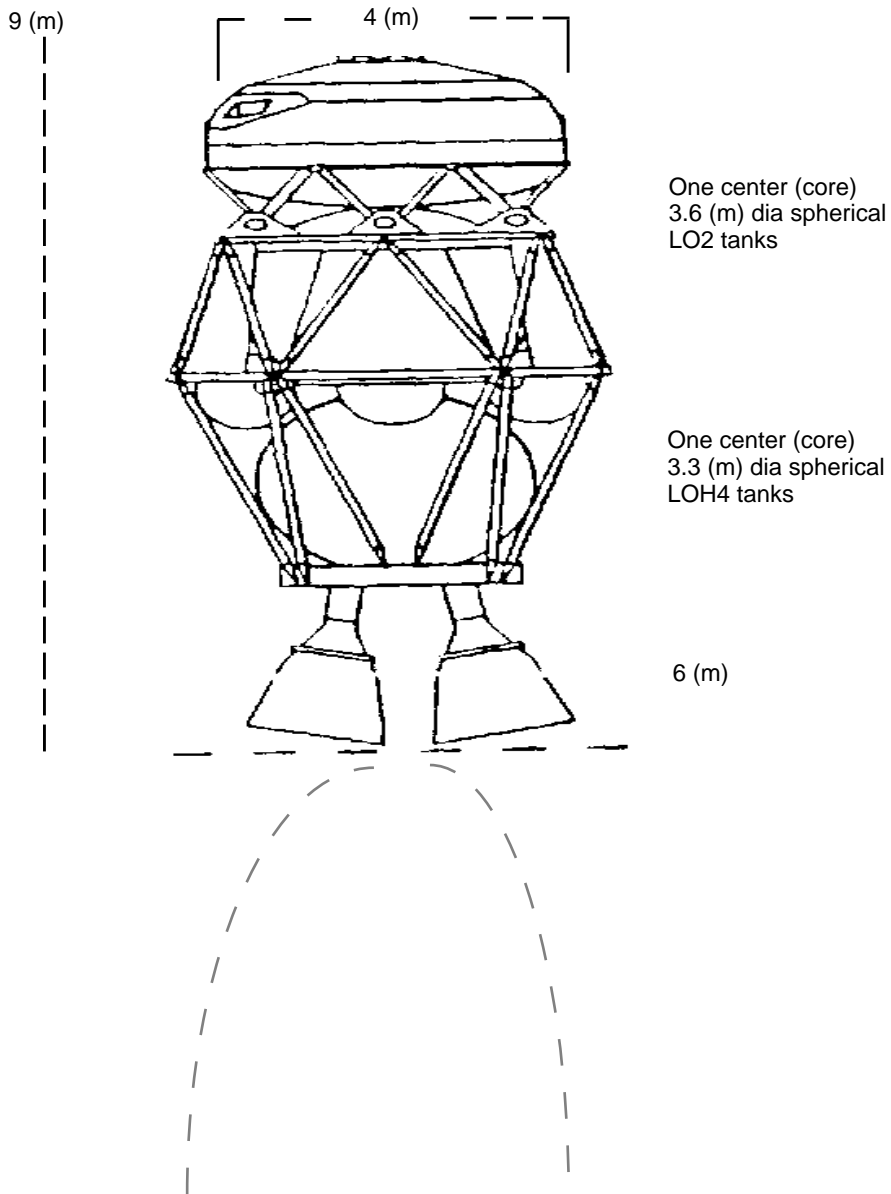


Figure 3-29 Mars surface lander and biconic aeroshell.



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





*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<sub>4</sub>. 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<sub>2</sub> reduction, O<sub>2</sub> and N<sub>2</sub> 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
<b>Total estimate</b>	<b>53.90</b>	<b>24.50</b>	<b>29.40</b>

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

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.



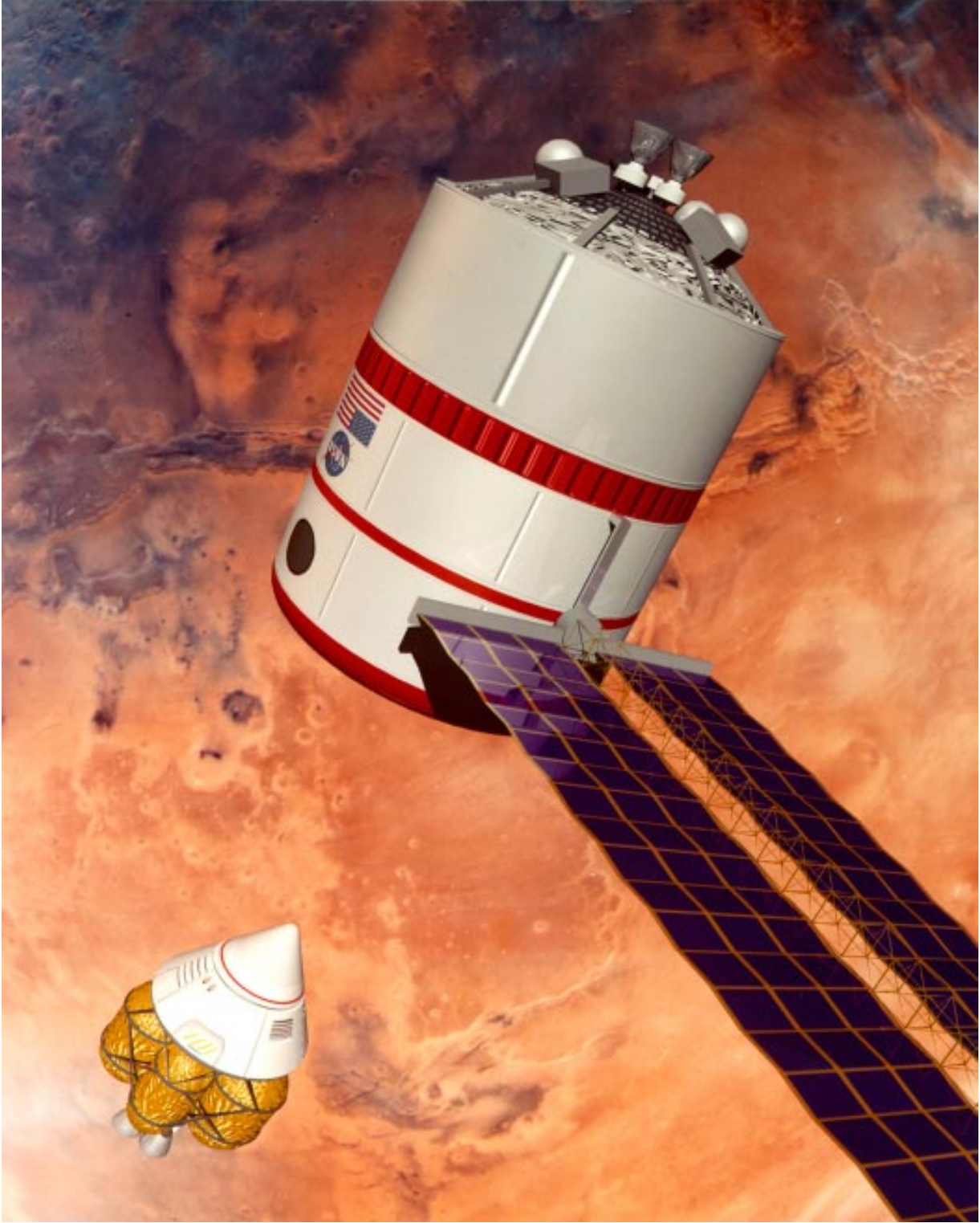


Figure 3-33 Solar array power source for interplanetary spacecraft.



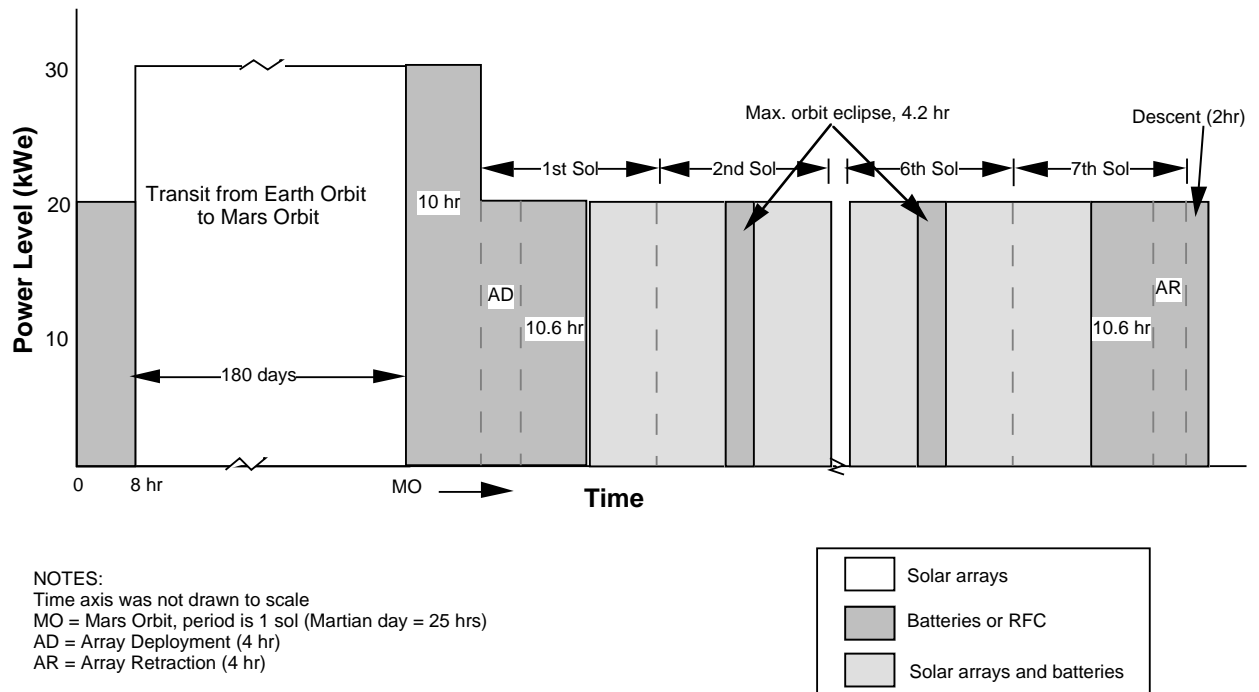


Figure 3-34 Nominal power profile for the transit/surface habitat.

### 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 (m <sup>3</sup> )	Array Area (m <sup>2</sup> )	Mass (kg)	Volume (m <sup>3</sup> )	Array Area (m <sup>2</sup> )
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
<b>Total</b>	<b>4711</b>	<b>3.454</b>	<b>965</b>	<b>2974</b>	<b>5.38</b>	<b>555</b>

**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 (m <sup>3</sup> )	Array Area (m <sup>2</sup> )	Mass (kg)	Volume (m <sup>3</sup> )	Array Area (m <sup>2</sup> )
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
<b>Total</b>	<b>1269</b>	<b>1.469</b>	<b>260</b>	<b>827</b>	<b>1.109</b>	<b>147</b>



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
<b>Total estimate</b>	<b>38.50</b>	<b>11.50</b>	<b>27.00</b>

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<sub>2</sub> 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



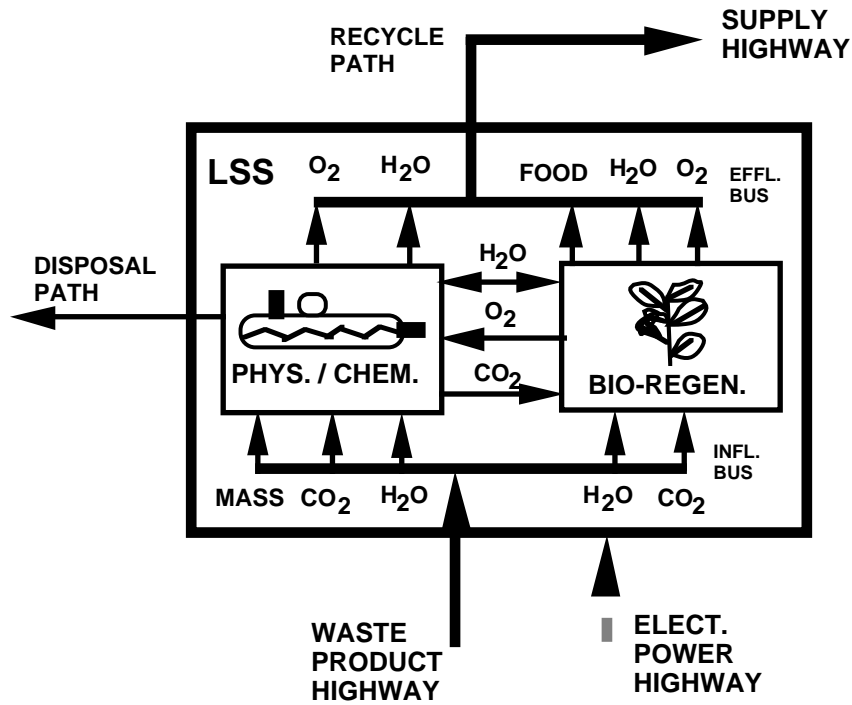


Figure 3-35 Hybrid LSS process distribution.

Table 3-19 LSS Mass, Volume, Power Comparison.

Architecture	Functional Redundant Levels	Mass (mt)	Volume (m <sup>3</sup> )	Maximum $\Delta$ 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.





**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 <sub>2</sub> Electrolysis	53.2 kg	2128	63.31
Sabatier	22.9 kg	504	1.15
H <sub>2</sub> O 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 <sub>2</sub> Electrolysis	18.5 kg O <sub>2</sub>	740	22.00
Sabatier	12.4 kg CH <sub>4</sub>	272	0.62
H <sub>2</sub> O Electrolysis	27.8 kg H <sub>2</sub> O	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

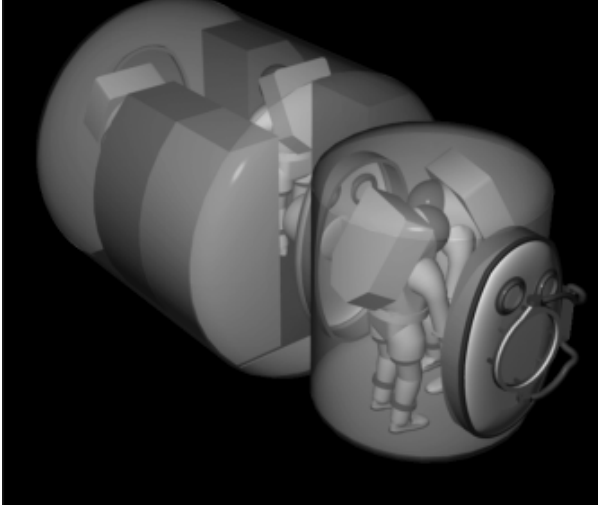
allow the crew to safely exit and enter the pressurized habitats.

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



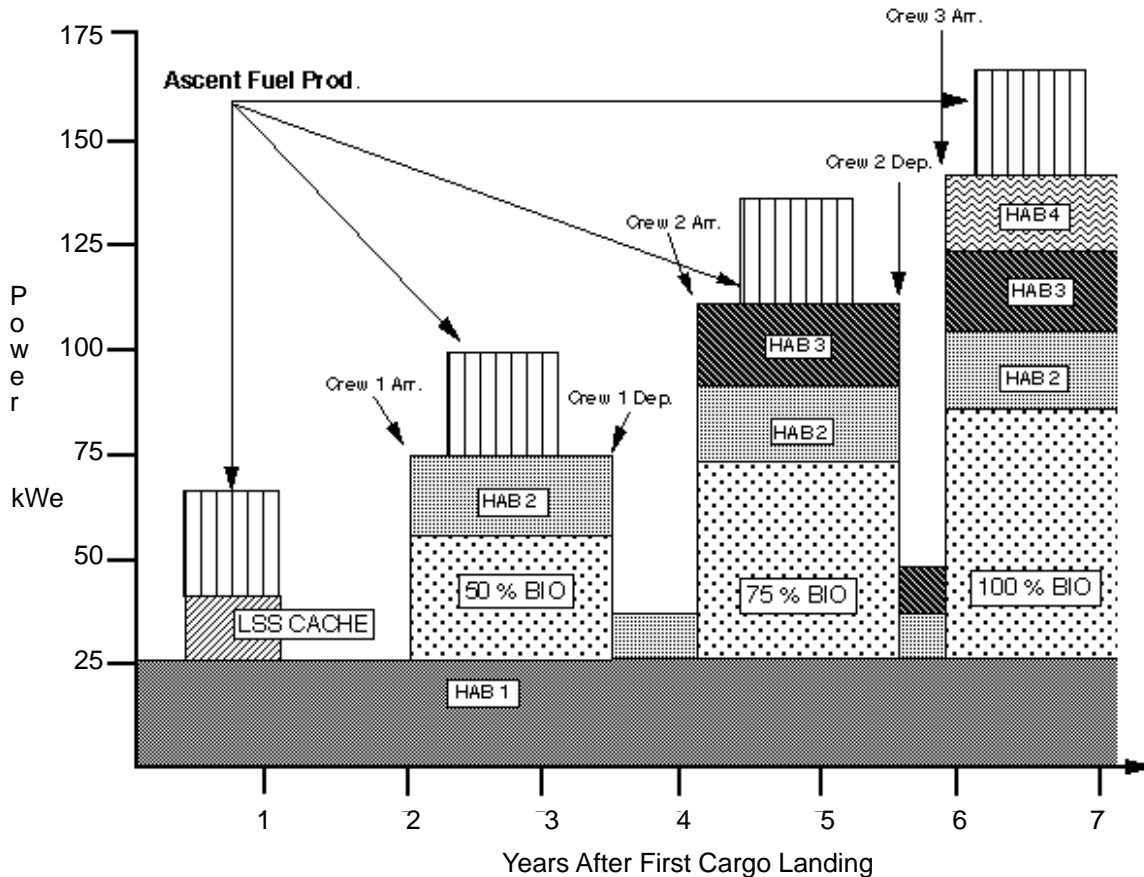


Figure 3-40 Mars surface power profile.

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 (m <sup>3</sup> )	Area (m <sup>2</sup> )
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 than 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 (Withdraw, 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 <sup>238</sup>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 <sup>238</sup>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<sub>2</sub> and O<sub>2</sub>, 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<sub>2</sub>.

**Table 3-23 Rover Power System Characteristics**

Power System	Mass (MT)	Volume (m <sup>3</sup> )	Area (m <sup>2</sup> )	Mass (MT)	Volume (m <sup>3</sup> )	Area (m <sup>2</sup> )
	<i>Regional Rover</i>			<i>Local Rover</i>		
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, atmospheric, 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*

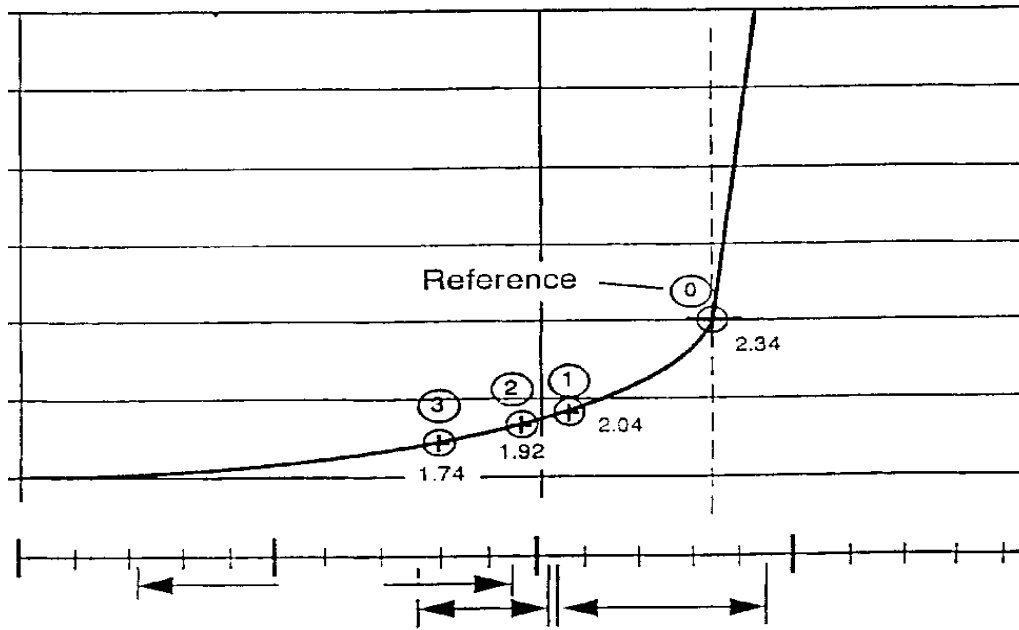
The cost model used for the technical content of the Reference Mission is the Advanced Missions Cost Model (AMCM)

(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 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 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**

<b>Environment Factor</b>	<b>"Skunk Works" Management</b>	<b>NASA Human Program Management</b>
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**

<b>Parameter</b>	<b>Commercial Aircraft Program</b>	<b>NASA Human Program Management</b>
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.

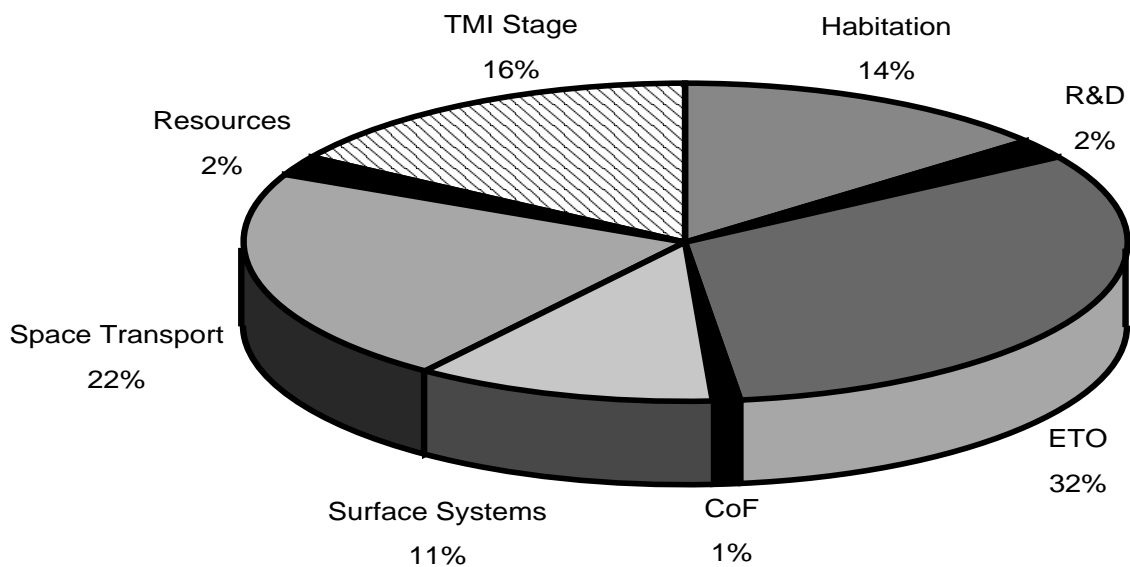
To reduce the cost of the HLLV component, several possible strategies could be used.

- 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 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 geographic 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
<ul style="list-style-type: none"> <li>• Nuclear Reactors</li> <li>• Weapons and Nuclear Waste Disposal</li> <li>• High-Efficiency Heat Engines (Turbines, Thermostructural Integrity)</li> </ul>	<ul style="list-style-type: none"> <li>• High-Temp Materials</li> </ul>	<ul style="list-style-type: none"> <li>• NTR</li> <li>• Aerobraking</li> </ul>
<ul style="list-style-type: none"> <li>• Clean-Burning Engines (H<sub>2</sub>/O<sub>2</sub>)</li> </ul>	<ul style="list-style-type: none"> <li>• High Efficiency Cryo-Refrigeration</li> </ul>	<ul style="list-style-type: none"> <li>• Propellant Maintenance</li> </ul>
<ul style="list-style-type: none"> <li>• Higher Performance Commercial Launches</li> </ul>	<ul style="list-style-type: none"> <li>• Methane/O<sub>2</sub> Rocket Engines</li> </ul>	<ul style="list-style-type: none"> <li>• ISRU-Based Space Transportation</li> </ul>

**Table 3-28 Dual-Use Technologies: Communications/Information Systems**

Terrestrial Application	Technology	Space Application
<ul style="list-style-type: none"> <li>• Communications High-Definition TV Broadcast</li> </ul>	<ul style="list-style-type: none"> <li>• Ka Band or Higher</li> </ul>	<ul style="list-style-type: none"> <li>• Telepresence: Vision and Video Data</li> <li>• Interferometers: Raw Data Transmission</li> </ul>
<ul style="list-style-type: none"> <li>• Entertainment Industry</li> <li>• Commercial Aviation</li> </ul>	<ul style="list-style-type: none"> <li>• Machine-Human Interface</li> </ul>	<ul style="list-style-type: none"> <li>• Control Stations</li> <li>• System Management</li> </ul>
<ul style="list-style-type: none"> <li>• Communications</li> <li>• Archiving</li> </ul>	<ul style="list-style-type: none"> <li>• Data Compression</li> <li>• Information Processing</li> <li>• Large Scale Data Management Systems</li> </ul>	<ul style="list-style-type: none"> <li>• Interferometers: Raw Data Transmission Information Processing</li> <li>• System Management, Expert Data</li> <li>• Archiving/Neural Nets</li> </ul>

spin-in →  
 spin-off ←  
 Both ↔



**Table 3-29 Dual-Use Technologies: In Situ Resource Utilization**

Terrestrial Application	Technology	Space Application
<ul style="list-style-type: none"> <li>• Mineral Analysis, Yield Estimation-Deep Mine Vein Location and Tracking</li> <li>• Wall and Ceiling Integrity</li> </ul>	<ul style="list-style-type: none"> <li>• Advanced Sensors</li> </ul>	<ul style="list-style-type: none"> <li>• Mineral Analysis, Yield Estimation Surface Mineral Analysis, and Resource Location</li> </ul>
<ul style="list-style-type: none"> <li>• Deep Mine Robotic Operations                             <ul style="list-style-type: none"> <li>• Mining</li> <li>• Beneficiating</li> <li>• Removal</li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>• Advanced Robotic Mining</li> </ul>	<ul style="list-style-type: none"> <li>• Surface Mining Operations                             <ul style="list-style-type: none"> <li>• Mining</li> <li>• Beneficiating</li> <li>• Removal</li> </ul> </li> </ul>
<ul style="list-style-type: none"> <li>• Improved Automated Processing; Increased efficiency</li> </ul>	<ul style="list-style-type: none"> <li>• Automated Processing: Advanced FDIR</li> </ul>	<ul style="list-style-type: none"> <li>• Remote, Low-Maintenance, Processing</li> </ul>
<ul style="list-style-type: none"> <li>• Reliable, Low-Pollution Personal Transmission</li> <li>• Regenerable Energy Economies</li> <li>• Small, Decentralized Power Systems for Remote or Third World Applications</li> </ul>	<ul style="list-style-type: none"> <li>• Alternative, Regenerable Energy Economies                             <ul style="list-style-type: none"> <li>• Methane/O<sub>2</sub></li> <li>• H<sub>2</sub>/O<sub>2</sub></li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>• ISRU-Based Engines</li> <li>• Regenerable Energies</li> <li>• High-Density Energy Storage</li> </ul>
<ul style="list-style-type: none"> <li>• Environmentally Safe Energy Production</li> </ul>	<ul style="list-style-type: none"> <li>• Space-Based Energy Generation and Transmission</li> </ul>	<ul style="list-style-type: none"> <li>• Surface Power Generation and Beaming</li> </ul>

spin-in →  
 spin-off ←  
 Both ↔



**Table 3-30 Dual-Use Technologies: Surface Mobility - Suits**

Terrestrial Application	Technology	Space Application
<ul style="list-style-type: none"> <li>• Hazardous Materials Cleanup</li> <li>• Fire Fighting Protection and Underwater Equipment</li> </ul>	<ul style="list-style-type: none"> <li>• Lightweight, Superinsulation Materials</li> </ul>	<ul style="list-style-type: none"> <li>• Surface Suits: Thermal Protection</li> </ul>
<ul style="list-style-type: none"> <li>• Robotic Assisted Systems</li> <li>• Orthopedic Devices for Mobility Impaired Persons</li> </ul>	<ul style="list-style-type: none"> <li>• Robotics</li> <li>• Mobility Enhancement Devices and Manipulators</li> </ul>	<ul style="list-style-type: none"> <li>• Robotic Assisted Suit Systems</li> </ul>
<ul style="list-style-type: none"> <li>• Hazardous Materials Cleanup</li> <li>• Fire Fighting Protection and Underwater Equipment</li> </ul>	<ul style="list-style-type: none"> <li>• Dust Protection, Seals, Abrasive Resistant Materials</li> </ul>	<ul style="list-style-type: none"> <li>• Surface Suits: Outer Garment</li> </ul>
<ul style="list-style-type: none"> <li>• Hazardous Materials Cleanup, Underwater Breathing Gear</li> </ul>	<ul style="list-style-type: none"> <li>• Lightweight Hi-Rel, Life Support</li> </ul>	<ul style="list-style-type: none"> <li>• Portable Life Support for Surface Suits</li> </ul>
<ul style="list-style-type: none"> <li>• Remote Health Monitoring</li> </ul>	<ul style="list-style-type: none"> <li>• Portable Biomedical Sensors and Health Evaluation Systems</li> </ul>	<ul style="list-style-type: none"> <li>• Surface EVA Crew Member Health Monitoring</li> </ul>
<ul style="list-style-type: none"> <li>• Hypo-Hyper Thermal Treatments</li> <li>• Fire Fighting Protection and Underwater Equipment</li> <li>• Artic/Antartic Undergarments</li> </ul>	<ul style="list-style-type: none"> <li>• Small, Efficient, Portable, Cooling/Heating Systems</li> </ul>	<ul style="list-style-type: none"> <li>• Surface Suits: Thermal Control Systems</li> </ul>

**Table 3-31 Dual-Use Technologies: Surface Mobility - Vehicles**

Terrestrial Application	Technology	Space Application
<ul style="list-style-type: none"> <li>• All-Terrain Vehicles</li> <li>• Research (Volcanoes)</li> <li>• Oil Exploration</li> </ul>	<ul style="list-style-type: none"> <li>• Mobility</li> </ul>	<ul style="list-style-type: none"> <li>• Surface Transportation</li> <li>• Humans</li> <li>• Science Equipment</li> <li>• Maintenance and Inspection</li> </ul>
<ul style="list-style-type: none"> <li>• Reactor Servicing/Hazardous Applications</li> </ul>	<ul style="list-style-type: none"> <li>• Robotics and Vision Systems</li> </ul>	<ul style="list-style-type: none"> <li>• Teleoperated Robotic Systems</li> </ul>
<ul style="list-style-type: none"> <li>• Earth Observation, Weather, Research</li> </ul>	<ul style="list-style-type: none"> <li>• Super-Pressure Balloons (110,000 ft - Earth Equiv)</li> </ul>	<ul style="list-style-type: none"> <li>• Mars Global Explorations</li> </ul>
<ul style="list-style-type: none"> <li>• Efficient, Long-Term Operations Low-Maintenance</li> <li>• Machines in Artic/Antaric Environments</li> </ul>	<ul style="list-style-type: none"> <li>• Tribology</li> </ul>	<ul style="list-style-type: none"> <li>• Surface Vehicles</li> <li>• Drive Mechanisms</li> <li>• Robotic Arms</li> <li>• Mechanisms</li> </ul>
<ul style="list-style-type: none"> <li>• Helicopters, Autos</li> </ul>	<ul style="list-style-type: none"> <li>• Variable Speed Transmissions</li> </ul>	<ul style="list-style-type: none"> <li>• Surface Vehicles</li> </ul>
<ul style="list-style-type: none"> <li>• Automated, Efficient Construction Equipment</li> </ul>	<ul style="list-style-type: none"> <li>• Multipurpose Construction Vehicle Systems and Mechanisms</li> </ul>	<ul style="list-style-type: none"> <li>• Robotic Construction and Set-up Equipment</li> </ul>

spin-in →  
 spin-off ←  
 Both ↔



**Table 3-32 Dual-Use Technologies: Human Support**

Terrestrial Application	Technology	Space Application
<ul style="list-style-type: none"> <li>• Stored Food</li> <li>• US Army</li> <li>• NSF Polar Programs</li> </ul>	<ul style="list-style-type: none"> <li>• Long-Life Food Systems</li> <li>• With High Nutrition</li> <li>• Efficient Packaging</li> </ul>	<ul style="list-style-type: none"> <li>• Efficient Logistics</li> <li>• Planetary Bases</li> <li>• Long Spaceflights</li> <li>• Space Stations</li> </ul>
<ul style="list-style-type: none"> <li>• Improved Health Care</li> <li>• Sports Medicine - Cardiovascular</li> <li>• Osteoporosis - Immune Systems</li> <li>• Isolated Confined Environments/Polar Operations</li> <li>• Noninvasive Health Assessments</li> </ul>	<ul style="list-style-type: none"> <li>• Physiological Understanding of the Human/Chronobiology</li> <li>• Understanding of Psychosocial Issues</li> <li>• Instrumentation Miniaturization</li> </ul>	<ul style="list-style-type: none"> <li>• Countermeasures for Long-Duration and/or Micro-g Space Missions</li> <li>• Health Management and Care</li> </ul>
<ul style="list-style-type: none"> <li>• Health Care</li> <li>• Disaster Response</li> <li>• US Army</li> </ul>	<ul style="list-style-type: none"> <li>• Long-Term Blood Storage</li> </ul>	<ul style="list-style-type: none"> <li>• Health Care for Long-Duration Space Missions</li> </ul>
<ul style="list-style-type: none"> <li>• Office Buildings ("Sick Building" Syndrome)</li> <li>• Manufacturing Plants</li> </ul>	<ul style="list-style-type: none"> <li>• Environmental Monitoring and Management</li> </ul>	<ul style="list-style-type: none"> <li>• Environmental Control for</li> <li>• Spacecraft Cabins</li> <li>• Planetary Habitats</li> <li>• Pressurized Rovers</li> </ul>
<ul style="list-style-type: none"> <li>• Contamination Cleanup</li> <li>• Waste Processing</li> </ul>	<ul style="list-style-type: none"> <li>• Waste Processing/SCWO</li> <li>• Water Purification</li> </ul>	<ul style="list-style-type: none"> <li>• Closed Water Cycles for</li> <li>• Spacecraft Cabins</li> <li>• Planetary Habitats</li> <li>• Pressurized Rovers</li> </ul>
<ul style="list-style-type: none"> <li>• Long-Life Clothes</li> <li>• Work Clothes in Hazardous Environments</li> <li>• US Army</li> </ul>	<ul style="list-style-type: none"> <li>• Advanced Materials/Fabrics</li> </ul>	<ul style="list-style-type: none"> <li>• Reduced Logistics Through Long-Life, Easy-Care Clothes, Wipes, Etc.</li> <li>• Fire Proof/Low-Out-gassing Clothes</li> </ul>
<ul style="list-style-type: none"> <li>• Efficient Food Production</li> </ul>	<ul style="list-style-type: none"> <li>• Advanced Understanding of Food Production/Hydroponics</li> </ul>	<ul style="list-style-type: none"> <li>• Reduced Logistics Through Local Food Production for</li> <li>• Spacecraft Cabins</li> <li>• Planetary Habitats</li> </ul>

**Table 3-33 Dual-Use Technologies: Power**

Terrestrial Application	Technology	Space Application
<ul style="list-style-type: none"> <li>• Batteries/RFCs for</li> <li>• Autos</li> <li>• Remote Operations</li> <li>• DOD</li> <li>• NSF Polar Programs</li> </ul>	<ul style="list-style-type: none"> <li>• High-Density Energy Storage</li> <li>• Alternate Energy Storage (Flywheels)</li> </ul>	<ul style="list-style-type: none"> <li>• Reduced Logistics for Planetary Bases</li> <li>• High-Rel, Low-Maintenance Power Systems</li> </ul>
<ul style="list-style-type: none"> <li>• Clean Energy From Space</li> </ul>	<ul style="list-style-type: none"> <li>• Beamed Power Transmission</li> </ul>	<ul style="list-style-type: none"> <li>• Orbital Power to Surface Base</li> <li>• Surface Power Transmission to Remote Assets</li> </ul>
<ul style="list-style-type: none"> <li>• Remote Operations</li> <li>• DOD</li> <li>• NSF Polar Programs</li> </ul>	<ul style="list-style-type: none"> <li>• Small Nuclear Power Systems</li> </ul>	<ul style="list-style-type: none"> <li>• Surface Base Power</li> <li>• Pressurized Surface Rover</li> <li>• Interplanetary Transfer Vehicle</li> </ul>
<ul style="list-style-type: none"> <li>• Remote Operations</li> <li>• DOD</li> <li>• NSF Polar Programs</li> <li>• High-Efficiency Auto Engines</li> </ul>	<ul style="list-style-type: none"> <li>• High-Efficiency, High-Rel, Low-Maintenance Heat-to-Electric Conversion Engines</li> </ul>	<ul style="list-style-type: none"> <li>• Energy Conversion for Planetary Bases</li> <li>• Low Servicing Hours</li> <li>• Little or no Logistics</li> </ul>

spin-in →

spin-off ←

Both ↔



**Table 3-34 Dual-Use Technologies: Structures and Materials**

Terrestrial Application	Technology	Space Application
<ul style="list-style-type: none"> <li>• Vehicles</li> <li>• Fuel-Efficient Aircraft</li> <li>• Modular Construction (Homes, etc.)</li> </ul>	<ul style="list-style-type: none"> <li>• Composite Materials                             <ul style="list-style-type: none"> <li>• Hard</li> <li>• Soft</li> </ul> </li> <li>• Advanced Alloys, High-Temperature</li> </ul>	<ul style="list-style-type: none"> <li>• Cryo Tanks</li> <li>• Habitat Enclosures</li> <li>• Pressurized Rover Enclosures</li> <li>• Space Transit Vehicle Structures</li> </ul>
TBD	<ul style="list-style-type: none"> <li>• Superinsulation</li> <li>• Coatings</li> </ul>	<ul style="list-style-type: none"> <li>• Cryo Tanks</li> <li>• Habitable Volumes</li> </ul>
<ul style="list-style-type: none"> <li>• Large Structures, High-Rises, Bridges</li> <li>• Commercial Aircraft                             <ul style="list-style-type: none"> <li>• Improved Safety</li> <li>• Lower Maintenance</li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>• Smart Structures</li> <li>• Imbedded Sensors</li> </ul>	<ul style="list-style-type: none"> <li>• Space Transit Vehicle Structures</li> <li>• Planetary Habitat Enclosures</li> <li>• Surface Power Systems</li> <li>• Rover Suspensions</li> </ul>

**Table 3-35 Dual-Use Technologies: Science and Science Equipment**

Terrestrial Application	Technology	Space Application
<ul style="list-style-type: none"> <li>• Energy Resource Exploration</li> <li>• Environmental Monitoring, Policing</li> </ul>	<ul style="list-style-type: none"> <li>• Spectroscopy                             <ul style="list-style-type: none"> <li>• Gamma Ray</li> <li>• Laser</li> <li>• Other</li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>• Geo-chem Mapping</li> <li>• Resource Yield Estimating</li> <li>• Planetary Mining Operation Planning</li> </ul>
<ul style="list-style-type: none"> <li>• Undersea Exploration</li> <li>• Hazardous Environment Assessments, Remediation</li> </ul>	<ul style="list-style-type: none"> <li>• Telescience</li> </ul>	<ul style="list-style-type: none"> <li>• Remote Planetary Exploration</li> </ul>
<ul style="list-style-type: none"> <li>• Environmental Monitoring</li> <li>• Medicine</li> </ul>	<ul style="list-style-type: none"> <li>• Image Processing</li> <li>• Compression Technique</li> <li>• Storage</li> <li>• Transmission</li> <li>• Image Enhancements</li> </ul>	<ul style="list-style-type: none"> <li>• Communication of Science Data</li> <li>• Correlation of Interferometer Data</li> </ul>
<ul style="list-style-type: none"> <li>• Improved Health Care</li> <li>• Sports Medicine - Cardiovascular</li> <li>• Osteoporosis - Immune Systems</li> <li>• Isolated Confined Environments/Polar Operations</li> <li>• Noninvasive Health Assessments</li> </ul>	<ul style="list-style-type: none"> <li>• Physiological Understanding of the Human</li> <li>• Instrumentation Miniaturization</li> </ul>	<ul style="list-style-type: none"> <li>• Countermeasures for Long-Duration and/or Micro-g Space Missions</li> <li>• Health Management and Care</li> </ul>

spin-in →  
 spin-off ←  
 Both ↔



**Table 3-36 Dual-Use Technologies: Operations and Maintenance**

Terrestrial Application	Technology	Space Application
	<ul style="list-style-type: none"> <li>• Task Partitioning</li> <li>• R &amp; QA in Long-Term, Hazardous Environments</li> <li>• System Health Management and Failure Prevention Through AI and Expert Systems, Neural Nets</li> </ul>	
<p><i>We mentioned this area as important, but did not complete. Recommend that we work with Jon Ericson and bob Savely to get it right.</i></p>		
←		
←		

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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