Report of the 90-Day Study on Human Exploration of the Moon and Mars

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NASA Moon/Mars Database Report

This is an internal NASA report prepared for NASA Administrator Truly by a team led by Johnson Space Center Director Aaron Cohen. It was commissioned by Admiral Truly after the President's July 20 speech, and its purpose is to provide a database for the Space Council to refer to as it considers strategic planning issues.

The report will be used as an input and one data source for Council consideration of approaches to program, schedule and technology, international cooperation and management.

The Space Council will examine the reference cases described in the report and also intends to examine a range of robust technical alternatives and approaches to mission planning.

The report does not contain any specific recommendations.

The report does not contain any estimates of total mission cost.

The report provides information regarding the potential benefits of the human exploration initiative, international participation considerations, and potential management system enhancements.

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Preface

In his speech on July 20, 1989, President Bush asked Vice President Quayle to lead the National Space Council in determining what is needed to chart a new and continuing course to the Moon and Mars and beyond: the necessary money, manpower, and materials, the feasibility of international cooperation, and realistic timetables with milestones along the way.

To support this endeavor, NASA Administrator Richard H. Truly created a task force to conduct a 90-day study of the main elements of a Human Exploration Initiative. The Initiative described in this report encompasses robotic as well as human missions. It is, nonetheless, a distinctly human adventure in the broadest sense, involving not only human space travelers, but also extending into the solar system the skills, imagination, and support of many thousands of people who will never leave Earth.

This report describes study progress and serves as a reference point to assist the Council in its deliberations. Five reference approaches are modeled building on past programs and recent studies to reflect wide-ranging strategies that incorporate varied program objectives, schedules, technologies, and resource availabilities.

The five reference approaches presented reflect the President's strategy: First, Space Station Freedom, and next back to the Moon, and then a journey to Mars. The destination is, therefore, determined, and with that determination the general mission objectives and key program and supporting elements are defined. As a result, regardless of the implementation approach selected, heavy-lift launch vehicles, space-based transportation systems, surface vehicles, habitats, and support systems for living and working in an extraterrestrial environment are required.

As deliberations proceed, the task force is prepared to support the analysis of implementation options and option variations identified by the Administrator, the Vice President, and the members of the National Space Council.

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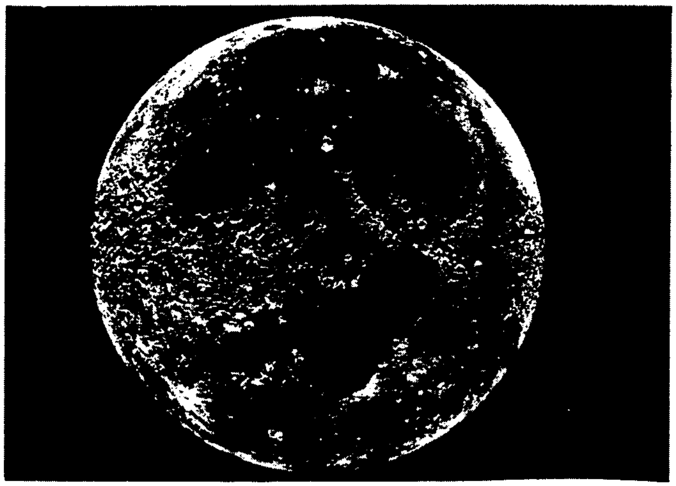

... And next, for the next century,
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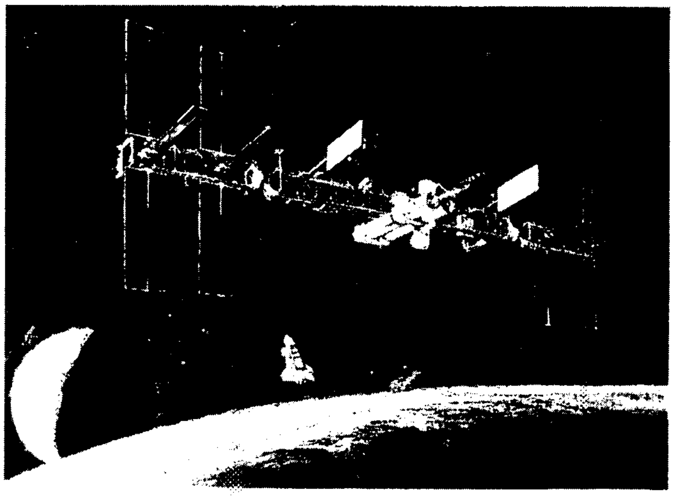
and this time, back to stay.



First, for the coming decade,
for the 1990s,
Space Station Freedom,
our critical next step in
all our space endeavors.

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Executive Summary

Section 1

SECTION 1

Executive Summary

On July 20, 1989, President Bush charted a new course for the human exploration of space:

> ". . . a long-range continuing commitment. First, for the coming decade, for the 1990s, Space Station Freedom, our critical next step in all our space endeavors. And next, for the next century, back to the Moon, back to the future, and this time, back to stay. And then a journey into tomorrow, a journey to another planet, a manned mission to Mars. Each mission should and will lay the groundwork for the next."

With these words, the President provided specificity to the goal contained in the 1988 Presidential Directive on National Space Policy: to expand human presence and activity beyond Earth orbit into the solar system. President Bush has answered the question "Where are we going?" We are going back to the Moon, and then we are going to Mars. The shape of human exploration of space is clear.

Space Station Freedom, to be followed by a return to the Moon to stay, and a subsequent journey to Mars, will be rational extensions of the United States civil space program. From its very beginning, that program has expanded human activities in space. From Mercury and on through Gemini, Apollo, Skylab, the Space Shuttle, and now, Space Station Freedom, the United States has moved steadily into larger and more ambitious programs of ever-increasing complexity. Each has been a logical extension of what came before. Each built on past experience.

The rationale for exploring and settling space mirrors the spirit that has compelled explorers through the ages: the human urge to expand the frontiers of knowledge and understanding and the frontiers where humans live and work. That is the basic reason people explore on land, sea, and in space, and has been since humans first walked on Earth.

The imperative to explore is embedded in our history, our traditions, and our national character. Throughout the drama of American history, our forefathers, with resourcefulness, audacity, and ingenuity, explored a seemingly limitless continent, using the wealth of natural resources to sustain them along the way. Today, men and women have explored nearly every corner of the planet, even to the bleak center of remote Antarctica. Now, in the late 20th Century and the early 21st, men and women are setting their sights on the Moon and Mars, as the exploration imperative propels us toward new discoveries.

The Human Exploration Initiative

To enrich the human spirit, to contribute to national pride and international prestige, to inspire America's youth, to unlock the secrets of the universe, and to strengthen our Nation's technological foundation: human exploration of the Moon and Mars will fulfill all these aspirations and more. This document provides a framework within which various approaches to meeting these national goals may be analyzed. The basic mission sequence is clear: begin with Space Station Freedom in the 1990s, return to the Moon to stay early in the next century, and then journey on to Mars. An end-to-end strategy for implementing the mission begins with robotic exploration to determine and characterize the lunar and martian environments in which spacecraft and crew must function. The next step is to build a permanent outpost on the Moon to support human presence for science and exploration. In addition to the benefits to be gained from lunar exploration for its own sake, the lunar outpost serves a vital parallel purpose. Just a 3-day journey from Earth, the Moon provides the ideal location to develop the systems and experience to prepare for the next step of the Initiative: an outpost on Mars.

The mission objectives dictate a common profile for both outposts, beginning with the launch of crew and cargo from Earth, with the crew on the Space Shuttle and most of the cargo on new heavy lift launch vehicles. The destination is Space Station Freedom, where vehicles are assembled, fueled, and serviced for the next stage of the journey. Concepts have been developed for transfer vehicles that carry the crew and cargo from Freedom and to and from lunar and Mars orbit and for excursion vehicles that meet the crew and cargo in orbit and bring them to the surfaces of the Moon and Mars.

Specialized concepts have also been developed for the systems that support human explorers as they live and work on the Moon and Mars. A combined habitation and laboratory module provides a comfortable environment for living, recreation, and scientific research. Power system concepts ranging from photovoltaic to nuclear were developed to support increasing levels of activity and scientific research. For travel across planetary surfaces, various rovers will be used, some that crew members drive, and others that operate robotically. In situ resource utilization, which would increase outpost independence from planet Earth, may also be supported at the outposts. And finally, launch and landing sites have been designed for the vehicles that bring crew members to planetary surfaces and take them on the first leg of their journey home.

Reference Approaches

The Human Exploration Initiative provides a framework within which various elements of and approaches to human exploration of the Moon and Mars can be examined. In order to provide the data necessary to make these types of assessments, several reference approaches have been selected to determine which parameters drive such things as cost, schedule, complexity, and program risk. Five reference approaches were analyzed, each of which is characterized by a particular emphasis: (1) balance and speed; (2) the earliest possible landing on Mars; (3) reduced logistics from Earth; (4) schedule adapted to Space Station Freedom; and (5) reduced scale. The information generated through this process can be used as a data base for determining the appropriate scope, schedule, and ultimate approach to be used in implementing the program. The data generated by this process are intended to capture the range of possibilities based on our technical understanding today, and, consequently, can be used to develop implementation approaches for any number of options.

Infrastructure

The existing NASA infrastructure of Earth-to-orbit transportation systems, Space Station Freedom, and telecommunications, navigation, and information management systems will be an integral element of any human exploration program. In parallel with the development of the Initiative, current and projected capabilities in these areas were assessed to determine where augmentation might be necessary.

In the area of Earth-to-orbit transportation, the Nation's current mixed fleet of Space Shuttles and expendable launch vehicles clearly requires enhancement. The Space Shuttle will be used to carry the crew to Space Station Freedom, but the massive cargo flights necessary to support extraterrestrial human exploration mandate launch vehicles with much greater lift capacity: approximately 60 metric tons for the lunar outpost, and about 140 metric tons for the Mars outpost. (The current Shuttle has a capability of 17.3 metric tons.) Various concepts for vehicles to accommodate these requirements range from Shuttle-derived vehicles to versions of the planned Advanced Launch System. New ground facilities will also be required to support the new vehicles.

Space Station Freedom will serve a vital role in human exploration: it will provide the essential scientific and technological foundation for later human missions to the planets, and it will serve as a transportation node for the missions of the Initiative. Space Station Freedom will serve as an on-orbit laboratory for conducting research and developing technology that is required by the

Initiative. Freedom is the ideal location for such studies and demonstrations because no terrestrial laboratory can adequately simulate the characteristics of the space environment. Research will determine acceptable long-term micro-gravity countermeasures and obtain data for the design of self-sufficient life support systems. Freedom can advance technology by serving as a test-bed for new lunar and Mars system developments. Further, the hardware, software, and other technologies used to assemble and operate Freedom can be applied to exploration vehicles and systems.

A significant feature of Space Station Freedom's design is its capability to add pressurized laboratory and habitation modules, power generation equipment, truss extensions, and specialized facilities. This capacity allows Freedom to evolve gracefully as its requirements as a research facility and transportation node increase over the lifetime of the Initiative. Freedom will evolve sequentially through four configurations to support four Human Exploration Initiative milestones: the verification flight of the lunar transfer vehicle, expendable lunar transfer vehicle operations, reusable lunar transfer vehicle operations, and orbital operations in support of Mars missions.

The Human Exploration Initiative is also expected to stimulate new developments in telecommunications, navigation, and information management. These enabling support functions monitor and control mission elements, acquire telemetered data from engineering and science measurements, provide radiometric data for navigation and video data for operations and science activities, and provide a capacity to communicate, receive, distribute, and process information. These functions must be provided efficiently, with human-related reliability.

Several challenges must be met: incorporating highly unattended operations for many of the local Mars telecommunications and navigation functions, achieving a high Mars-Earth data rate, providing robust system connectivity for manned links, and providing an information management discipline, including standards, for use in transferring data between system nodes.

Meeting Human Needs in Space

Exploring the frontier has always been risky to the lives of the men and women at its edges. Now, astronauts are preparing to venture for long periods of time into environments more harsh, albeit more challenging and fascinating, than any encountered on Earth. Fundamental differences between space and Earth–the lack of gravity, inadequate atmospheres, deep cold, and radiation hazards–challenge our ability to protect, nurture, and sustain the individuals who will be the pioneers of the solar system.

Life scientists have major responsibilities under the Human Exploration Initiative: to the crew, to assure their health, productivity, and safety throughout the mission and the postflight rehabilitation period; to the mission, to provide a productive working environment; and to the scientific community, to advance knowledge and understanding of human adaptation to the space environment.

Critical areas essential to support of human exploration include protection from the radiation hazards of the space environment, of the utmost importance both for journeying to and living on other planetary bodies. Limits must be determined, and protective measures, including shielding, storm shelters, and warning systems, must be developed.

Other important health-related areas include reduced gravity countermeasures, medical care, and life support systems. The final area that must be investigated is one about which we have very little data: behavior, performance, and human factors in an extraterrestrial environment.

Science Opportunities and Strategies

A long-standing policy goal of the U.S. civil space program is "to expand knowledge of the Earth, its environment, the solar system, and the universe." The Human Exploration Initiative will significantly advance scientific knowledge as we explore the Moon and Mars and learn to use their surfaces for observatories and laboratories. The act of exploration will provide new insights into the natural history of the bodies visited and may lead to their use for practical purposes. Many diverse scientific disciplines — geology and geophysics, astronomy and astrophysics, human and plant physiology, and evolutionary biology — will be greatly enhanced. Exploring the Moon and Mars will help us in many ways to understand the past and to look into the future of our own planet, the solar system, and the universe.

Our first stop as we move outward from Space Station Freedom into the solar system is the Moon, where we can find clues about the early days of Earth. Current scientific theory holds that the Moon formed when a Mars-sized body collided with Earth. By exploring lunar origins, we may understand not only the formation of Earth, but also other mysteries of our solar system, such as the tilt of Uranus and the rotational spin of Venus. The lunar surface also contains records of cratering processes, obliterated on Earth by erosion, which may contain clues about the extinction on Earth of entire species. Such breakthroughs may lead to profound discoveries about how life, including human life, evolves. Studies of the Moon will also yield important information about its natural resources, which is a vital first step in becoming a multi-planet species.

In addition to studying the Moon itself, from the lunar surface we will look outward. The Moon is a valuable platform for studying distant stars and galaxies, the rest of the solar system, and Earth itself; its quiet, stable environment provides an excellent base for astronomy. From the Moon, we can make great strides in understanding the universe, strides that are currently impossible on Earth or using orbiting telescopes. And when men and women live there, scientists will learn about the long-term effects on humans of a low-gravity environment; this is an essential step for longer-duration stays on Mars.

We will not stop at the Moon, because the imperative to explore will lead men and women to Mars. The planet most like Earth, Mars offers many unique scientific opportunities, but perhaps the most intriguing question is whether life exists or has ever existed on Mars. Ancient river beds and channels indicate that water once flowed on Mars and that life could have formed there. Life may exist on Mars today in underground habitats where volcanic heating melts ground ice, producing a warm, wet environment protected from harsh surface conditions. Only scientists working on Mars can discover the answer to this age-old question.

Studying Mars will also help us better understand changes on Earth, both natural changes and those that are caused by the presence of our species. By understanding the fascinating geological diversity on Mars, caused by drastic global climate change, we can understand more about our own changing planet.

And exploration will not stop at the Moon and Mars. As with all pioneering ventures, the Human Exploration Initiative will open new vistas of discovery tomorrow that can only be imagined today.

Technology

Space is an infinite source of challenges. To send humans to explore it and use its resources, development must begin today of new technologies in many areas, including regenerative life support systems, aerobraking, advanced cryogenic hydrogen-oxygen engines, surface nuclear power systems, in situ resource utilization, radiation protection, and nuclear propulsion. Advancements in automation and robotics, as incorporated into these and many other technologies, will significantly increase the effectiveness of operational systems. Perhaps the most tangible benefits of the Human Exploration Initiative, these developments will inevitably have spinoff applications that may profoundly affect our everyday lives and will certainly improve our position in the increasingly technological world economy.

During the decade of exploration from the late 1960s to the late 1970s, the astronauts of Apollo and the machines of Viking began to explore the surfaces of the Moon and Mars, achievements that were made possible by revolutionary advances in technologies and aerospace engineering capabilities. Innovative technological solutions to challenging engineering problems will also be one of the hallmarks of the coming era of exploration. Each step of the march to Mars — sending robotic missions to the Moon and Mars, establishing a lunar outpost, staging initial expeditions of humans to Mars, and ultimately emplacing an outpost on Mars — will drive technological and engineering expertise to greater heights and new standards of excellence.

The Human Exploration Initiative will involve dozens of major systems and will span decades. Technology development will be a multifaceted process that tests the best scientists and engineers in the Nation, builds on the considerable base that NASA has accumulated over the years, and evolves as the Initiative progresses. As mission objectives are crystallized, system concepts developed, and applicable technologies selected for pursuit, nearer-term advanced development programs will focus on creating individual operational systems. These advanced development programs will in turn feed into the design, development, test, and evaluation programs that will produce the flight hardware and software for specific Human Exploration Initiative systems. Throughout all programmatic phases in the life of the program, engineering ingenuity and technological innovation will characterize the Initiative.

Significant technology development needs to begin as soon as possible. A balanced, focused investment in technology will make possible the levels of performance and the scope of operations envisioned. Technology development will precede and foretell the major accomplishments of exploration, leading by several years the actual missions to the Moon and Mars.

National and Institutional Impact

The Human Exploration Initiative presents our Nation with exhilarating challenges, significant opportunities, and enormous benefits into the first part of the next century and beyond.

The Human Exploration Initiative will draw heavily on NASA's personnel, facilities, and equipment. This resource base, the NASA institutional core capability, is built on 75 years of research, development, and operational experience and hundreds of unique national facilities. From the National Advisory Committee on Aeronautics to the creation of NASA in 1958 to the present, the Agency has developed an unparalleled capability in civil space research and development and aeronautics.

NASA will request a significant augmentation of civil service positions to support the Human Exploration Initiative. These positions will provide the necessary technical expertise, program management, and administrative support to meet the objectives of the Initiative. The augmentation will also enhance the in-house work force, providing a solid balance between in-house and contracted efforts.

The Human Exploration Initiative will challenge current management systems. It presents a unique opportunity to explore and test streamlined administrative and management processes for directing long-term, complex, highly visible U.S. programs having significant international implications. The lessons learned may yield invaluable guidance transferable to other important U.S. programs.

Three areas will offer the greatest opportunity to realize significant efficiencies and enhanced effectiveness: the acquisition system, the budget process, and human resource management systems. NASA has already begun to address these areas internally, but some elements are outside NASA's control and will require active support from other Government quarters.

Potential international participation in the Human Exploration Initiative is the subject of a separate policy analysis being conducted under the direction of the National Space Council. That analysis will assess international capabilities, opportunities, issues, and options related specifically to the Human Exploration Initiative. This document complements that activity by pulling together information based on NASA's extensive experience in conducting space missions with foreign partners.

With the growing capabilities and increasing number of other spacefaring nations, the environment for international participation is considerably different than it has been in the past. The Human Exploration Initiative offers the potential for a variety of cooperative approaches with a number of potential partners. Different models may be appropriate for cooperation with different nations or for different phases of the Initiative. The National Space Council will consider these and other factors in assessing the feasibility of further international participation.

International cooperation and the use of the Initiative to serve important foreign policy goals are only two of its many benefits. The Initiative will also stimulate interest in science and engineering education, strengthen our national technological capabilities, offer a wealth of new scientific knowledge, and serve as a source of national pride.

NASA contributes to the Nation's base of technology through the transfer of research knowledge into the public and private sectors. The application and reapplication of this knowledge has a multiplicative effect, in which the general increase of efficiency and wealth from the advanced knowledge spreads throughout society. The Human Exploration Initiative will expand this contribution as advanced technologies are developed.

Another increasingly important benefit is the stimulus that the Human Exploration Initiative can provide to education. To help ensure that the Nation has an adequate, continuing supply of scientists, engineers, and other technical personnel to successfully implement the President's Human Exploration Initiative, an aggressive and targeted educational action plan is needed. To contribute to solving the predicted shortage of scientists and engineers, NASA will redirect and enhance its existing aerospace education program into a new, comprehensive, educational initiative entitled "Space Literacy for the 21st Century."

The educational frontiers opened by space exploration will captivate new generations of students, the scientific and technical work force of the future. This phenomenon, combined with the other scientific and political benefits of the Initiative, will open new horizons of achievement and will serve as a source of national pride. Taken together, the benefits of the Initiative — scientific understanding, technological advancement, motivation of our Nation's youth, and more — will significantly strengthen our position in the global community.

Some day it may be said that the residents of Earth had to leave their planet in order to find it. Indeed, from space, humans first got to see their own planet, floating in blackness above the barren moonscape like a blue and white marble. Perhaps more than anything else, this view of Earth dramatized our planet's uniqueness, and its fragility.

The last half of the 20th Century and the first half of the 21st Century will almost certainly be remembered as the era when men and women broke the bonds that bound them to Earth and set forth on a journey into space.

That journey will, in time, extend human presence throughout the solar system. Historians will note that the Moon became a familiar place to Earthlings very early in that period. They returned there to follow in the bootprints of Armstrong, Aldrin, and their Apollo colleagues, to establish an outpost for further exploration and expansion of human activities, to Mars and beyond.

Historians will further note that the journey to expand human presence into the solar system began in earnest on July 20, 1989, the 20th anniversary of the Apollo 11 lunar landing when President George Bush announced his proposal for a long-range continuing commitment to a bold program of human exploration of the solar system.

Introduction

Section 2

SECTION 2

Introduction

Human exploration of the Moon and Mars has been a sustaining vision of the U.S. civil space program almost since its inception. With the Apollo Program, we took our first small steps on the surface of another world; never again would our vision be restricted to the narrow confines of Earth's boundaries. Throughout the 20 years that have passed since the Apollo 11 astronauts first landed on the Moon, the aspiration to further explore has remained a beacon to the future.

In fact, during the Apollo era, Wernher von Braun led a task force to develop long-range goals for the space program after Apollo: more lunar missions, a space transportation system, a space station, and human journeys to Mars. The Space Shuttle became the space transportation system, Skylab was the first and Freedom will be the second space station, and several studies throughout the years have examined concepts and identified supporting requirements for human missions to the Moon and Mars.

Events over the past several years have increased awareness of the significant opportunities for human exploration and have provided a wealth of technical data to support a response to the President's bold new initiative. In 1986, the National Commission on Space published its report, "Pioneering the Space Frontier." The Commission was appointed by then-President Ronald Reagan and mandated by Congress to formulate a visionary agenda to lead America's civilian space enterprise into the 21st century. The Commission recommended to the Nation a bold plan for the next half century in space: "To lead the exploration and development of the space frontier, advancing science, technology, and enterprise, and building institutions and systems that make accessible vast new resources and support human settlements beyond Earth orbit, from the highlands of the Moon to the plains of Mars."

Later that year, then-NASA Administrator James C. Fletcher asked scientist astronaut Sally Ride to lead a NASA-wide task force to define and evaluate potential long-range goals for the U.S. civilian space program, building on earlier technical studies conducted throughout NASA and outside NASA in direct response to the Commission. The task force report, "Leadership and America's Future in Space," was released in August 1987. The report identified and analyzed four potential initiatives that could ensure continued civilian space program leadership: Mission to Planet Earth, Robotic Exploration of the Solar System, Outpost on the Moon, and Humans to Mars.

NASA's Office of Exploration was established in June 1987 in response to the task force's recommendation that NASA establish a focal point to fund, lead, and coordinate studies examining potential approaches to human exploration of the solar system, based on the Outpost on the Moon and Humans to Mars Initiatives. For the past 2 years, NASA has examined in detail a number of potential strategies: Apollo-type expeditions to Mars and its moons, evolutionary plans for permanent human presence on the Moon and Mars, and scientific observatories on the Moon. The goal of this effort has been to develop a substantial base of knowledge on technical and programmatic requirements in order to enable the President to define a pathway for the human exploration of the Moon and Mars.

With the President's historic announcement, that pathway has been defined. We are going to build Space Station Freedom, and then we are going back to the Moon and on to Mars, to continue the remarkable journey of exploration that began more than 25 years ago when human beings first rocketed into space. Exploration is a human imperative, one deeply rooted in American history and its destiny. Our flag still flies on the Moon, and exploration is an endeavor in which our Nation excels. Returning to the Moon and journeying to Mars are goals worthy of our heritage, signalling an America with the vision, courage, and skills essential for leadership among spacefaring nations in the 21st Century.

Now that the President has defined where we are going, the next step is to decide how and when. To support the Vice President and the National Space Council in this task, NASA initiated a study to develop the reference base from which strategic options could be derived. The pages that follow describe the results of a 90-day internal study for which NASA assembled a team of representatives from the NASA program offices and field centers. The purpose of the study was to examine the elements of a human exploration program, assess current capabilities, determine ways in which the capabilities might need to be augmented, identify areas in which new developments would be required, and provide this information in a cohesive package to support the decision-making process.

The process by which this information was derived began with the examination of the basic objectives of the Human Exploration Initiative: to return to the Moon to stay, and then to journey on to Mars, conducting significant scientific research every step of the way. An end-to-end strategy was then developed, beginning with robotic missions to characterize the environment in which humans and machines must function. The next steps are launching personnel and equipment from Earth, exploiting the unique capabilities of human presence in low Earth orbit aboard Space Station Freedom, transporting crew and cargo from

Earth orbit to lunar and Mars orbits and surfaces, and developing the planetary surface systems that support human life, extraterrestrial work, and science, and allow a significant degree of self-sufficiency. In parallel, NASA's existing and planned infrastructure of Earth-to-orbit transportation, Space Station Freedom, and telecommunications, navigation, and information management was assessed to determine its ability to accommodate the increased demands of the Initiative. The synergistic areas of human needs, science, and technology were also intensively assessed for the opportunities they bring to and derive from this program. Finally, programmatic matters, such as resources, management systems, international participation, and national benefits were examined to develop a perspective embracing the broader implications of the Initiative.

Key Technical Variables Studied

- Launch vehicle size
- In-space assembly or direct to surface
- Space Station Freedom, new spaceport, or direct assembly
- Chemical, electric, nuclear, or unconventional propulsion
- Aerobraking or all-propulsive vehicles
- Expendable or reusable spacecraft
- Propellant or tank transfer
- Open or closed life support
- Zero-gravity or artificial-gravity Mars vehicle
- In situ or Earth-supplied resources

In developing a preliminary program plan for human exploration of the Moon and Mars, results of past studies examining a wide variety of fundamental approaches formed the basis for the selection of certain key technical parameters. For the most part, these assumptions were derived from the past 2 years of intensive trade analyses conducted as part of the human exploration case studies. However, the case studies themselves built upon a rich heritage of earlier studies that established a foundation of technical information from which to draw. Combined with the strategy established by President Bush, this foundation provided a starting point for the development of the Human Exploration Initiative.

Certain technological approaches, described in detail in Section 8 of this document, have been proven to be the most feasible ways of building capability in the development of an outpost either on the Moon or Mars. It is known, for example, that some degree of in-space assembly and maintenance is necessary for the vehicles that transport cargo and crew to their ultimate planetary destinations. Trade studies of the location and function of the transportation node at which these functions are performed have determined that Space Station Freedom is both a necessary and feasible approach to meeting this requirement. Power for outpost operations, for another example, is provided in initial stages by photovoltaic systems with regenerative fuel cells, a known and well-developed technology that is entirely adequate for early power requirements. As the outpost develops, the next level of power generation is provided by space-based nuclear systems. For life support, regenerative systems provide the most cost-effective approach.

A significant trade study conducted over the past 2 years addressed the consideration of balancing the need to occasionally deliver relatively large masses, such as living quarters and utilities, to planet surfaces with the need to more regularly deliver the smaller masses associated with logistics resupply and crew transfer. This balance affects the sizing of launch and space transportation vehicles, the need for vehicle reusability, and the buildup sequence of the outpost. The balance must be arrived at considering reasonable flight rates, on-orbit assembly capabilities, and operations scenarios.

For missions to the Moon, this balance has been found to be best achieved by launch vehicles in the 50 to 80 metric ton payload class, which carry payloads to Space Station Freedom for final assembly and checkout before departure for the Moon. Although designed for no human intervention, lunar vehicles and payloads will, realistically, require some hands-on activity in Earth orbit. Separate Earth-orbit-to-lunar-orbit and lunar ascent/descent vehicles are required to satisfy operational and abort considerations. The vehicles need to be reusable and capable of delivering in the range of 15 to 40 metric tons to the lunar surface. For Mars missions, launch vehicles having a payload capability well in excess of 120 metric tons are required to achieve a balance between larger, fewer launches and less assembly at Freedom and smaller, more numerous flights that greatly complicate the assembly tasks.

An area in which a very wide range of system technology options were examined is propulsion systems for space transfer vehicles. Approaches ranged from conventional all-chemical propulsion to a variety of nuclear systems to solar sails and mass drivers. What emerged from these analyses was a succinct definition of the relative advantages and disadvantages of each approach.

Whereas several techniques, such as nuclear and solar electric propulsion and solar sails offered efficient transportation of large payload masses, this advantage is somewhat negated by slow travel time or significant operational complexity. Further study determined that the use of an aerobrake in conjunction with chemical propulsion could reduce required initial mass in the low Earth orbit by more than 50 percent, in addition to reducing operations costs.

Therefore, all-chemical propulsion with aerobraking was selected as the baseline for space transfer vehicle propulsion, and this assumption was used in developing mission profiles for the Initiative. However, for transportation from Earth orbit to Mars, nuclear propulsion shows a great deal of promise as an option for significantly enhancing mission performance.

Solid-core nuclear thermal rockets, a mature technology that was designed, built, and tested from 1955 to 1973, offers a savings in mass in low Earth orbit of approximately 40 percent over chemical propulsion without aerobraking. Chemical propulsion with aerobraking and solid-core nuclear thermal rockets are, therefore, essentially equivalent in their advantage over chemical propulsion without aerobraking. However, gas-core nuclear rockets, for which concepts were also formulated during the same time, offer the significant advantage of reducing round-trip travel time to Mars to less than 1 year.

As the development of the Human Exploration Initiative unfolds, these and other issues will continue to be examined to identify the most efficient approaches to the various elements of the program.

The Human Exploration Initiative

Section 3

SECTION 3

The Human Exploration Initiative

The overarching goal of the Human Exploration Initiative is to expand human presence in the solar system, developing nearly self-sufficient communities on new worlds and promoting significant advances in science and technology. The Initiative will follow an evolutionary pathway over a 30-year horizon beginning with Space Station Freedom in the 1990s, followed by a permanent outpost on the Moon at the beginning of the next century, and culminating with Mars expeditions that lead to a permanent martian outpost. Figure 3-1 illustrates the relative timing of the full array of scientific and technical systems that will enable and support this goal. These systems are discussed in detail in this and subsequent sections.

Space Station Freedom, the first step on the pathway, will provide the essential scientific and technological foundation for later human missions to the planets. For example, a particularly critical factor in planning human exploration is the determination of the physiological and psychological effects of low gravity and long-term habitation of the space environment, which will be studied on Freedom. Initially, crew members will remain on Space Station Freedom for 3 months; research will focus on understanding the various mechanisms responsible for adaptation to weightlessness and the physiological problems encountered upon return to Earth. Later, an extended-duration crew certification program will prolong visits to 180 days or more and will include enhanced physiological countermeasures for low gravity and radiation effects.

Systems developed for use on Space Station Freedom will enhance and strengthen the technological base for human planetary exploration. Freedom will serve as a controlled test-bed for developing and validating systems and elements, such as habitation and laboratory modules and life support systems, to be used later on the Moon and Mars. In addition, Freedom will support technology experiments and advanced development in mission-critical areas, such as spacecraft assembly, servicing, and system development. When the exploration missions begin, Freedom will become a transportation node where both lunar and Mars vehicles will be assembled, tested, launched, and refurbished to fly again. (Freedom's role as a transportation node is discussed in more detail in Section 5.)

The next step in this evolutionary process will be to build a permanent outpost on the Moon to establish human presence for science and exploration.

Rovers and crew will explore the geology and geophysics of the Moon itself, and rock and soil samples will be analyzed in a lunar laboratory. The unique characteristics of the lunar environment make it an excellent platform from which to conduct astronomy, physics, and life sciences research. The Moon also provides an ideal location, just a 3-day trip from Earth, at which human beings can learn to live and work productively in an extraterrestrial environment with increasing self-sufficiency, using local lunar resources to support the outpost. In this way, the lunar outpost will both advance science and serve as a test-bed for validating critical mission systems, hardware, technologies, human capability and self-sufficiency, and operational techniques that can be applied to further exploration.

Once the lunar outpost has verified the techniques and demonstrated the systems, the next evolutionary step will be to launch the first human expedition to Mars. Initial missions to Mars will prove the systems and techniques required for continuing human missions and will conduct further reconnaissance of selected landing sites. Later missions will establish a Mars outpost with the objective of conducting science and exploration on the solar system's most Earth-like planet, expanding mankind's sphere of influence in the solar system, and living and working in an extraterrestrial environment with a high degree of self-sufficiency. Valuable scientific knowledge will be gained through the search for evidence of past and present life, exploration of the geology and geophysics of Mars and its moons, utilization of martian resources, and studies of biological responses in humans, plants, and animals.

To examine potential approaches to building permanent lunar and Mars outposts, an end-to-end strategy was developed that provides a logical mechanism for stepping through the various elements and milestones of the Initiative. The strategy begins with the preparatory phase of robotic exploration to obtain early scientific and technical data prior to the human exploration missions. Once the robotic missions have satisfied this requirement, the development of permanent, largely self-sufficient outposts on the Moon and Mars proceeds through three progressive phases: emplacement, consolidation, and operation.

The emplacement phase emphasizes accommodating basic habitation needs, establishing surface equipment and science instruments, and laying the foundation for future, more complex instrument networks and surface operations by testing prototypes of later systems. In the process, human explorers begin to learn to live and work on another planetary body, conducting local geologic investigations, performing experiments in mining the lunar soil to demonstrate the feasibility of oxygen production on the Moon, and examining the possibility of oxygen and water extraction on Mars. By the end of the emplacement phase, the support facilities include landing vehicle servicing equipment to prepare for

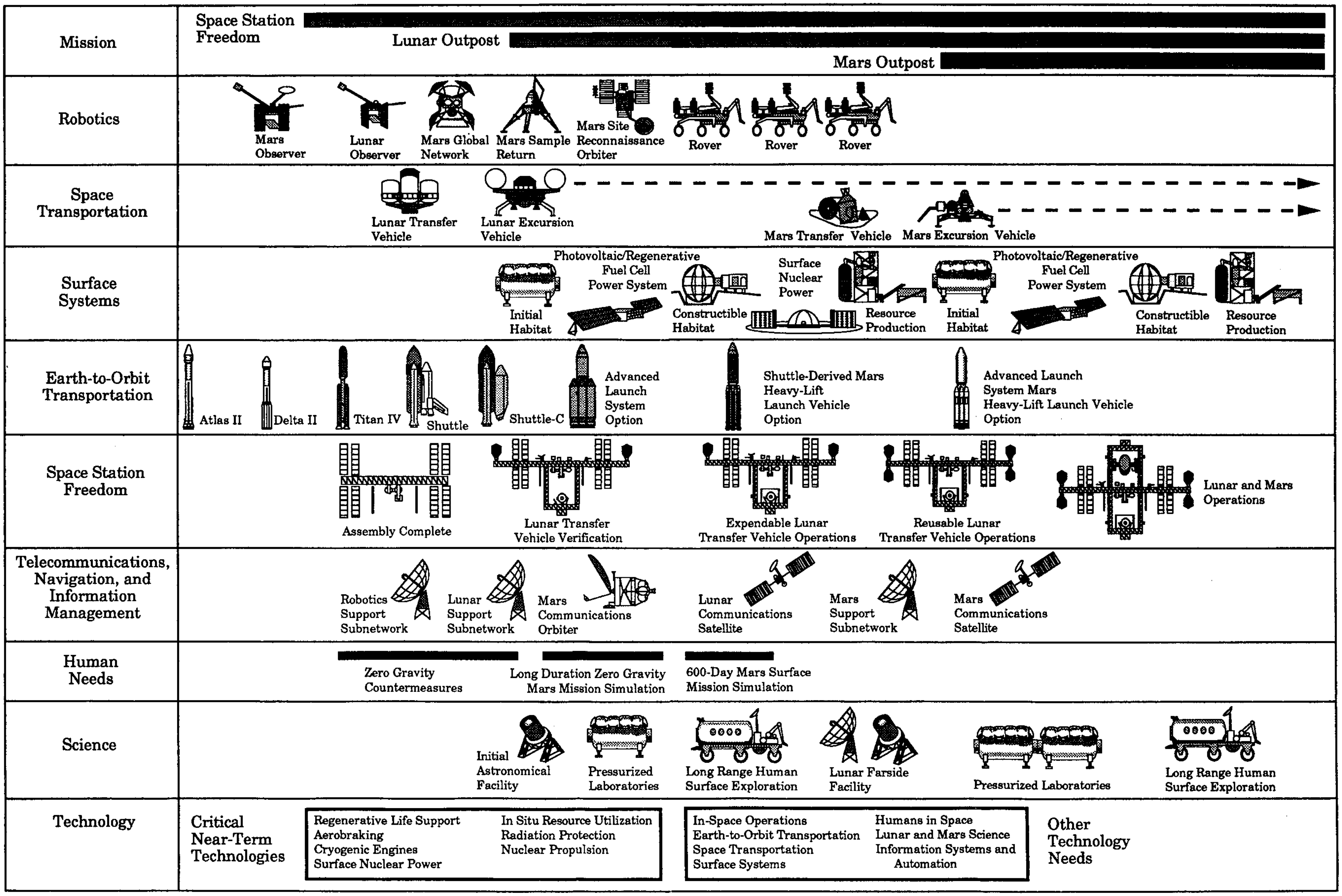
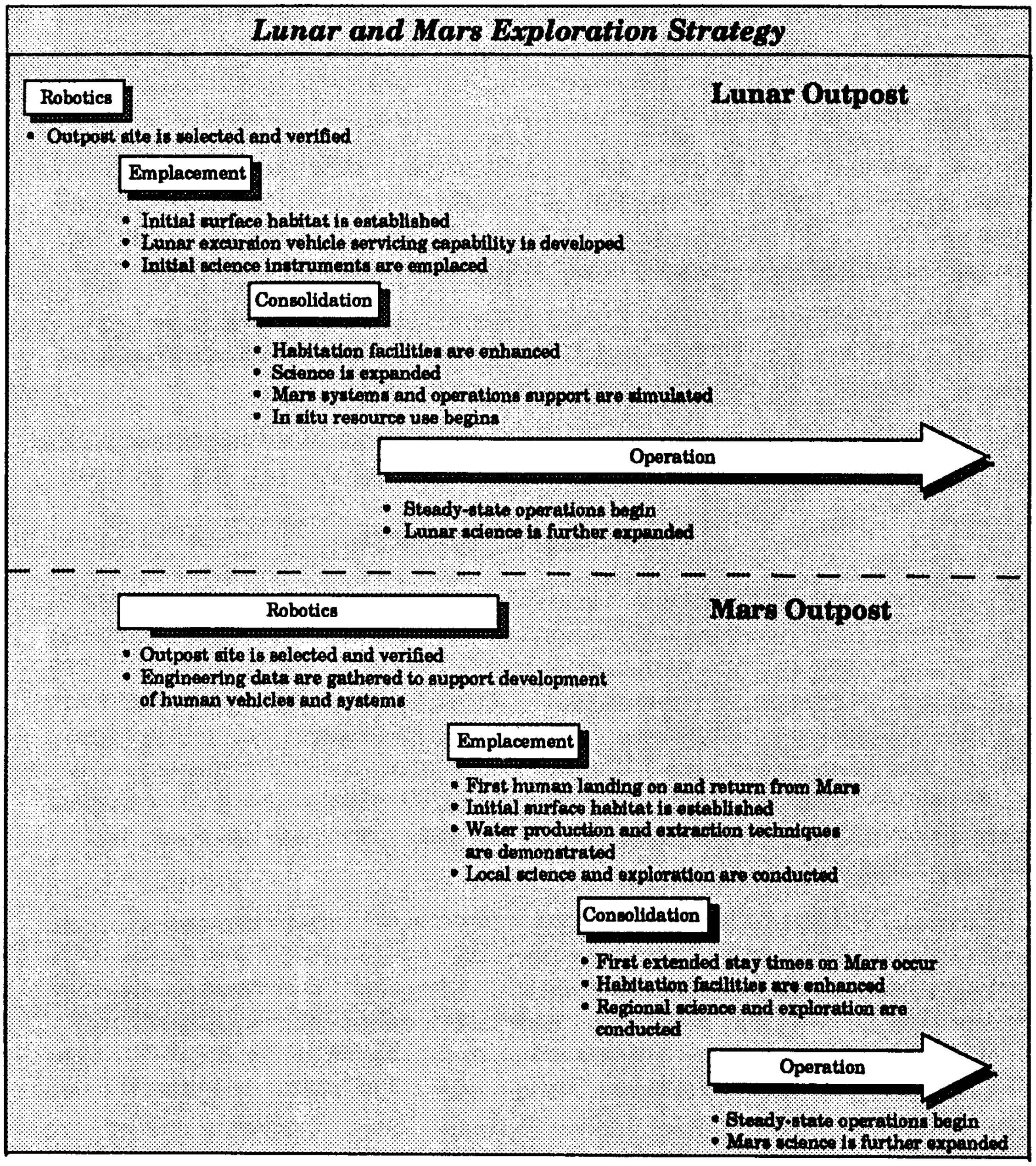


Figure 3-1 Human Exploration Initiative

longer visits. During this phase, human operations take place within tens of kilometers of the outpost, and unmanned rovers are used to explore more distant areas.

The consolidation phase further extends human presence, both in complexity of operations and in distances traveled from the outpost, and continues to develop experience in living and working in a planetary environment. During this



Lunar and Mars Exploration Strategy

Lunar Outpost

Robotics

- Outpost site is selected and verified

Emplacement

- Initial surface habitat is established
- Lunar excursion vehicle servicing capability is developed
- Initial science instruments are emplaced

Consolidation

- Habitation facilities are enhanced
- Science is expanded
- Mars systems and operations support are simulated
- In situ resource use begins

Operation

- Steady-state operations begin
- Lunar science is further expanded

Mars Outpost

Robotics

- Outpost site is selected and verified
- Engineering data are gathered to support development of human vehicles and systems

Emplacement

- First human landing on and return from Mars
- Initial surface habitat is established
- Water production and extraction techniques are demonstrated
- Local science and exploration are conducted

Consolidation

- First extended stay times on Mars occur
- Habitation facilities are enhanced
- Regional science and exploration are conducted

Operation

- Steady-state operations begin
- Mars science is further expanded

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phase, outpost capabilities, scientific facilities, and instruments are improved, and power and pressurized volume are increased. A constructible habitat is erected at the outpost to provide the increased volume required for both extended crew residence and laboratory sciences research. Human operations expand to a range of hundreds of kilometers from the outpost.

Learning to become more independent of Earth now takes on paramount importance. This involves developing confidence in operational strategies as well as developing improved outpost element subsystems. More efficient systems for life support are emplaced, prototypes of lunar resource processing plants are tested, and day-to-day activities are conducted without continual supervision and guidance from Earth.

The objectives of the operation phase are to make routine use of in situ resources, and to continue to live and work at the outpost with minimal dependence on Earth. The area of exploration opportunities is expanded to include routine human access to more distant points on the planet.

The result envisioned by the year 2025 is two permanent operating outposts – one on the Moon, one on Mars – with the knowledge base and experience to begin to seriously set our sights for further exploration.

The pages that follow describe in detail the robotic missions, lunar outpost, and Mars outpost implementation concepts for the Human Exploration Initiative.

Robotic Missions

The robotic exploration missions will obtain data to assist in the design and development of subsequent human exploration missions and systems, demonstrate technology and long communications time operations concepts, and dramatically advance scientific knowledge of the Moon and Mars. The mission set selected reflects an orderly strategy for compiling extensive data bases about the surface and subsurface of the Moon and the atmosphere, surface, and subsurface of Mars; validating remotely sensed data by in situ measurements at selected sites; selecting appropriate candidate landing locations; and characterizing potential outpost sites.

In formulating the robotic exploration mission set, the prime issues were properly sequencing the acquisition of global lunar and Mars data and systematically reducing the number of candidate sites, ranking those that remain in order of desirability. Other factors address scientific priorities, the need to provide design data for the human mission elements, and the development of the basis of the science investigations to be accomplished when humans inhabit the selected site.

Ranger, Surveyor, Lunar Orbiter, and Apollo have amassed a general knowledge base for the Moon, but these data are limited to a band about the equator, or in the case of subsurface data, to specific Surveyor and Apollo landing sites. Because the optimal site may be outside the well-known area, additional mapping of the Moon is required before the first human landing.

Lunar Observer will significantly enhance the global lunar data base to verify the requirements for surface equipment and excursion vehicles, select the outpost site, and plan lunar surface operations. These data will also help to resolve important issues related to long-duration human presence on the Moon, including the selection of sites of high scientific potential for human exploration, minimization of risks for human landing and habitation, and assessment of resource availability.

Two identical flight systems will be launched on the 3- to 5-day flight to the Moon. The spacecraft will be propulsively captured into an elliptical orbit in which a subsatellite will be released to conduct preliminary gravitational mapping. About a month later, the spacecraft orbit will be circularized into a 100-kilometer polar mapping orbit, and mapping will continue for about 1 year.

The primary objectives of robotic missions to Mars are to advance our understanding of the planet and its origin, history, and current conditions; to provide science and engineering data to support selection and certification of the expeditionary and permanent outpost sites; to return a sample of Mars to Earth for scientific analysis and determination of the potential of back-contamination; to conduct studies that diminish risks to human explorers; to provide data to assist in designing piloted vehicles and surface systems; to search for martian resources; and to generally demonstrate readiness to proceed with a human Mars mission.

The 1992 Mars Observer, enhanced to allow additional high resolution mosaics, higher data rates, and an extended operations period, will establish global martian data bases. In addition, the mission will begin global monitoring of climate and characterization of the atmosphere. If the 1992 mission fails to meet its objectives, a modified 1996 mission will back it up.

The Mars Global Network Mission will provide essential data to address scientific issues and develop specific engineering requirements for subsequent robotic and human presence on Mars. Two identical flight systems carrying an orbiter and multiple landers will be launched within a 20-day period using two expendable launch vehicles. The landers will provide high-resolution surface data at multiple locations and will obtain extended-duration seismic and meteorological measurements. These landers will most likely emplant scientific instruments beneath the surface and leave instruments on the surface.

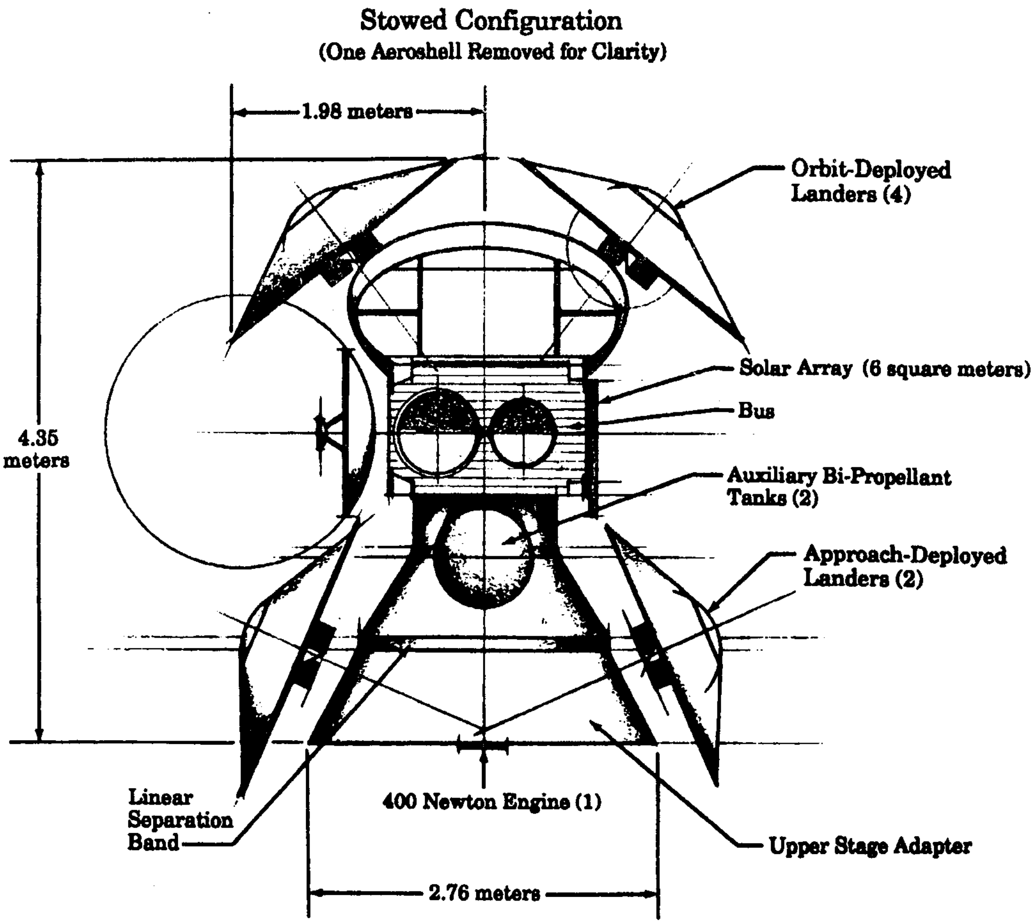


Figure 3-2 Mars Global Network Mission Vehicle Concept Using Landers

One possible implementation of this concept (see Figure 3-2) involves a spacecraft that carries six surface instrument packages mounted in aeroshells for entry into the martian atmosphere. Two aeroshells are deployed during Mars approach and targeted to land in regions above 65 degrees latitude. The remaining four aeroshells and their carrier bus are propulsively captured into elliptical orbit. As the orbit precesses and rotates due to perturbations, different regions of the planet will be targeted for deployment of the remaining aeroshells. After deployment, the orbiters will receive telemetry data from the landers and relay the information back to Earth.

The landers' descent imaging will aid in refining the geologic modeling of Mars surface processes at multiple spatial scales and contrasting locations. Approach imaging is also essential for selecting the landing site for the sample return mission. Long-lasting scientific packages will produce a meteorological data base for both atmospheric investigations and studies of the complex interactions between the surface and atmosphere. Seismic monitoring will further the understanding of the crustal structure of Mars and regional differences related to geophysical evolution. Biological and subsurface chemistry experiments will contribute directly to the scientific objectives of the Human Exploration Initiative by validating and calibrating remotely sensed data to assess the resource potential, trafficability, risks, and habitability issues associated with human and robotic exploration of the surface of Mars.

A Mars Sample Return with Local Rover mission (Figure 3-3) is the centerpiece of the robotic Mars missions. In addition to important scientific advancement, this mission will demonstrate technologies that will be used in the piloted missions, and it will serve as a flight test of technologies that include aerocapture and aeromaneuvering, hazard avoidance for landing, automatic rendezvous and docking, and long communication delay time technologies used for operations at Mars.

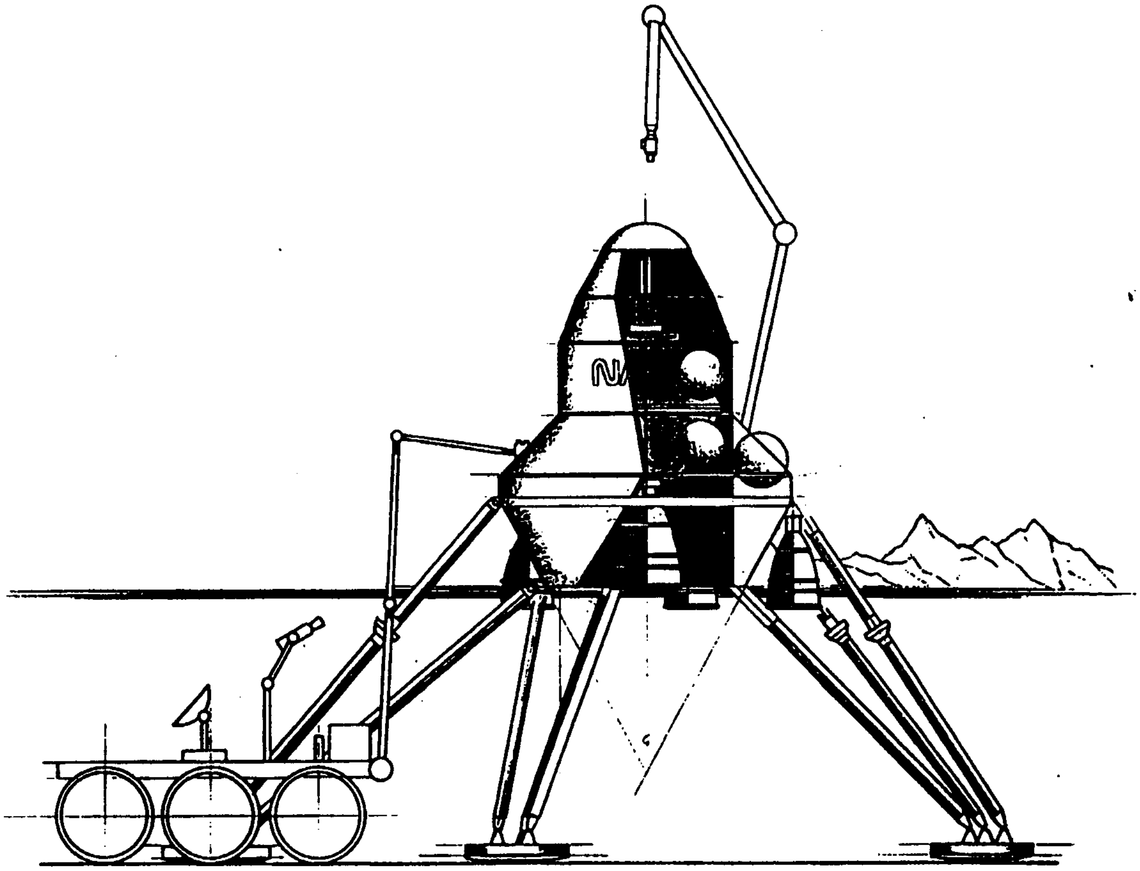


Figure 3-3 Sample Return Vehicle with Local Rover

Five kilograms of martian rocks, soil, and atmosphere will be returned to Earth prior to the development of the human mission vehicles and surface systems. Scientific analysis of martian samples should resolve a great deal of speculation about the nature and composition of martian surface rocks and soils and enable a detailed assessment of the surface environment for incorporation into design of the human exploration elements. The mission will also provide an Earth-Mars-Earth engineering test and a first test of surface mobility. Samples will be contained to preclude release on Earth until adequate testing of potential biological activity can be completed.

Two identical flight systems will be launched within a 20-day period using two expendable launch vehicles. The flight systems will be aerocaptured into a circular orbit around Mars at an altitude of 400 to 500 kilometers. After aerocapture, the sample return orbiter is separated from the landing segment of the flight system. A deorbit burn is executed by the landing segment, and aeromaneuvering techniques are used to land the Mars ascent vehicle with its local rover near one of the global network lander sites while the sample return orbiter remains in orbit. After landing, the local rover, capable of traverses to about 100 meters from the lander, will be deployed to collect samples outside the area contaminated by the lander's propulsion system.

Mars ascent is planned about a year later with autonomous rendezvous and docking of the upper stage of the Mars ascent vehicle and the sample return orbiter. Once docking is completed, the sample canister assembly will be transferred to the sample return capsule of the Earth return vehicle portion of the sample return orbiter. The rendezvous/docking module will then be separated from the Earth return vehicle. Departure from the vicinity of Mars is planned approximately 1 month after ascent.

The Mars Site Reconnaissance Orbiter mission consists of two orbiters (see Figure 3-4) and two communications satellites. It will provide detailed imaging to characterize landing sites, assess landing site hazards, and provide a data base for subsequent rover traverses and piloted surface operations. The orbiters will be targeted to a sun-synchronous, near polar, 1-day repeat orbit at an altitude of 299 kilometers to provide moderate resolution visual maps of 30 to 50 percent of Mars. For selected regions of the planet, high-resolution imaging will be obtained at a low Sun angle and transmitted to Earth using a high signal-to-noise ratio data link. The data will be transmitted via the two communications satellites, which also will support subsequent surface elements, significantly increasing their data return capabilities. In particular, the data relay capability will provide more efficient path planning, which significantly increases the area that the rover can cover.

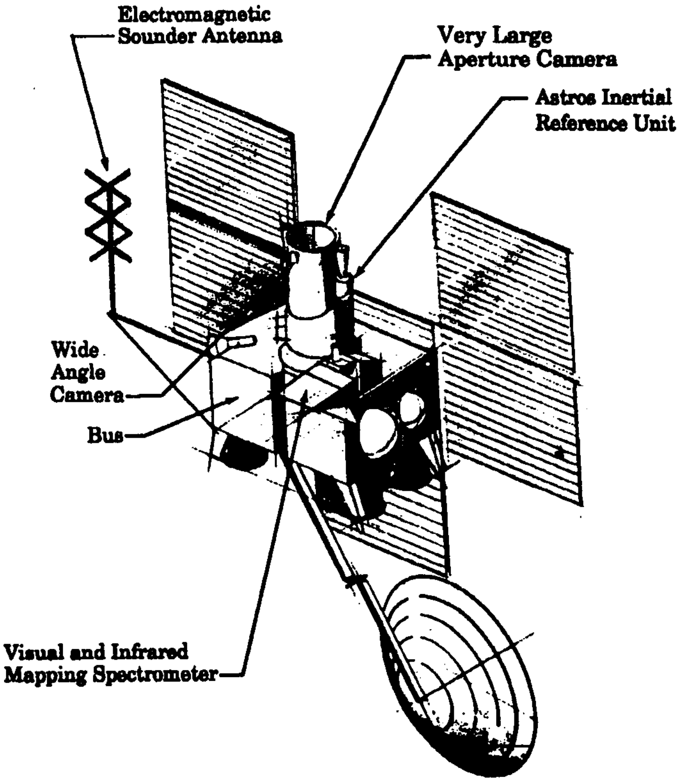


Figure 3-4 Mars Site Reconnaissance Orbiter Concept

Each orbiter/satellite combination will be launched on an expendable vehicle, and the two launches will occur within a 20-day period. Immediately after trans-Mars injection, orbiter and satellite will be separated and propulsively captured at Mars. The satellite will be maneuvered into a Mars-synchronous orbit.

Up to five Mars Rover missions will certify three sites selected using the data gathered by the Mars Observer, Mars Global Network, and Mars Site Reconnaissance missions to determine the sites with the greatest potential for piloted vehicle landing and outpost establishment. The rovers (Figure 3-5) will characterize available resources at these sites, provide data for determining the suitability of the sites for a human outpost, and collect diverse geological samples for return to Earth by later sample return missions or by piloted flights. The rovers will also emplace infrastructure elements, such as navigation aids and meteorological stations, to support piloted missions.

Each rover will survey a different 10 by 10 kilometer area for surface trafficability, subsurface structure, and mineral composition. Within this area, the rover

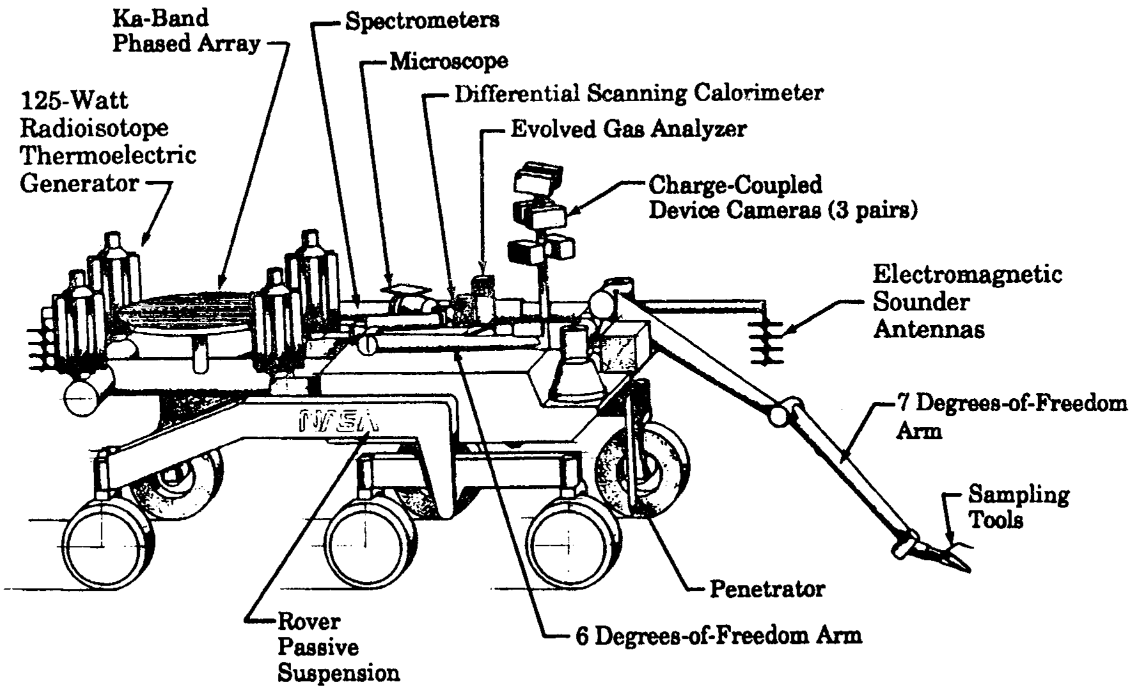


Figure 3-5 Long-Range Mars Rover

will survey nine 100-meter sites for selection of locations for a power plant, a habitat, and a landing site for human missions. Regional exploration is possible during the mission. The rovers are assumed to be similar to the rovers used on the Moon in a robotic mode, and allow for a 25-percent technology or capability upgrade between flights. Manned expeditionary missions could also carry into orbit a rover and its lander packaged in a biconic aeroshell.

On Mars, a rover with local access to the vicinity of its landing site will perform a preliminary characterization of the martian surface material composition, mineralogy, and petrology. This characterization will calibrate and validate the regional and local geological data from prior orbital missions. The rover will examine, in situ, a variety of biochemical and environmental indicators of ancient life-forms. The rover will also play a vital role in direct resource assessment of the site for subsequent manned landings.

Lunar Outpost

The next step in the strategy is the development of a permanent lunar outpost, which begins with two to three launches of the lunar payload, crew, transportation vehicles, and propellants from Earth to Space Station Freedom. At Freedom, the crew, payloads, and propellants are loaded onto the lunar transfer vehicle that will take them to low lunar orbit. The lunar transfer vehicle meets in lunar orbit with an excursion vehicle, which will either be parked in lunar orbit or will ascend from the lunar surface, and payload, crew, and propellants are transferred. After the excursion vehicle descends to the lunar surface, the transfer vehicle will return to Freedom. The transfer vehicles will be serviced and maintained at Freedom, and the excursion vehicles will be serviced and maintained at the outpost. Facilities will be provided at the outpost site to maintain the excursion vehicle during the crew's stay on the surface, which can be as long as 1 year.

Missions to the Moon fall into two categories: piloted and cargo. Figure 3-6 illustrates the typical mission profile for delivering crew and cargo to the lunar surface. A piloted mission delivers a crew of four and some cargo to the lunar surface and returns a crew of four and limited cargo to Freedom; a cargo mission delivers only cargo, and the vehicle is either expended or returned empty. The missions use common transfer and excursion vehicles: the piloted missions add

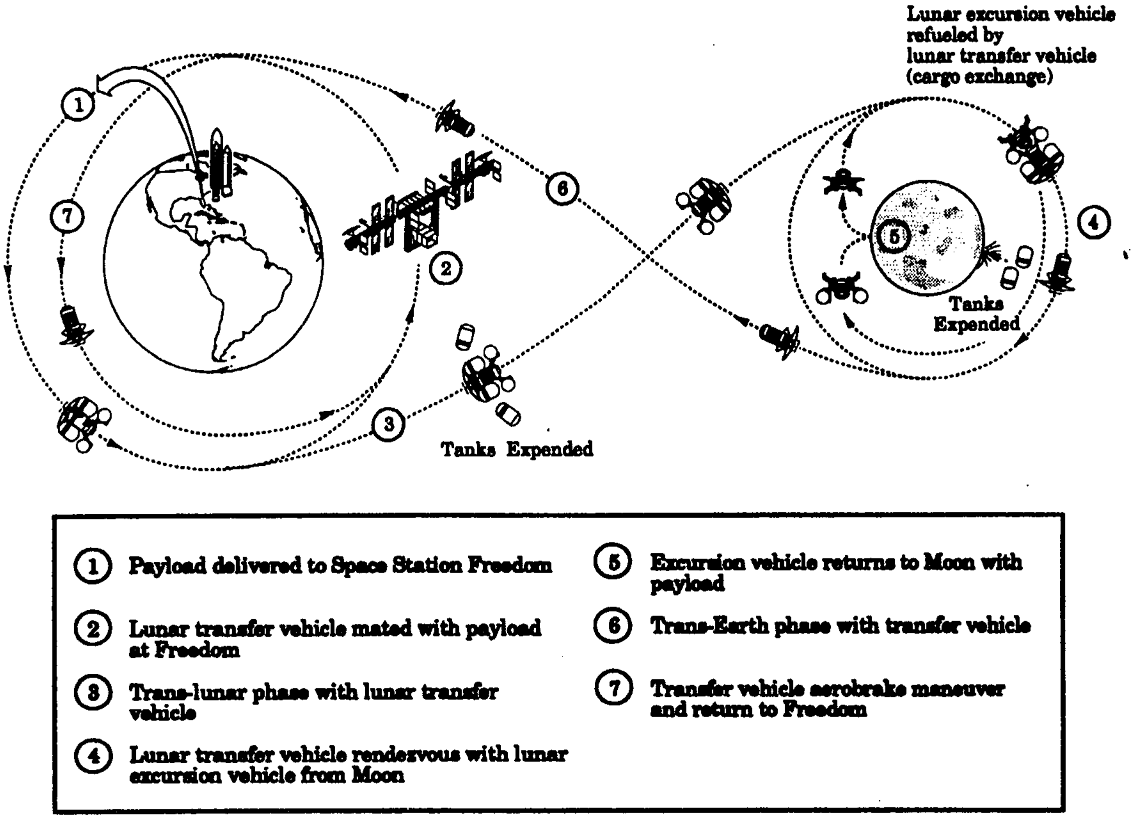


Figure 3-6 Lunar Mission Profile

a crew cab for personnel transfer, and cargo missions use only a cargo pallet. The vehicle for cargo missions can be expended, which increases the payload delivery capability to the lunar surface. For piloted flights, the transfer vehicle employs an Earth-to-Moon trajectory that allows the crew to return safely to Space Station Freedom if necessary.

Emplacement of the lunar outpost begins with an unmanned cargo mission that delivers the first elements to the selected outpost site and is also an extensive flight test of the lunar transportation system, including vehicle assembly, fueling, and integration at Freedom. It is flown as a partially loaded mission, delivering an unpressurized manned/robotic rover and the equipment necessary to prepare the outpost site and off-load payloads from the excursion vehicles. The rover, which will initially be operated telerobotically, will enable the study of subsurface characteristics and aid in determining where the outpost will be located. The second flight to the Moon is also a cargo mission, which will deliver the initial permanent habitation facilities: a habitation module, airlock, power system, and associated support equipment. The module will be telerobotically emplaced on the surface at the prepared location and covered with lunar soil to provide radiation shielding.

The first two cargo missions will be followed by a piloted mission with a crew of four, who stay on the lunar surface for up to 30 days. This crew will check out the habitation module and associated support systems and use the rover to conduct geologic traverses and to emplace scientific instruments, including the first few elements of astronomical telescope arrays. Longer visits will begin after cargo missions deliver additional habitation and laboratory space and facilities to service and maintain excursion vehicles. At this point, the outpost can be operated in a human-tended mode, or permanent occupation of the outpost can begin. The crew will perform experiments to demonstrate in situ resource utilization and will conduct a variety of scientific experiments. When the pressurized laboratory module is emplaced, geochemistry, life sciences, and biomedical research will begin.

The initial lunar outpost will consist of self-contained systems that allow for relatively simple emplacement operations. Later, to expand the capabilities at the outpost, a constructible habitat will be erected to provide additional habitable volume for a larger crew to stay longer and to provide additional space for increased biomedical and life sciences research. The design of the facilities is driven by the desire to simulate the eventual 600-day surface stays anticipated for the Mars outpost, and the constructible lunar module will serve as the prototype for the Mars module. In later years, the outpost can support scientific exploration activities distant from the outpost using a manned pressurized rover for regional access or using the excursion vehicle for expeditions to the farside of the Moon.

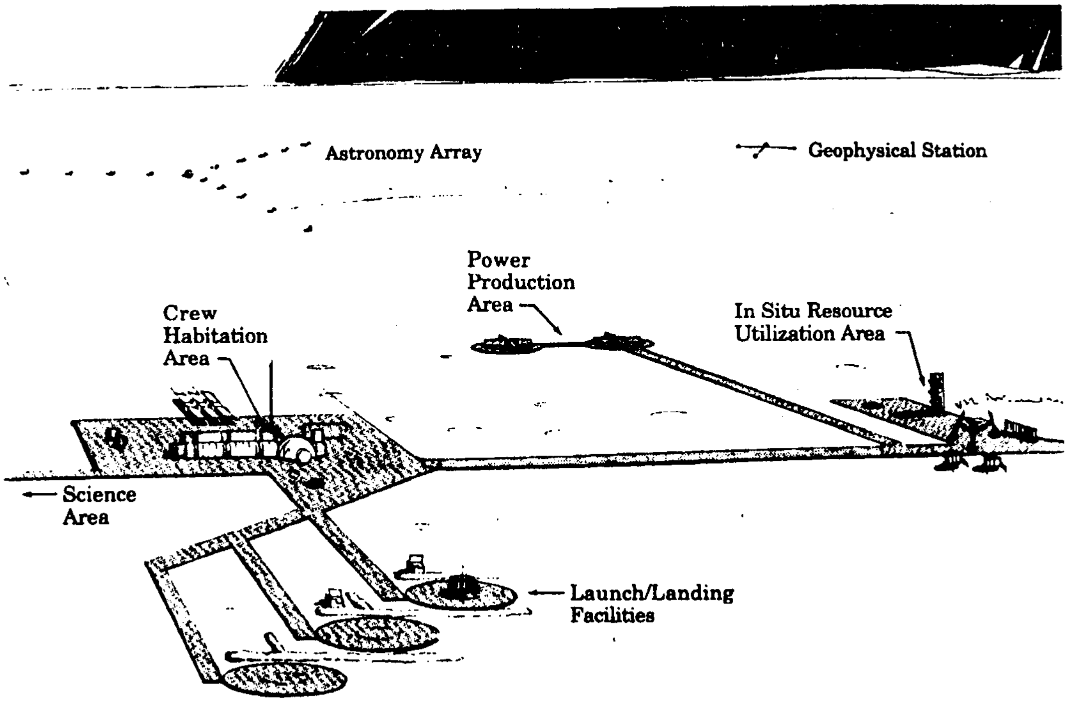


Figure 3-7 Lunar Outpost Architecture

Power capacity at the lunar outpost will be expanded to support increased demands. The increased power capacity at the outpost will be used to begin operational processing of the Moon's resources and to help reduce the outpost's dependence on Earth. For example, oxygen extracted from the lunar soil can help make up losses from the outpost's life support system and could be used as propellants for the excursion vehicles. Nitrogen, hydrogen, and helium could also be extracted from the lunar soil and used at the outpost. Processing resources on the Moon will also develop an experience base for operational techniques for use in Mars resource utilization. In addition, dependency on Earth will be reduced by relying on systems with higher levels of recovery of life support consumables. Figure 3-7 depicts a typical lunar outpost in the operation phase of development.

The size of the lunar vehicles and payload and the amount of material delivered to Space Station Freedom require a heavy-lift launch vehicle with capabilities beyond those of the current fleet of Shuttles and expendable launch vehicles. The launch vehicles must be sized to provide a balance between the degree of assembly and integration required at Freedom and the size of the vehicles. Figure 3-8 depicts two lunar heavy-lift launch vehicle options, one derived from the Shuttle and the other a version of the Advanced Launch System. Both will have

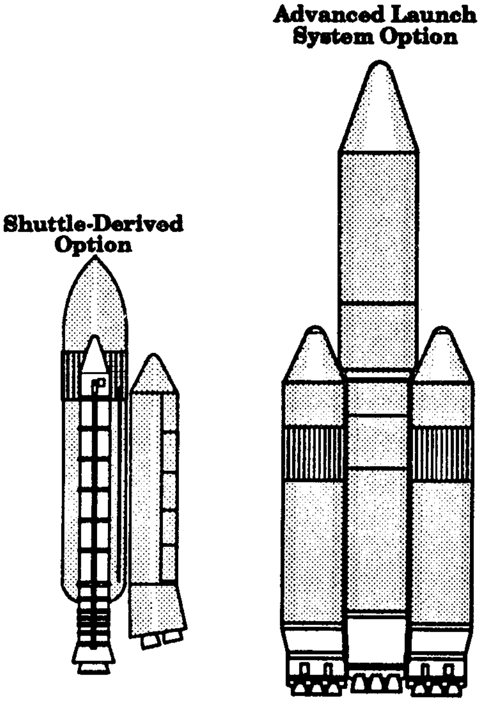


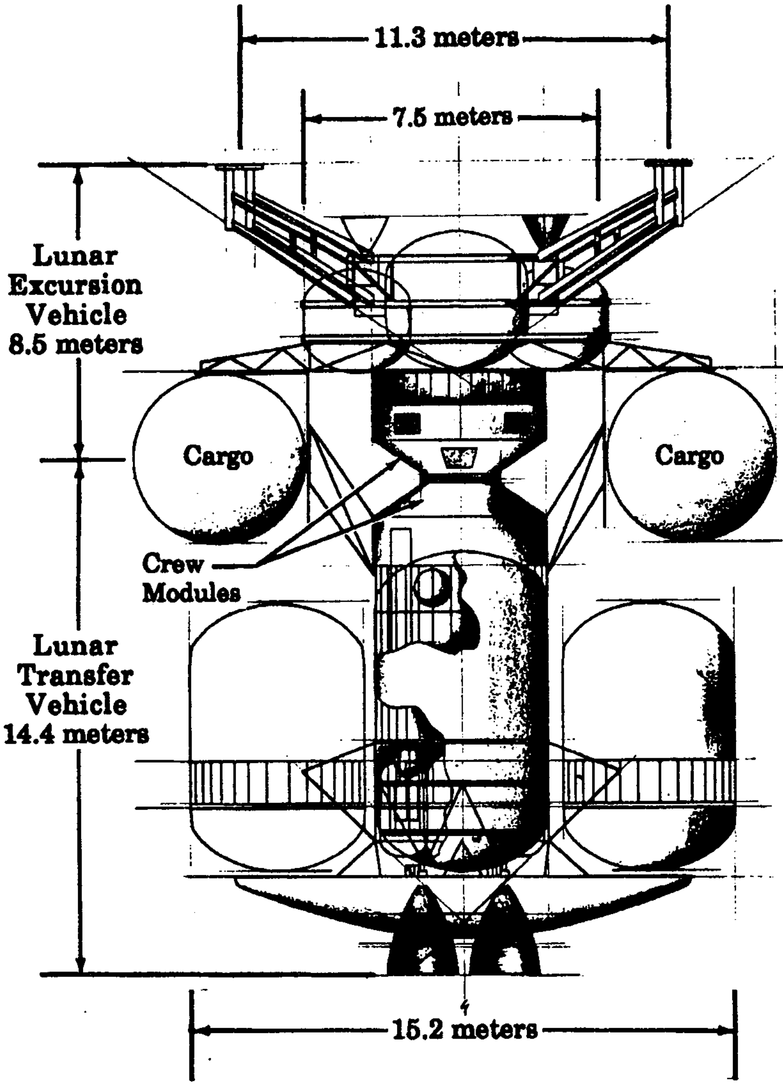
Figure 3-8 Lunar Heavy-Lift Launch Vehicle Options

a payload shroud large enough to allow lunar transfer and excursion vehicles to be launched virtually intact from Earth, but a single launch approach would require an extremely large launch vehicle. Instead, the transfer and excursion vehicles will be launched with the cargo in one flight, and the required propellant will be delivered to Freedom in two additional flights.

The various components are assembled and checked out at Space Station Freedom, which will serve as a transportation node for exploration missions. The planned baseline configuration of Freedom is capable of accepting the evolutionary modifications to support the processing and storage facilities for the lunar vehicles. An additional habitat module will supply the volume to house the vehicle assembly and maintenance crews and the transient lunar mission crews. Additional crew and vehicle processing activities will require additional power and thermal control capability.

The lunar transfer vehicle transports crew and cargo between Space Station Freedom and lunar orbit; the lunar excursion vehicle provides transportation between lunar orbit and the surface of the Moon. The vehicles shown in Figure 3-9 allow mission flexibility by employing a common design for delivery of both cargo and crew. Key mission design criteria are: (1) timing of the launch and return opportunities from Freedom, (2) payload mass delivered to the lunar surface and mass required in low Earth orbit, (3) mission abort/safe-return options, and (4) Earth-to-orbit launch vehicle/payload manifesting. To maximize cargo delivery to the lunar surface, initial flights will expend the lunar transportation vehicles. On subsequent flights, the lunar transportation system will be reused up to five times to reduce vehicle and operational costs.

The lunar transfer vehicle concept is a 1–1/2 stage design consisting of a reusable core and expendable propellant tanks. Using expendable drop-tanks reduces the vehicle's propellant load by approximately 10 percent compared to a single-stage reusable lunar transfer vehicle. The lunar transfer vehicle



Lunar Excursion Vehicle

Inert Mass:
5.8 metric tons
Propellant Load:
22.4 metric tons
Crew Module*:
4.4 Metric tons

Lunar Transfer Vehicle

Propulsion/Avionics Module Core
Inert Mass:
8.1 metric tons
Propellant Load:
7.0 metric tons
Crew Module*:
8.4 metric tons

Drop Tanks
Inert Mass Total:
5.8 metric tons
Propellant Load Total:
129.8 metric tons

*Includes Crew

Figure 3-9 Lunar Transportation System

elements include a core propulsion/avionics module, main expendable propellant tanks, aerobrake, crew module, and other vehicle subsystems.

On initial crew delivery flights, the vehicles will be packaged and launched to Freedom on a single heavy-lift launch vehicle. Packaging includes the fully fueled core propulsion/avionics module, the aerobrake central core and peripheral segments, transfer vehicle crew module, excursion vehicle crew cab, and partially fueled excursion vehicle. At Freedom, the eight peripheral segments of the aerobrake will be attached to the aerobrake central core, and the combination will be checked out for structural integrity. Two additional heavy-lift vehicles will launch four fully loaded expendable main propellant tanks to Freedom for mating to the transfer vehicle. The Space Shuttle will deliver cargo modules and crew to Freedom, where the cargo modules will be added to complete the integrated lunar transportation vehicle. Two propellant tanks will be dropped just after trans-lunar injection, and two will be dropped in low lunar orbit. The transfer vehicle will become a staging base in low lunar orbit for the excursion vehicle and the cargo, and it will also transfer cryogenic propellants and consumables to the excursion vehicle when it is reused.

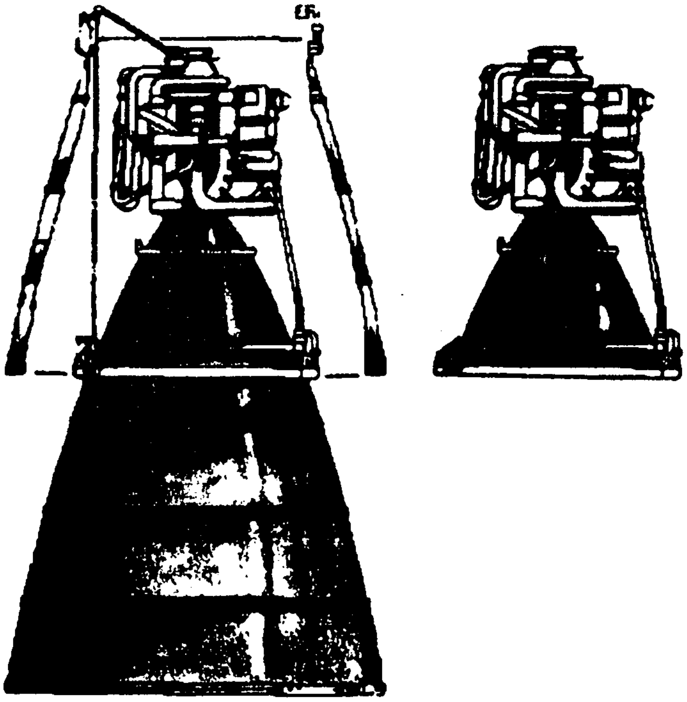
Lunar transfer vehicle engines were selected on the basis of vehicle thrust-to-weight, number of engines, throttle range, and man-rating. The need for man-rating with multiple engines for engine-out capability, the desire for a common engine, and the excursion vehicle touchdown "g" limit with a throttling requirement of less than 20:1 resulted in the selection of four engines at 89 kilonewtons of thrust each (Figure 3-10).

Compared to all-propulsive Earth return, aerobraking significantly reduces the initial mass required in low Earth orbit. The aerobrake is a rigid structure made of composite materials with advanced thermal protection materials used to protect the aerobrake in the maximum heating region. Aerobrake reuse for five missions is assumed. After each mission, the aerobrake will be refurbished and verified at Space Station Freedom.

The lunar transfer vehicle uses an integral cryogenic reaction control system for attitude control and stabilization. Electrical power is provided by solar arrays and batteries or fuel cells. Advanced, man-rated, redundant avionics and communications use hardware and software elements that are common with the excursion vehicle. Multiple communications capabilities between the lunar excursion vehicle, lunar transfer vehicle, Earth, Space Station Freedom, the lunar surface, and communications satellites are provided. An automated rendezvous and docking system is provided for the lunar transfer vehicle.

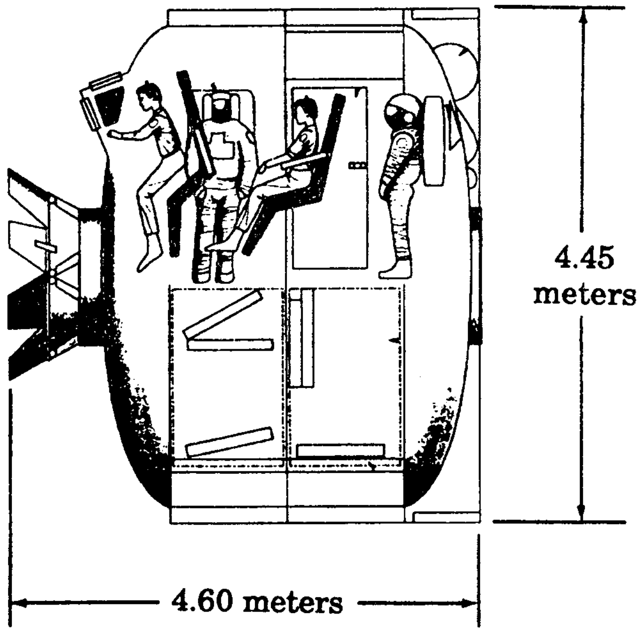
The lunar transfer crew module illustrated in Figure 3-11 attaches to the transfer vehicle and provides habitable support to the crew for 4 days on the trans-lunar segment and up to 7 days for return to Space Station Freedom. With the crew module attached to the transfer vehicle, the crew can override the automated rendezvous and docking system.

The design concept is based on structures and subsystems from Freedom and previous spacecraft. The environmental control and life support system is a Freedom-derived two gas, open loop system. Power comes from the transfer vehicle, and the module has a galley, a zero-gravity toilet, and personnel hygiene provisions. Shuttle-type medical supplies are provided, and two ingress/egress



	Transfer Vehicle	Excursion Vehicle
Thrust, kilonewtons	89	89
Vacuum Isp, seconds	481	465
Vacuum Chamber Pressure, Psia	1,500	1,500
Mixture Ratio	6	6
Throttling Range	Tank Head Idle Pumped Idle Full	Tank Head Idle <20:1

Figure 3-10 Lunar Transfer and Excursion Vehicle Reference Engines



Mass - 8.4 metric tons
Pressurized volume
37 cubic meters

Figure 3-11 Lunar Transfer Crew Module Reference Concept

routes are provided through Shuttle-size hatches. Transfer into the module and between modules is by intravehicular activity. Contingency extravehicular activities are achieved by depressurizing the module rather than by using an airlock. Repressurization gas is supplied for two contingency extravehicular activities. Water-filled solar flare radiation shielding is provided. The water is vented overboard before Earth atmosphere reentry to reduce the aerobrake design loads.

The lunar excursion vehicle shown in Figure 3-12 can be based on the lunar surface, covered by a thermal tent and ready for launch and rendezvous with the lunar transfer vehicle, or it can be stored in low lunar orbit awaiting the return of the lunar transfer vehicle. The lunar excursion vehicle is sized to deliver approximately 33 metric tons to the lunar surface in an expendable cargo-only mode or approximately 13 to 15 metric tons of cargo plus a crew module in a piloted mode. The lunar excursion vehicle elements include a propulsion system, landing legs, crew cab, and other subsystems.

The lunar excursion vehicle and the lunar transfer vehicle share common system designs for some elements, including the main engines, cryogenic reaction control system thrusters, avionics and selected software, and communications. Four advanced fuel cells are provided for electrical power. For low lunar orbit

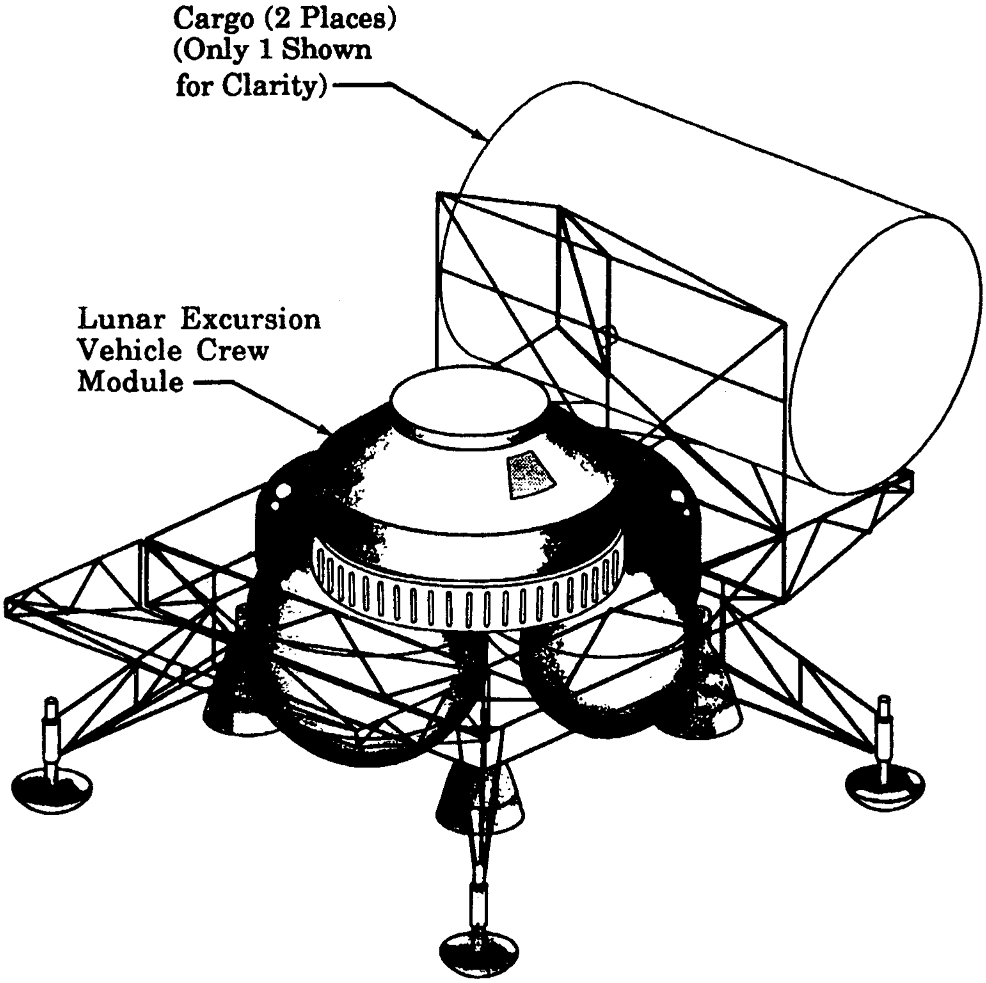


Figure 3-12 Lunar Excursion Vehicle

storage of the lunar excursion vehicle, solar arrays are also required. Lunar excursion vehicle legs and landing pads are provided with height control for landing on unimproved areas.

Automated rendezvous and docking in low lunar orbit are provided for reusable cargo missions, whereas piloted missions provide crew monitoring and control for rendezvous and docking operations. The propellant system is designed for 30 days on the lunar surface, and it will require surface support for longer stays. The capability to utilize lunar-generated oxygen is provided. Hydrogen would still be provided by fluid transfer from the lunar transfer vehicle to the lunar excursion vehicle in low lunar orbit.

The lunar excursion crew module, which shares a common system design with the transfer crew module, has no radiation shielding and accommodates both lunar-gravity and zero-gravity operations. It transports four crew members between the crew transfer module in lunar orbit and the lunar outpost. During landing operations, the lunar excursion crew module provides two crew members with console positions and windows from which to visually monitor all critical landing activities, including forward landing pad touchdown. Systems are quiescent with the exception of 4 days during descent/ascent missions: 2 days during crew descent and initial surface operations and 2 days for preparation and return to low lunar orbit. During quiescent periods on the Moon, power, thermal control, and propellant conditioning are provided by surface support systems.

Transfer between modules and surface systems is initially by extravehicular activity, and later by pressurized transfer using surface-based systems. The lunar excursion crew module has no airlock; therefore, extravehicular activity is supported by depressurizing the module. Repressurization gas is provided for two contingency extravehicular activities. A docking adapter is provided for low lunar orbit docking and crew transfer for incoming and outgoing crews.

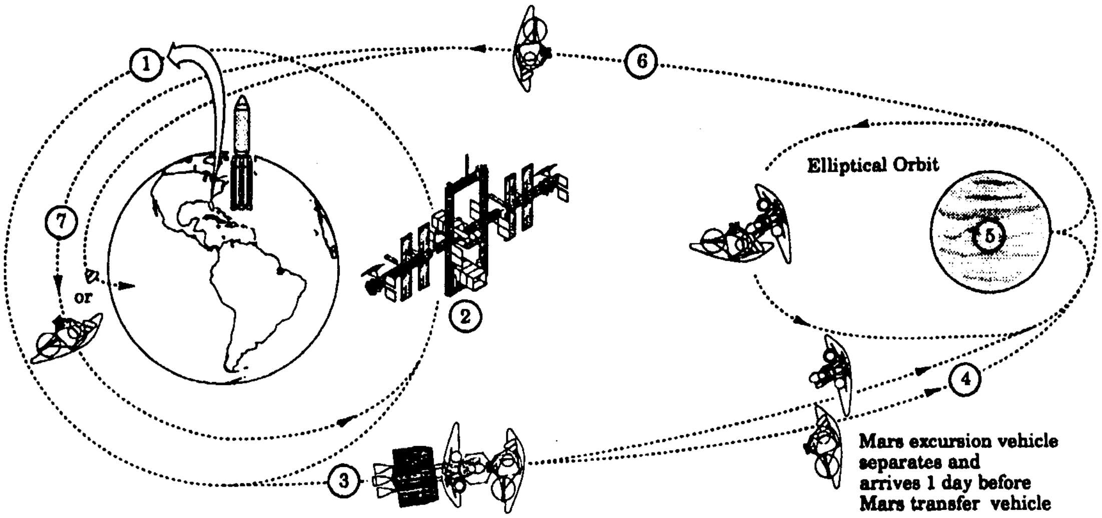
Mars Outpost

The next step in the strategy is the development of a permanent Mars outpost, which begins with the launch of the crew, surface payload, transportation vehicles, and propellant from Earth to Space Station Freedom. The transfer and excursion vehicles are assembled, checked out, and fueled at or in the vicinity of Freedom.

Upon approach to Mars, the transfer and excursion vehicles separate and perform aerobraking maneuvers to enter the martian atmosphere separately. The vehicles rendezvous in Mars orbit, and the crew of four transfers to the excursion vehicle, which descends to the surface using the same aerobrake. When their tour of duty is complete, the crew leaves the surface in the ascent module of the Mars excursion vehicle to rendezvous with the transfer vehicle in Mars orbit. The transfer vehicle leaves Mars orbit and returns the crew to Space Station Freedom.

For cargo flights, an integrated configuration of two excursion vehicles is launched. Upon approach to Mars, the two vehicles separate and enter Mars orbit using aerobrakes. The first cargo flight in the Mars outpost mission sequence delivers the habitat facility to the outpost site, and both excursion vehicles are left on the martian surface.

A typical mission profile is shown in Figure 3-13 for flights to Mars. Piloted flights to Mars employ two different trajectory classes, distinguished by round-trip mission time: 500-day round-trip missions with short stays (up to 100 days) on the surface; and 1000-day round-trip missions with much longer surface stays of approximately 600 days. The 500-day missions will be used for the first flights to Mars, whereas the 1000-day missions will be used later in the sequence for outpost buildup when longer stays are necessary. All trajectories for the Mars outpost have an option available to allow the crew to bypass Mars if necessary. For the piloted flights, a zero-gravity Mars transfer vehicle will serve as the crew's living quarters during interplanetary transit. The feasibility of using zero gravity for such long trip times, and the required countermeasures, will have been previously determined on Freedom and the Moon. If long-term zero gravity is not feasible, an artificial gravity vehicle will be developed instead.



Mars excursion vehicle separates and arrives 1 day before Mars transfer vehicle

① Payload delivered to Space Station Freedom
② Mars transfer vehicle matcd with payload at Freedom
③ Trans-Mars phase with Mars transfer vehicle
④ Mars transfer vehicle remains in Mars orbit; Mars excursion vehicle descends to surface
⑤ Excursion vehicle to/from Mars surface
⑥ Trans-Earth phase with transfer vehicle
⑦ Transfer vehicle aerobrake maneuver and return

Figure 3-13 Mars Mission Profile

All scenarios under consideration begin with an initial four-crew expedition. The surface stay-time for this first flight is limited to approximately 30 days, and the total mission duration is approximately 500 days. During these short stays on the surface, the crew will live in a fully integrated habitation module, similar to that used on the Moon. However, in order to accommodate crew stay times up to 600 days, a constructible habitat facility is erected after delivery on a one-way cargo mission. The crew's early activities include local geologic exploration and characterization of the Mars outpost area and the search for resources, water environments, and past and present life. One concept of the Mars outpost in the consolidation phase is shown in Figure 3-14.

Emplacement of the Mars outpost begins with an initial flight by an expeditionary crew to reconnoiter the selected outpost site. In addition to conducting a final site assessment, the crew conducts local science and exploration investigations, resource evaluations, and resource extraction demonstrations. The crew is provided an unpressurized rover for their local science and exploration trav-

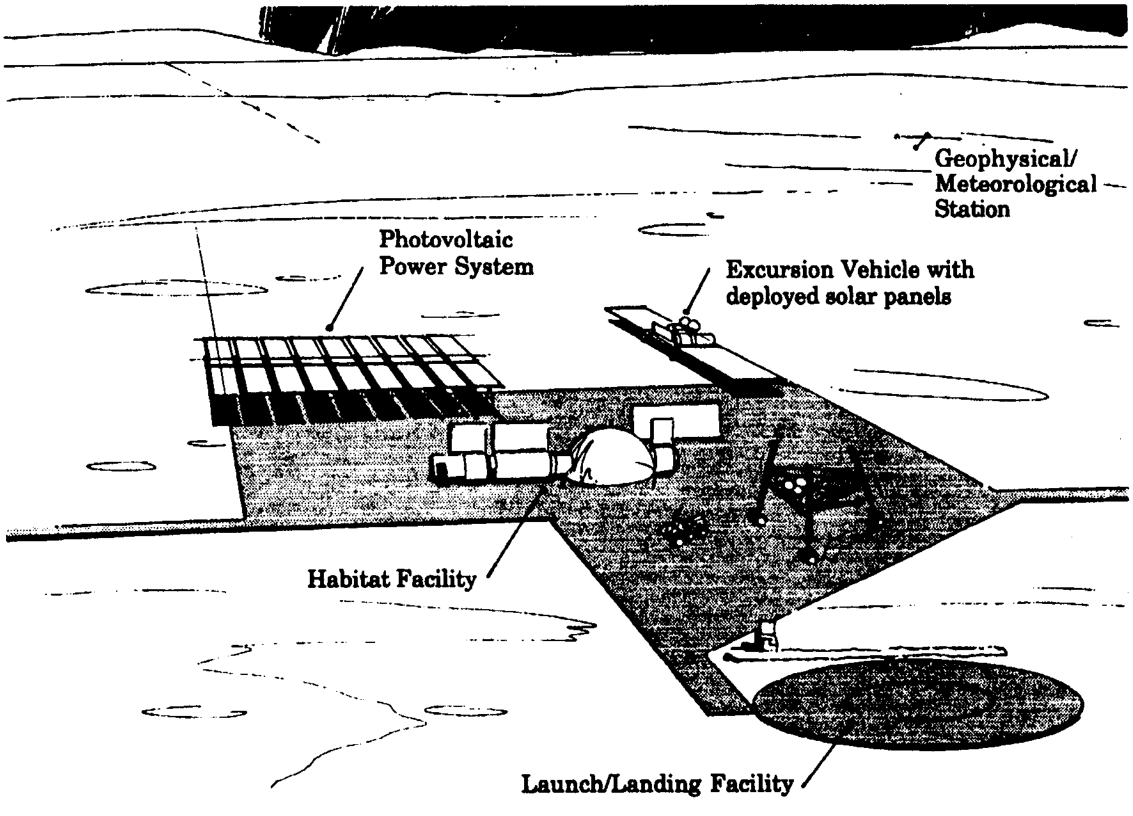


Figure 3-14 Mars Outpost Architecture

erses. During their 30-day surface stay, the crew resides in a separate habitat module delivered as part of the surface payload. The second flight, an unmanned cargo flight, delivers the permanent habitation facility, which includes a habitation module, airlock, power system and associated support equipment. The module is telerobotically deployed at the site prepared by the previous expeditionary crew. These first two missions are followed by a piloted flight that performs the first long-duration stay on the martian surface. This crew checks out the habitation module and associated support systems and uses rovers to conduct geologic traverses and to emplace scientific instruments.

The initial Mars outpost consists of self-contained systems that allow for relatively simple emplacement operations. Later, to expand the capabilities at the outpost, a constructible habitat is erected to provide additional habitable volume for a larger crew to stay longer, and it provides additional space for increased biomedical and life sciences research. In later years, the outpost can support scientific exploration activities distant from the outpost using a manned pressurized rover for regional access.

The large masses required to undertake Mars missions necessitate the development of a larger class of heavy lift launch vehicle, with a capability approximately double that required for lunar missions. The Mars heavy lift vehicle will also require larger payload compartments to accommodate the volume of the Mars exploration systems. Conceptual designs of potential Mars heavy-lift vehicles are shown in Figure 3-15.

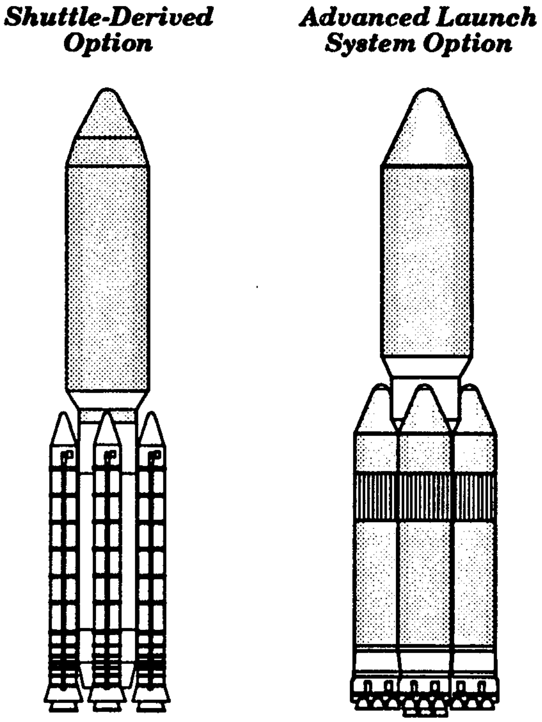


Figure 3-15 Mars Heavy-Lift Launch Vehicle Options

Further modifications and enhancements to the lunar node configuration of Freedom will be required to perform Mars vehicle operations in addition to the continued processing of the lunar transfer vehicle. With the lunar configuration as a baseline, additional structure is added to accommodate the processing facilities for the Mars mission vehicles. The vehicle assembly and maintenance crews and transient mission crews will be housed within the second habitation module added to Freedom in the lunar operations phase. Increased vehicle processing activities will require additional power; however, this increase is within the power generation capability of the Space Station Freedom lunar node configuration.

The Mars transportation system consists of the Mars transfer vehicle and Mars excursion vehicle shown in Figure 3-16. The Mars transportation system must

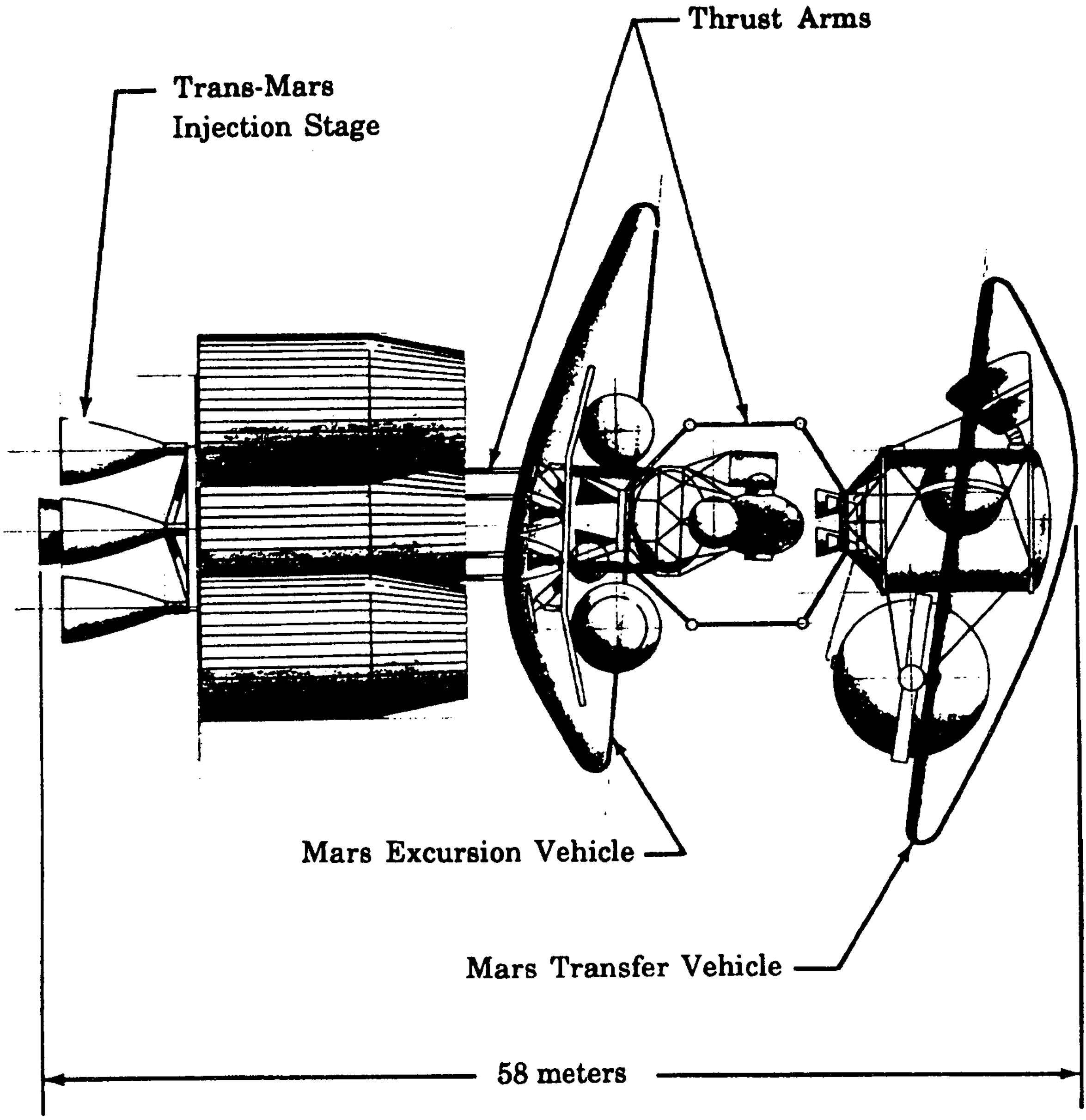


Figure 3-16 Mars Transportation System

support a piloted mission mode to deliver a crew of four and 25 metric tons of payload to the surface of Mars and return the crew and 1 metric ton to Earth, and it must support a cargo mode that delivers 100 metric tons of cargo to Mars using two Mars excursion vehicles. Other key mission design requirements include the zero-gravity Mars transfer vehicle, direct entry capability for Earth return, extravehicular activity capability, accommodation of in-transit science activities, and expendable excursion vehicles.

Major mission maneuvers include trans-Mars injection, Mars capture, Mars descent and landing, ascent and rendezvous, trans-Earth injection, and Earth capture. Mars and Earth capture are accomplished by aerobraking, with the nominal entry velocity constrained to 8.5 kilometers per second at Mars and 12.5 kilometers per second at Earth, although this may be exceeded at Earth during abort trajectories. Aeromaneuvering of the lander provides cross-range landing capability to reach an out-of-plane landing site.

The Mars transfer vehicle consists of a core vehicle and an expendable trans-Mars injection stage. The vehicle is placed on a Mars transfer trajectory by the injection stage, which consists of a core propulsion module with five engines and up to three additional strap-on tanks. The strap-on tanks are the same configuration as the core module tanks. When the injection stage has completed its job, it is jettisoned.

The Mars transfer vehicle carries a crew and the excursion vehicle to Mars and returns a crew to Earth. The transfer vehicle provides long-duration crew accommodations for the transfers from Earth to Mars and back, and it also includes an Earth crew capture vehicle, an Apollo-like capsule designed to return the crew directly to Earth's surface after the early expeditionary Mars missions.

The Mars transfer vehicle has a large aerobrake, which is used for aerocapture at both Earth and Mars during the later flights. The aerobrake provides lift for trajectory control as well as drag to slow the vehicle for capture into orbit. When the aerobrake is also used for Earth return, its heat shield uses an advanced, lightweight material capable of surviving the high-velocity entry into Earth's atmosphere. For trans-Earth injection from Mars orbit, the vehicle includes a propulsion system that uses four engines previously developed for the lunar transfer vehicle. The cryogenic propellant system is designed to minimize boiloff before the trans-Earth injection.

The crew module (Figure 3-17) is a single, pressurized structure 7.6 meters in diameter and 9 meters in length with an internal bulkhead to provide redundant pressure volumes, and a life support system that recycles water and oxygen. The crew is provided private quarters, exercise equipment, and space suits that are appropriate for the long (up to 3 years) mission duration.

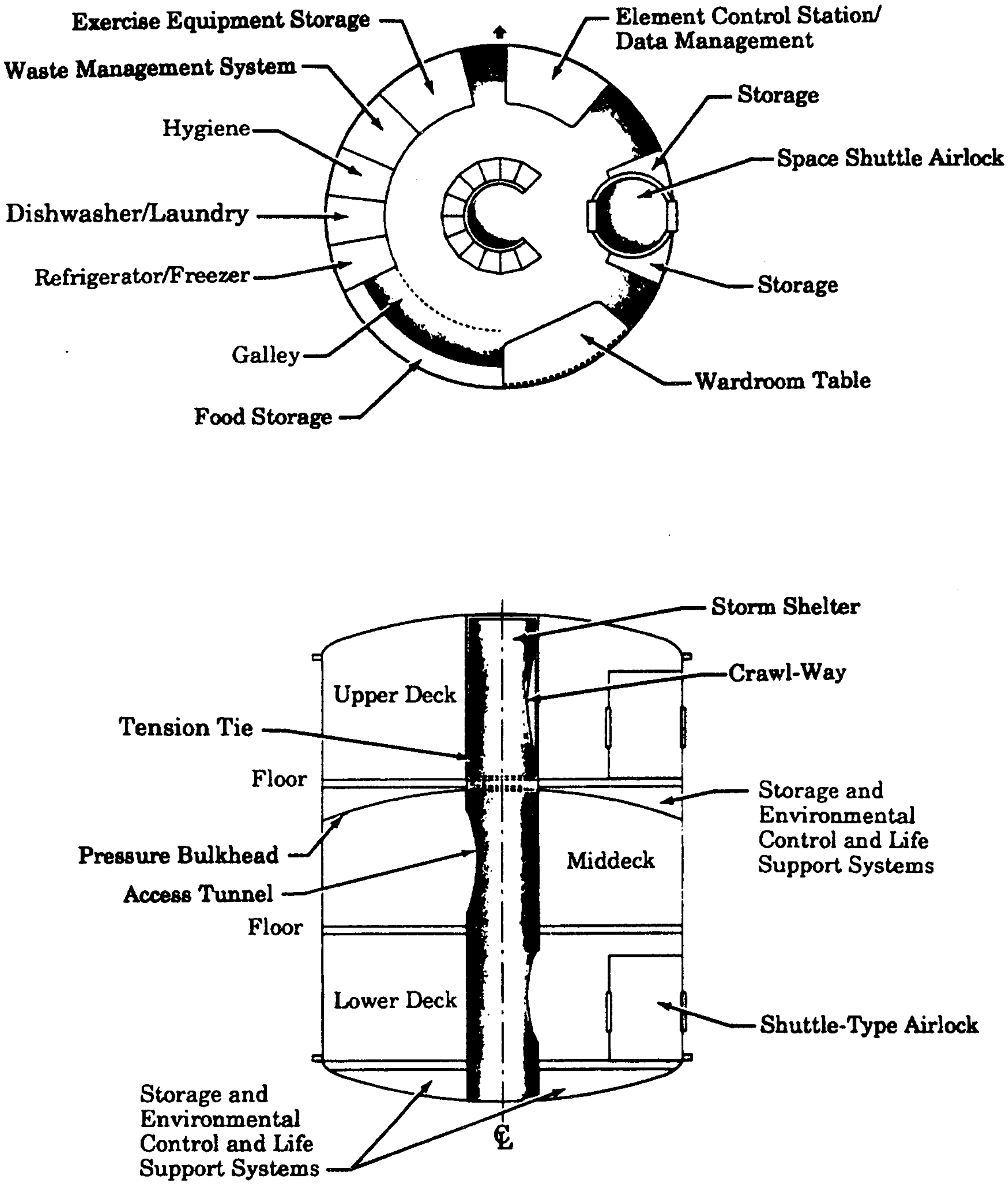


Figure 3-17 Mars Transfer Vehicle Crew Module

The Mars excursion vehicle shown in Figure 3-18 is designed to transport 25 metric tons of payload and the ascent stage from the transfer vehicle to the surface of Mars. For manned missions, the crew pilots the Mars excursion vehicle.

The Mars excursion vehicle crew module, which has a design based on the lunar excursion vehicle crew module, supports the crew during descent and ascent and allows the crew to control Mars excursion vehicle maneuvers. It provides spartan crew accommodations for up to 30 days to cover contingencies in activating a surface habitat. The Mars excursion vehicle design presumes that the crew members, once on the surface, live in and operate out of a surface habitat (delivered as cargo). Consumables provided in the crew module are only sufficient for landing, 2 days on the surface, and ascent. Use of the crew module as a contingency surface habitat presumes that power and consumables can be obtained from the surface payload.

The Mars excursion vehicle aerobrake, which is identical in shape and size to the Mars transfer vehicle aerobrake, provides enough lift to maneuver from Mars parking orbit to a preselected landing site. The heat shield for Mars capture and landing is an advanced thermal protection material. Landing legs are deployed after the aerobrake is dropped. The five Mars excursion vehicle descent engines, like the lunar excursion vehicle engines, provide single engine-out capability and can be throttled to 15 percent of rated thrust to enable a soft

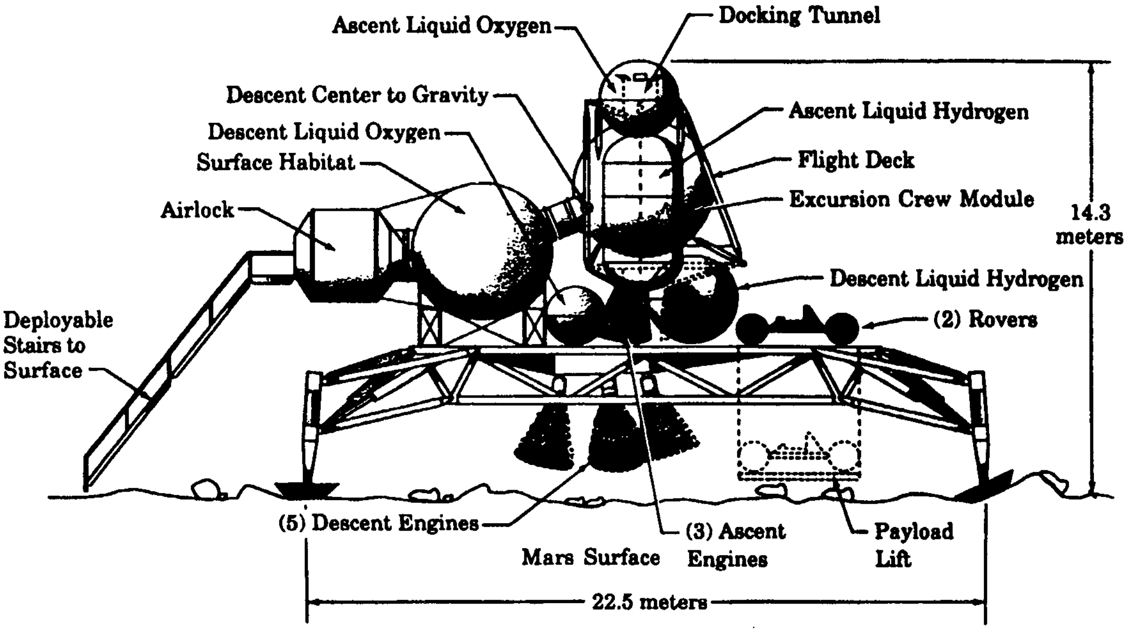


Figure 3-18 Mars Excursion Vehicle

landing of the excursion vehicle. The Mars excursion vehicle ascent stage uses three of the same engines to provide single engine-out capability and has vacuum-jacketed propellant tanks to minimize boiloff losses while the ascent stage is on the Mars surface.

Planetary Surface Systems

Concepts have been identified and defined for lunar and Mars surface habitats, power systems, vehicles, and in situ resource utilization systems that will satisfy the requirements of a focused set of mission objectives. First and foremost, these systems fulfill the overall objective of expanding human presence in the solar system while providing for crew health and safety throughout each mission. The systems that support crew operations on the surfaces of the Moon and Mars include modular and constructible habitats, extravehicular mobility units, airlocks, shirt-sleeve laboratories, rovers, construction equipment, and logistics modules.

The habitat, extravehicular mobility units, and airlock are designed to use the lunar missions as a proving ground for subsystem technologies, system lifetime and reliability, and increasingly autonomous outpost operations. The human systems elements to be used on the Moon and Mars are expected to be essentially the same.

The initial habitat module for both outposts is a horizontal Space Station Freedom-derived cylinder 4.45 meters in diameter and 8.2 meters long. Freedom technology is used for the outer structure of the pressurized modules, and the interior structure uses a modular rack system.

A laboratory module is subsequently attached to the habitat to provide expanded habitable volume. This module is identical to the habitat in size, structure, life support system, and thermal control system. Figure 3-19 shows the connected "Hab/Lab" configuration with partially deployed regolith containers. When filled with lunar soil, the containers will protect the habitat from the lunar radiation environment.

The Freedom-derived initial habitat and laboratory modules use a regenerative life support system that recovers more than 90 percent of the oxygen from carbon dioxide and reclaims potable water from hygiene and waste water. In addition to oxygen and water recovery, this system provides temperature and humidity control, atmosphere and pressure control, stowage for refrigerated and frozen food, trash compaction, and shower, dishwashing, and laundry facilities. The laboratory uses the same life support systems as the habitat.

To accommodate larger crews and longer stays, and to provide larger pressurized volume for outpost and science operations, an expanded habitat is required. This habitat, shown in Figure 3-20, is a constructible 1-meter diameter inflatable structure partially buried in a crater or a prepared hole. This structure is an order of magnitude lighter than multi-module configurations of equivalent volume. Its internal structure includes self-deploying columns that telescope upward and lock into place when the structure is inflated. When fully assembled and outfitted, the constructible habitat provides three levels, and has the volume required for expansion of habitat and science facilities.

Major subsystems of the constructible habitat include the life support and thermal control systems, pressure vessels and internal structure, communications and information management systems, and interior outfitting. Equipment for outfitting the habitat will be delivered in logistics modules, pressurized containers capable of docking to a cargo port on the habitat. The constructible habitat has egress hatch ports for connection to the Hab/Lab, the airlock, and the logistic modules.

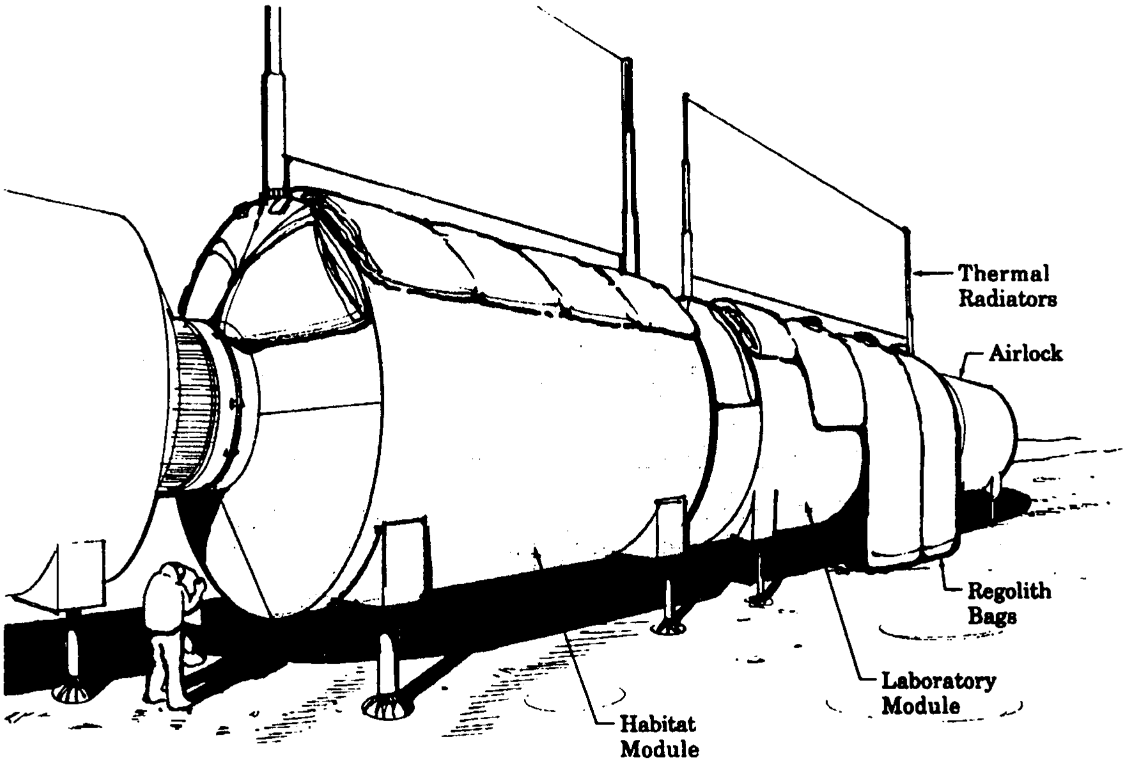


Figure 3-19 Initial Habitat and Laboratory Modules Conceptual Design

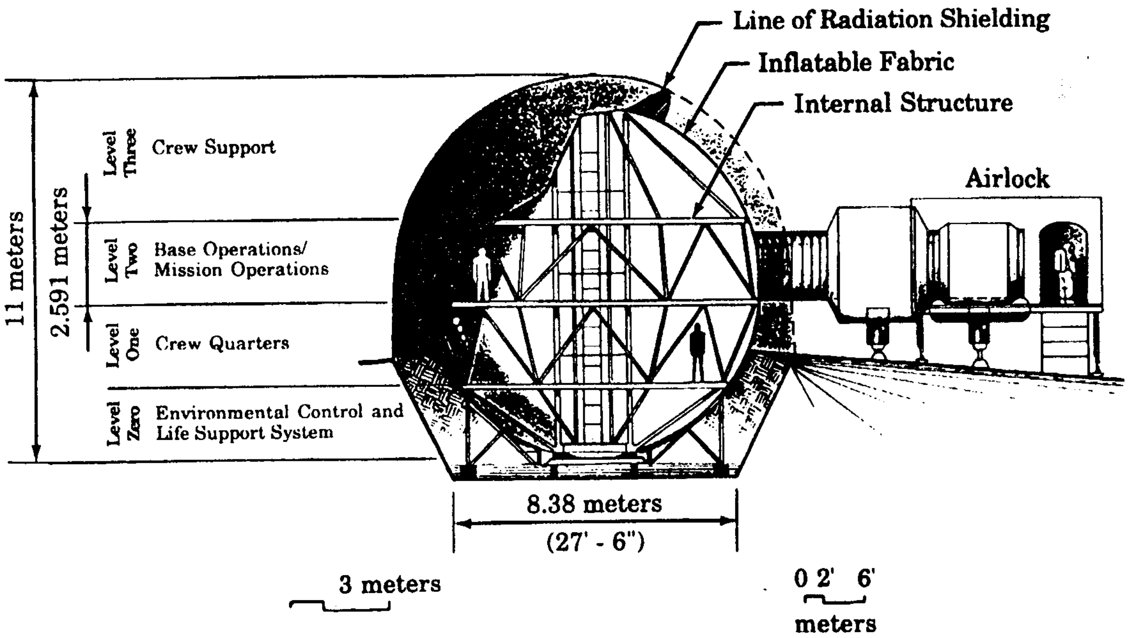


Figure 3-20 Constructible Habitat Concept Design

A thermal coating covers the habitats to reduce thermal loads before the facilities are covered with lunar soil for radiation shielding. An active thermal control system, consisting of a heat pump with lightweight deployable radiators, will remove metabolic, latent, and equipment waste heat.

Extravehicular mobility units for lunar and Mars exploration will be designed for long-term use and maintainability. Units consist of a suit and its portable life support system. The suit is a hybrid structure of both hard and fabric components, designed for mobility on uneven, rugged, partial gravity terrain, and it is modular to facilitate resizing and maintenance of individual parts, and a back-entry design will expedite donning and doffing in a partial gravity environment. To minimize mobility unit mass and size, the portable life support system will use a 4-hour regenerable system that can be quickly recharged or replaced to accommodate work periods longer than 4 hours.

A reliable, long life power system is required to support virtually all surface system activities. The system employs a modular design to meet power demands that evolve from tens of kilowatts in early emplacement phases to hundreds of kilowatts in later operation phases. For initial outpost emplacement, the system consists of three photovoltaic array/regenerative fuel cell assemblies, each of which provides 25 kilowatts during the day and 12.5 kilowatts at night (see Figure 3-21). The power system is designed for telerobotic deployment and is located near the habitat.

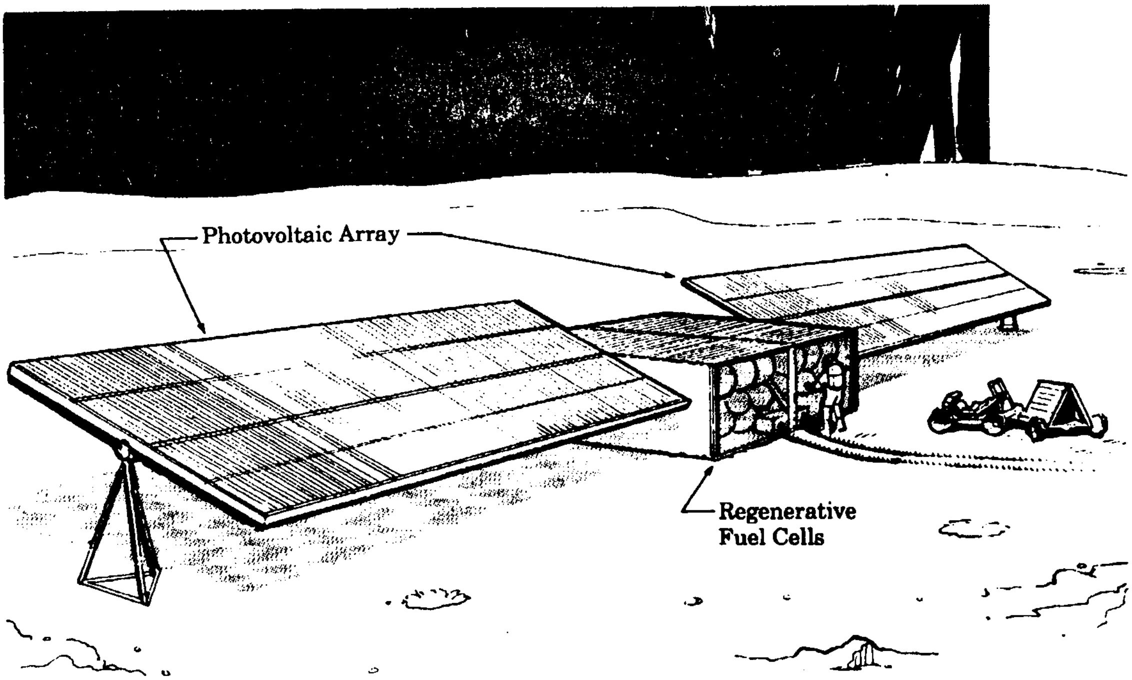


Figure 3-21 Photovoltaic Array / Regenerative Fuel Cell (Stationary) Power System

As outpost development proceeds, power demands rapidly increase. In addition, the 354-hour lunar night makes reliance on photovoltaic systems, which convert light to electricity, impractical for long-term lunar operations because of fuel cell limitations. Nuclear power systems will both meet these increasing demands and allow progress toward increasing operational capability. The SP-100 reactor with dynamic or thermoelectric conversion systems will supply 100 kilowatts of electrical power (see Figure 3-22). As outpost power demands grow still higher, a reactor coupled to a larger dynamic conversion system is emplaced to supply 550 kilowatts for the lunar outpost. This power plant is more extensive than the 100-kilowatt power module, and it will require more assembly and construction. For both systems, the reactors are buried in order to use soil as shielding material.

Expeditions to Mars require 25 kilowatts during both day and night. Photovoltaic array/regenerative fuel cell systems are baselined to supply power to the Hab/Lab modules. The permanent Mars outpost requires 75 kilowatts, which is supplied by three units. The 12-hour martian night does not impact the mass of the regenerative fuel cells as much as the 354-hour lunar night. Therefore, the need for nuclear power on Mars is not as great until large power increases are required.

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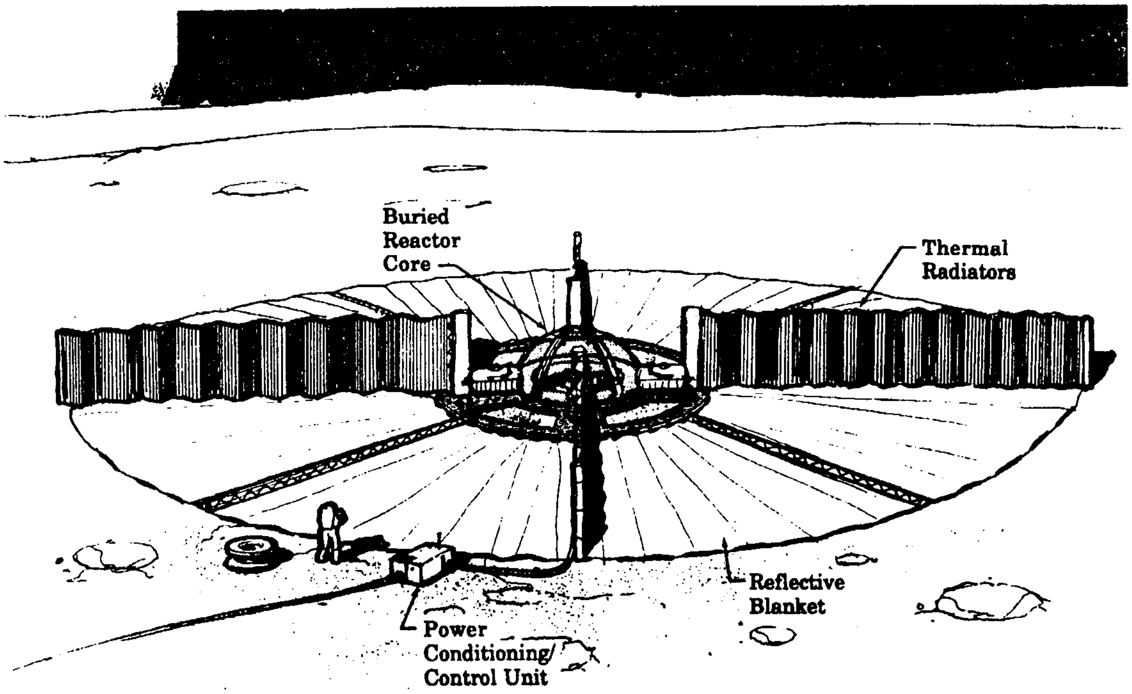


Figure 3-22 Nuclear Dynamic Power System (100 kilowatts)

Offloading cargo, surveying, and setting up the lunar outpost heavily utilize surface rovers remotely controlled from Earth. These rovers require nominal power levels up to 5 kilowatts. Rovers with onboard continuous power systems, such as radioisotope thermoelectric generators or dynamic isotope power systems, could be fully utilized, since they will not need any recharge. Local transport and construction and mining vehicles would use rechargeable energy storage because of their lower energy needs and limited range. Batteries and regenerative fuel cells are options for this application.

The requirement for lunar and martian surface transportation of crew and payloads for outpost operations and for exploration and science missions will be satisfied by an unpressurized rover similar to the Apollo lunar rover, but enhanced in range and payload capability and able to be operated telerobotically.

An unpressurized manned/robotic rover (Figure 3-23) is used to transport both crew and cargo about the outpost, and to perform human exploration and science missions up to 50 kilometers from the outpost. This rover also transports crew members on inspection and maintenance excursions around the habitation and launch and landing areas, the in situ resource utilization production facility,

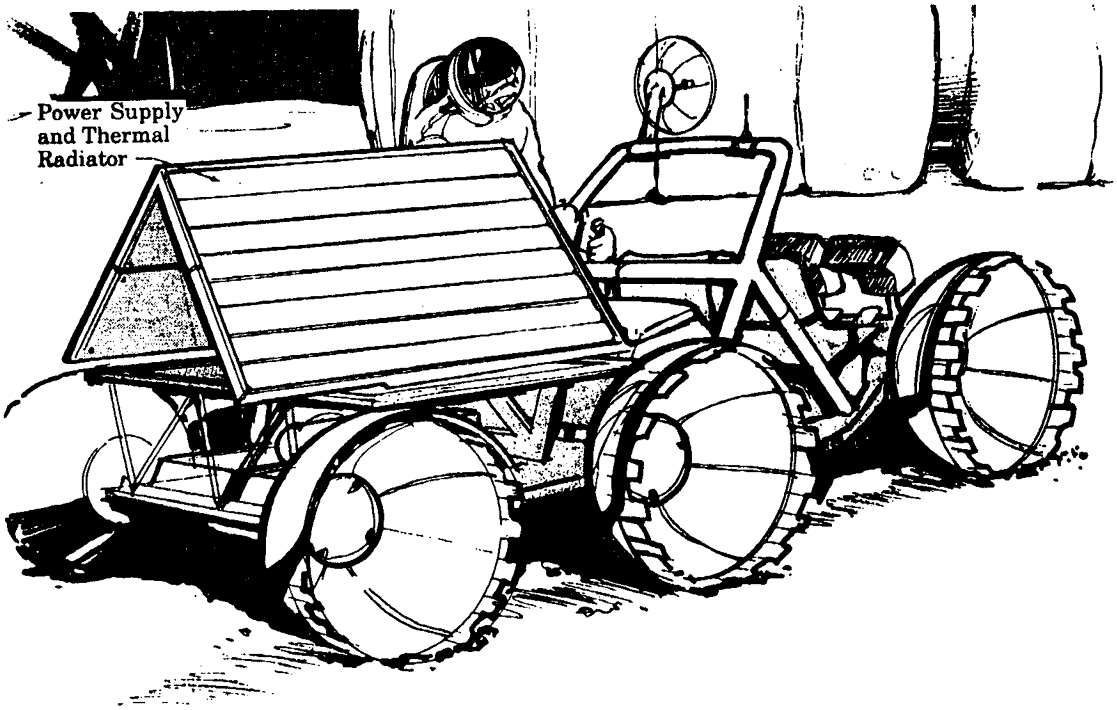


Figure 3-23 Unpressurized Manned/Robotic Rover Design Concept

and the power production facility. The rover will carry either a crew of two and up to 300 kilograms of payload or a crew of four (if rescue from a stranded rover is required). The rover has an onboard extended life support capability for up to 18 hours for each of the two crew members.

For exploration to distances greater than 50 kilometers, the rover will be reconfigured either to be controlled by a telerobot that autonomously navigates the rover and performs science missions, or to be teleoperator-controlled from the outpost. The reconfigured rover will be able to travel to distances of up to 1,000 kilometers from the outpost for 1- to 2-year missions. The emphasis in the design of this rover is to produce a multi-purpose vehicle that can be used both for crew travel around the outpost and for robotic exploration and science far from the outpost.

Cargo will be unloaded from the lunar excursion vehicles by a moveable gantry crane called a payload unloader (illustrated in Figure 3-24). The payload unloader has three telescoping legs to vary overall height or to level the overhead load platform. Each leg is equipped with large diameter powered wheels. Six degrees of freedom of the overhead platform enable alignment of one component, such as an airlock, with a stationary one such as a habitat module. A set of

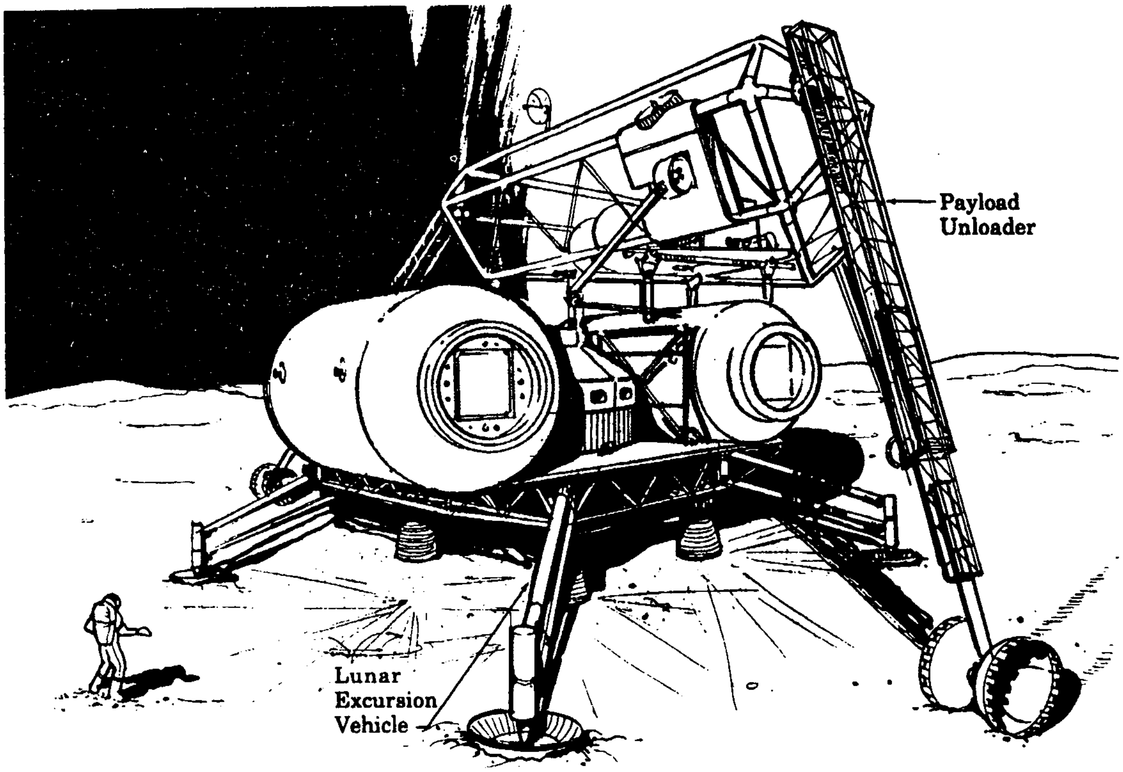


Figure 3-24 Transportation Vehicle Payload Unloader Design Concept (Shown Unloading Elements from a Lunar Excursion Vehicle)

interchangeable "implements" enables the payload unloader to perform construction tasks such as excavating, relocating and smoothing regolith, and grasping and lifting objects such as boulders or structural components. The implement set also includes mining and hauling equipment for lunar soil. The payload unloader is principally teleoperated with on-site supervision by robots or a crew member.

Surface vehicles utilize as many common technologies as possible. For example, wheels are sized appropriately for loads and traction but are based on the same materials and fabrication technologies. Teleoperating systems will be variations of the same basic technology, adapted only for specific operations that are unique to a function. Power generation and storage systems will generally use common technology, also scaled to provide the required power level and duty cycle. Thermal control techniques will be common among all the mobile surface elements. Daytime operation of these elements is likely to require the use of a heat pump for efficient heat rejection.

Using resources that exist on the Moon and Mars is highly desirable if permanent human presence is to be achieved and maintained. By minimizing the propellant resupply needs for lunar operations, the amount of mass to low-Earth orbit, as well as the operations cost of the outpost, can be reduced dramatically. Liquid oxygen production will allow lunar excursion vehicles to be refueled on the Moon for return to lunar orbit. By eliminating the need to transport liquid oxygen from Earth to fuel the excursion vehicles, more intrinsically valuable cargo can be taken to the lunar surface. Figure 3-25 displays a concept for a lunar liquid oxygen production plant. As the lunar outpost evolves, even greater self-sufficiency can be developed by using the co-products of oxygen production to provide metals, structural ceramics, and even some volatile compounds. Early demonstration of oxygen production and extraction of gases will be performed on the Moon.

The Mars outpost will also provide opportunities for resource utilization. The martian atmosphere, consisting largely of carbon dioxide, can be used to provide oxygen for life support and propellant. Water on Mars may be available from the permafrost, hydrated minerals, or moisture in the atmosphere. Small dem-

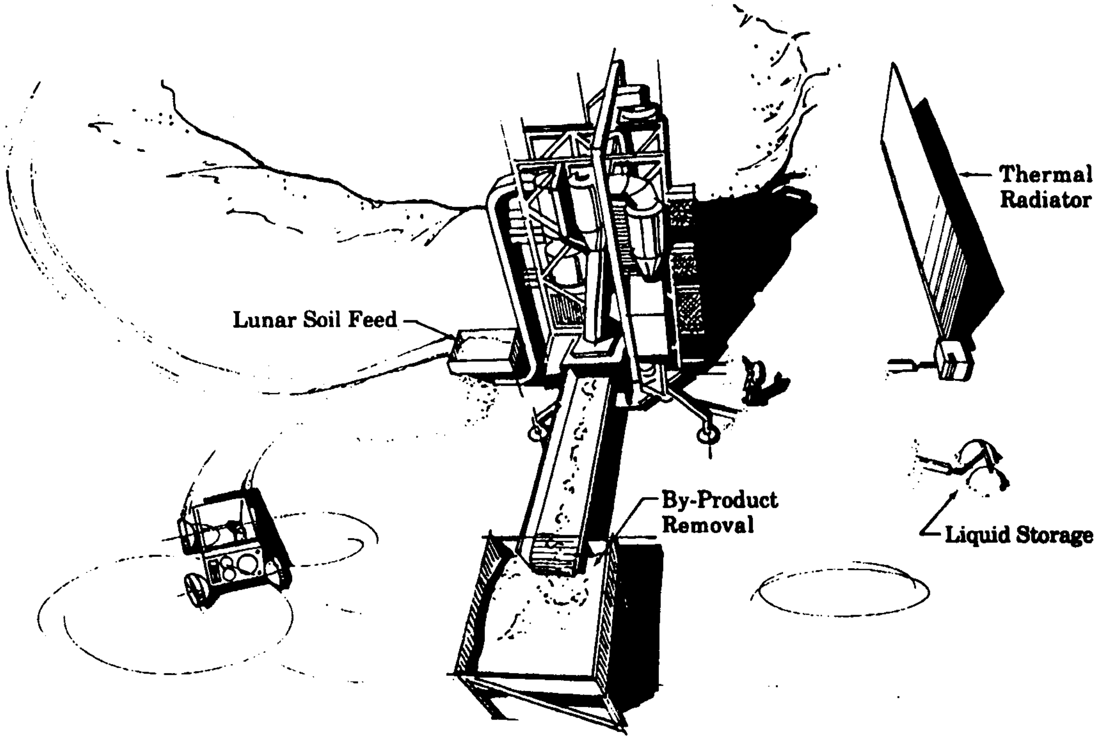


Figure 3-25 Lunar Liquid Oxygen Production Plant Design

onstrations of both water and oxygen extraction technologies are to be completed by the end of the Mars emplacement phase.

Launch and landing support required on the lunar and martian surfaces primarily involves preparation and maintenance of launch and landing sites and servicing and communication facilities to accommodate vehicles during landing, post-landing, quiescent, and pre-launch periods.

Site preparation and maintenance include selecting and leveling a 100-meter diameter launch and landing area and providing for blast protection of any equipment or element already emplaced on the surface. Tracking, navigation, and communications systems are also emplaced near the site.

After landing, the vehicles require servicing to supply power, provide thermal control and protection, actively limit cryogenic fuel boil-off, and monitor subsystems. To accommodate these requirements, a lunar excursion vehicle servicer (as shown in Figure 3-26) located next to each reusable excursion vehicle provides power, thermal control and heat rejection, and fuel reliquefaction capabilities. A thermal tent composed of a deployable support frame and an insulation blanket is used to cover the lander and provide passive thermal shielding.

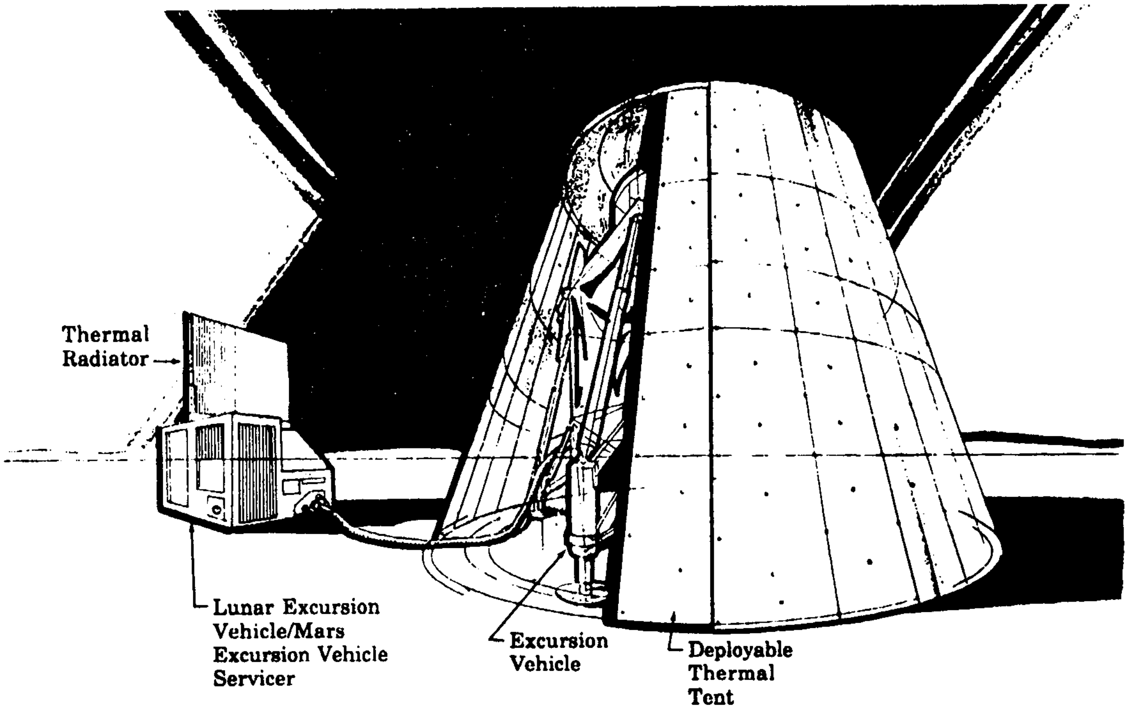


Figure 3-26 Lunar Excursion Vehicle/Mars Excursion Vehicle Servicer and Thermal Tent

Reference Approaches

Section 4

SECTION 4

Reference Approaches

The mission described in the previous section was developed to provide a framework within which various approaches to and elements of the Human Exploration Initiative could be examined. Once the mission itself had been defined, the next step in the study process was to examine a number of reference models to determine which parameters most significantly affect feasibility and cost. For instance, the program could be driven by schedule, as Apollo was, or phased so that a major technology and system development program precedes the actual development of the mission elements. Various elements could be more heavily emphasized; for example, the lunar outpost could focus more on achieving self-sufficiency than on serving as a proving ground for human exploration of Mars. The program could be budget-constrained, or the decision on final dates and associated funding could be varied to meet other policy objectives.

In order to provide the data necessary to make these types of assessments, several reference approaches were selected to determine which parameters drive such things as cost, schedule, complexity, and program risk. In all, five reference approaches were analyzed; these approaches can be used by the Agency and the National Space Council in determining the appropriate scope, scale, schedule, and strategy to be used in implementing the President's program. This information serves as a data base that can be used for the next phase of analysis.

Table 4-1 summarizes the key characteristics and milestones of these five reference approaches. The data provided in this report are intended to capture a broad range of possibilities based on our technical understanding today. Consequently, the reference approaches can be used to develop a variety of implementation approaches by changing key milestones or mission objectives.

Reference Approach A

The strategy around which this approach is formulated is to establish human presence on the Moon in 2001, using the lunar outpost as a learning center to develop the capabilities to move on to Mars. Robust science programs are conducted at both outposts. Key features include an aggressive schedule leading to permanent human occupancy of the Moon in 2002, with lunar development leveling off in 2012 to provide the funding flexibility to begin Mars exploration. An initial expedition to Mars allows a 30-day stay on the surface, with the first 600-day visit beginning in 2018.

Table 4-1 Key Characteristics of Reference Approaches

	Dates				
Milestone	**Reference Approach A**	**Reference Approach B**	**Reference Approach C**	**Reference Approach D**	**Reference Approach E**
Lunar Emplacement	1999-2004	1999-2004	1999-2004	2002-2007	2002-2007
Lunar Consolidation	2004-2009	2004-2007	2004-2008	2007-2012	2008-2013
Lunar Operation	2010→	2005→	2005→	2013→	2014→
Humans on the Moon	2001	2001	2001	2004	2004
Permanent Habitation	2002	2002	2002	2005	—
Constructible Habitat	2005	2006	2007	2008	2011
Eight Crew	2006	2007	2007	2009	—
Lunar Oxygen Use	2010	2005	2005	2013	—
Lunar Farside Sortie	2012	2008	2008	2015	2022
Lunar Steady State Mode	2012	2008	2012	2015	—
Mars Emplacement	2015-2019	2010-2015	2015-2019	2017-2022	2024→
Mars Consolidation	2020-2022	2015-2018	2020-2022	2022→	—
Mars Operation	2022→	2018→	2022→	—	—
Humans on Mars	2016	2011	2016	2018	2016
Extended Mars Stay	2018	2014	2018	2023	2027

An unmanned test flight of the lunar transfer and excursion vehicles in 1999 is the first lunar activity supported by Space Station Freedom. This partially loaded flight delivers an unpressurized manned/robotic rover, which performs final lunar outpost site inspection; the flight also delivers equipment for initial telerobotic site preparation. The lunar transfer vehicle returns to Freedom for engineering evaluation, and is then left in Earth orbit. The first unmanned cargo flight in 2000 emplaces the initial habitation module, airlock, and power system for four crew members who arrive in 2001 for a 30-day mission.

Two more flights emplace additional surface habitation, science equipment, laboratory, and power facilities. A lunar excursion vehicle servicer is provided to maintain a reusable vehicle on the lunar surface. (All flights to this point have operated the transfer and excursion vehicles in the expendable mode.) In early 2002, the second crew begins permanent occupancy of the lunar outpost with a 6-month stay. Beginning in mid-2002, when the third crew arrives, reusable lunar excursion vehicle operations are initiated, and the excursion vehicle is maintained at the outpost. Twelve-month crew tours of duty begin at this time. The initial nuclear power unit and the lunar oxygen production demonstration hardware are added in 2003.

Operations and science exploration are limited to a range of up to tens of kilometers from the outpost. Human exploration focuses on local geologic and geophysical exploration, with regional exploration accomplished telerobotically. The first elements of astronomy telescope arrays are deployed, and a network of geophysical and particle physics stations is started. Lunar laboratory activities include human biomedical research and geochemical sample analysis. Later, the science program is expanded, as telescopes are added to astronomy arrays, stations are added to the physics networks, and life sciences experiments expand into the larger laboratory facilities. Human and robotic geologic exploration continues.

Outpost capabilities increase as the constructible habitation module is erected, outfitted, and occupied in 2005. Two lunar excursion vehicles, one cargo and one piloted, are simultaneously maintained on the lunar surface.

In 2006, the number of crew members expands to eight, consisting of two groups of four who serve rotating 12-month tours of duty. At this point, the outpost is capable of conducting a long-duration partial-gravity test in support of Mars mission planning. In 2008, the surface nuclear power capability is augmented substantially to 550 kilowatts. Operations expand to a range of hundreds of kilometers from the outpost. Life sciences research is undertaken to determine the gravity level and rotation rate for Mars transfer vehicles if other than zero gravity is needed. A complete 1,000-day Mars mission is simulated using the outpost and Freedom to develop countermeasures.

In 2010, the lunar oxygen plant is emplaced and operated to produce 60 metric tons of oxygen per year, which saves transporting this oxygen from Earth. The lunar outpost continues to operate with a crew of eight until 2012, when the outpost enters a sustained steady-state period with one lunar flight per year and four crew members serving 12-month tours. Nearside astronomy arrays and geophysical and physics networks are completed. Teleoperated and human local and regional exploration continues on the nearside, and sites of scientific interest are revisited. A two-man sortie is made from low lunar orbit to the lunar farside to conduct geologic exploration and emplace a human-tended radio astronomy and geophysical network. At this point, the focus shifts to Mars.

The human exploration of Mars begins with an initial expeditionary piloted flight, a dedicated cargo flight, and a second piloted flight to begin extended-duration operations. The Mars transfer and excursion vehicles are assembled at Freedom. Full propellant tanks are launched separately and assembled to the vehicles at Freedom. The first piloted Mars expedition departs Space Station Freedom in 2015. Four crew members arrive at Mars in 2016, aerobrake into Mars orbit, and descend to the surface for a 30-day stay. Part of the payload delivered to the surface is a habitat module with an airlock and utility systems to support the crew during their stay. The crew members conduct local science and exploration within a 10-kilometer range of the outpost using unpressurized rovers. Teleoperated rovers explore and sample to distances of 50 kilometers, and provide regional geologic information and resource locations. Exploration focuses on studying past and present geologic and climatic environments, including the search for past and present life and water environments. The human explorers are studied to understand the effects of living and working on Mars. The Mars transfer vehicle is expendable for the first mission, and the transfer vehicle aerobrake is jettisoned in Mars orbit. The excursion vehicle is left at Mars. The crew returns to the vicinity of Earth in the transfer vehicle (without aerobrake) transferring to a separately carried Earth crew capture vehicle just prior to arrival at Earth orbit in 2016. The Earth crew capture vehicle makes a direct entry to Earth's surface.

The permanent habitation facility and its associated airlock and utility subsystems and the necessary emplacement and construction equipment to deploy it are delivered to Mars on the second flight, a cargo flight that departs Earth in 2017 and arrives at Mars in 2018. Other payload delivered includes an additional rover and a vehicle launch and landing facility capable of supporting the excursion vehicle for up to 600 days.

The second piloted flight leaves Earth and arrives at Mars in 2018. The four crew members live in the initial habitat module while they construct and activate the permanent habitation facility delivered on the previous cargo flight. When the permanent habitat has been activated and occupied, the crew can remain on the surface for 600 days. An early task is the demonstration of a Mars water extraction process.

The crew members develop and demonstrate the capability for extended Mars stays, operate the surface resource water extraction demonstration unit, and perform regional science and exploration activities within tens of kilometers of the outpost. Observational networks expand to monitor geophysical properties, climatic and atmospheric variations, and dust storms. Laboratory sciences activities include plant and animal research, and geochemistry and human biomedical and performance studies are enhanced. The crew from the second manned flight leaves Mars and arrives at Earth in 2020. The next manned flight departs Earth and arrives at Mars in 2020. During their 600-day stay, the four crew members continue the water extraction demonstration, the oxygen production experiments and more detailed geologic and geophysical exploration and evaluation of resources.

In 2022, a one-way cargo flight departs Earth, arriving at Mars in 2023. This flight transports additional consumables, spares, and science equipment to support the next piloted flight, which departs Earth in 2024 and arrives at Mars in 2025. Steady-state operations then commence.

To support this schedule, the Space Station Freedom "assembly complete" date must be accelerated to 1997, which will require a heavy-lift launch vehicle. Shuttle-C is the only concept being considered in this time frame. By 1999, Freedom's capability will have been augmented to support the first test flight of the lunar vehicles, which will involve space transportation vehicle assembly, integration, checkout, launch, post-flight recovery, and inspection. Freedom must support two expendable lunar missions per year through 2002, at which time it must be capable of supporting reusable vehicle operations at the same rate. Beginning in 2004, Freedom must support up to three lunar missions per year.

To support Space Station Freedom augmentation and initial growth and the launch of the lunar transportation vehicles, propellant, and cargo, a heavy-lift launch vehicle with two different size payload shrouds will be used. Employing the smaller shroud, the vehicle can deliver approximately 70 metric tons of payload to low Earth orbit. With the larger shroud, the vehicle can deliver approximately 60 metric tons to low Earth orbit. The smaller shroud configuration will be required in 1996, and between 1997 and 1999 it will be used to launch Freedom augmentation hardware to support readiness for the lunar transfer and excursion vehicle test flight in 1999. The larger shroud vehicle must be ready in 1999 to launch the lunar vehicles for the initial test flight, and for subsequent flights. The smaller vehicle will be used to transport to Space Station Freedom the filled cryogenic propellant tanks for the transfer vehicle for all lunar flights.

Beginning in 2011, the smaller heavy-lift vehicle configuration will be used to augment the Space Station Freedom lunar mission configuration to support a test flight of the Mars aerobrake in 2013, and again to support the initiation of human Mars missions in 2015. Freedom support for the Mars flights includes significant vehicle assembly, integration, checkout, launch, and recovery upon Earth return. The Mars transportation vehicle elements will be launched to Freedom beginning in 2014 for the Mars vehicle piloted flight in 2015, using a larger heavy-lift launch vehicle with a 12.5 meter diameter by 30 meter long payload shroud, which is capable of lifting 140 metric tons to Freedom. This vehicle will launch all subsequent Mars transportation vehicles.

The telecommunications network must support lunar data return in 2001 and the Mars data link to Earth. The telecommunications satellite in lunar halo orbit will be deployed in 2009 to support farside lunar communications. In addition, two Mars telecommunications satellites will be established in Mars orbit in 2014 to provide a high-percentage-time communications access between Earth and the Mars outpost.

Reference Approach B

This approach is a variation of reference approach A, which advances the date of the first human Mars landing to 2011. In order to preserve funding flexibility to initiate activities at Mars, it is also necessary to accelerate development of the capability for lunar oxygen production, leading to the need for very early emplacement of a nuclear power system on the Moon. This approach limits the degree to which lunar outpost operational experience can influence the design of the Mars transportation and surface systems. As a result, the development of lunar and Mars outpost hardware becomes a more parallel than sequential set of activities. Accelerating these key events also imposes early technology requirements.

The need to conduct the Mars outpost development activities in parallel with heavy lunar activity also results in a higher resource requirement in the first decade of the next century. In order to support the parallel set of lunar and Mars activities with minimum resources, other lunar infrastructure, such as the constructible habitat, is somewhat delayed, and lunar operations level off much earlier to a steady-state mode involving four crew members and one lunar flight per year. This also results in delayed lunar science activity, although Mars science activities commence 5 years earlier.

Reference Approach C

This approach is also a variation of reference approach A. The key emphasis is that this approach advances to 2005 the date by which lunar oxygen production is available to reduce lunar outpost logistics requirements, creating an earlier opportunity for Mars outpost development. As with reference approach B, early lunar oxygen production requires very early emplacement on the Moon of surface nuclear dynamic power system capability. Although this approach accelerates lunar activity, the milestones for Mars outpost development do not change. Therefore, this approach focuses on early in situ resource development on the Moon.

The early emplacement of the lunar oxygen plant delays the emplacement of other infrastructure, such as the constructible habitat, and also postpones the date for the transition to a crew of eight. The transition of the lunar outpost to a steady-state mode of four crew members and one lunar flight per year can be slightly accelerated, but a significant period is preserved in which the eight crew members are available for performing lunar science activities.

The relationship between lunar and Mars outpost hardware development remains a serial one, in which designs of Mars outpost transportation vehicles and surface elements are significantly influenced by lunar outpost operational experience.

The accelerated schedule for nuclear power and lunar oxygen production on the Moon also requires early technology development in these areas and may exclude the incorporation of beneficial technologies that would be available under less aggressive program schedules. The increased early costs imposed by this accelerated schedule are offset in later years by earlier reduction in lunar outpost operating costs and by the earlier leveling of lunar outpost activities to a steady-state mode.

Reference Approach D

The scale and content of this approach are identical to those of reference approach A. The sequencing and phasing relationships between key program milestones remain approximately the same, but the milestones are all delayed by 2 to 3 years, with a return to the Moon in 2004. This approach does not accelerate the "assembly complete" date of Space Station Freedom, and generally allows more time to complete and incorporate beneficial technology developments.

Reference Approach E

This approach reduces the scale of lunar outpost activity by using only a human-tended mode of operation and limiting the flight rate to the Moon to one mission per year. It also increases the number of expeditionary flights to Mars prior to establishing a permanent outpost there. Initial lunar operations are consistent with the currently planned Space Station Freedom "assembly complete" date of 1999. In 2004, the first humans return to the Moon. Occupation of the lunar outpost facilities is on a continuing man-tended operations basis involving one lunar flight per year, with crew tours of duty ranging from 30 days to 6 months, and with the outpost unmanned for periods up to 12 months. (One exception would be one or more 600-day stays to simulate stays on Mars.) In 2011, lunar oxygen production is accomplished, but only in small demonstration quantities. The first humans land on Mars in 2016. Three Mars expeditionary missions of increasing surface stay time up to 90 days precede the establishment in 2027 of a permanent Mars outpost with 600-day occupancy.

An unpiloted test flight of the lunar transfer and excursion vehicles in 2002 is the first lunar activity supported by Space Station Freedom. This mission includes the landing of an unpressurized manned/robotic rover to perform final outpost site inspection and the delivery of equipment for initial telerobotic site preparation. The lunar transfer and excursion vehicles are returned to Freedom for engineering evaluation, and are then expended. The first cargo flight in 2003 emplaces the initial habitation module, airlock, and supporting utility systems, including either a 100-kilowatt nuclear power system or four 25-kilowatt photovoltaic array/regenerative fuel cell systems. These facilities are activated and occupied in 2004 when the first crew of four arrives for a 30-day mission.

The transportation vehicles are expended in the cargo mode to maximize payload to the lunar surface, but they are reused in the piloted mode. The lunar outpost has significant automation and telerobotic capability to conduct activities during unoccupied periods. Much science activity relies on robotic capabilities during both occupied and unoccupied periods. When the lunar outpost is not occupied, the lunar transfer vehicle is maintained at Freedom, and the excursion vehicle is maintained in a quiescent mode in low lunar orbit. Both vehicles carry photovoltaic power arrays to support extended time in lunar orbit.

The second piloted flight arrives at the lunar outpost in 2005, also for a 30-day stay. A cargo flight in 2006 provides a laboratory module and an additional airlock. A third piloted flight in 2007 includes occupancy of the outpost for 90 days and delivery of a lunar excursion vehicle servicer to the outpost. The servicer is necessary to maintain the excursion vehicle on the lunar surface for periods exceeding 30 days. At this time, operations using the unpressurized manned/robotic rovers take place within a range of tens of kilometers.

Science activities focus on teleoperated geologic and geophysical exploration with limited local traverses by the crew. The first elements of astronomy telescope arrays are emplaced, and a network of geophysical and particle physics stations is started. Lunar laboratory activities include limited human biomedical research and basic geochemical sample analysis. The lunar science program later expands, as telescopes are added to the astronomy arrays, and stations are added to the geophysics and particle physics networks. Laboratory sciences activities expand to include the study of human performance and the analysis of lunar rocks and soil.

Piloted 90-day missions in 2008 and 2009 continue to develop operational experience and conduct lunar science activities. An extended range (500 kilometers) manned pressurized rover for regional geologic and geophysical exploration is delivered on the 2009 mission.

Outpost capabilities are significantly expanded by the delivery on a cargo flight in 2010 of a constructible habitat and its associated utility systems and outfitting provisions. A piloted flight arriving in 2011 for a 180-day stay constructs, outfits, and occupies this larger habitat. The 2011 mission also delivers initial experimental equipment for demonstrating the laboratory-scale production of oxygen from lunar soil. This completes the buildup of the lunar outpost infrastructure.

The crew arriving in 2012 occupies the outpost for 6 months. In 2013, a piloted flight arrives for a 600-day stay to simulate the upcoming extended occupancy of Mars. This crew of four is resupplied by an unpiloted lunar excursion vehicle in 2014. Surface operations take place within hundreds of kilometers of the outpost.

To expand lunar science activities, a piloted flight in 2022 visits a farside site to conduct geologic exploration and emplace a radio astronomy and geophysical observatory. This mission does not visit the outpost.

Human exploration of Mars begins in 2015 when the first piloted mission departs Space Station Freedom. The crew of four arrives in 2016, aerobrakes into Mars orbit, and descends to the surface for a nominal 30-day stay. A separate telerobotic rover package descends from the Mars transfer vehicle to the next planned expeditionary site. Part of the payload delivered to the surface is a separate habitat module including airlock and utility systems to support the crew during their stay. The crew will conduct local science and exploration investigations within a 10 kilometer range using a manned unpressurized rover. The Mars transfer vehicle aerobrake will be jettisoned in Mars orbit. The Mars excursion vehicle will be expended at Mars. The crew will return to the vicinity of Earth in the transfer vehicle (without aerobrake) entering a separately carried Earth crew capture vehicle just prior to arrival at Earth in 2016. The Earth crew capture vehicle will make a direct entry to Earth's surface.

The second Mars expeditionary flight departs Earth in 2017, arriving at Mars in 2018 for a 60-day stay. The third expeditionary flight departs Earth in 2021, arriving at Mars in 2022 for a 90-day stay and returning to Earth in 2023.

Each expeditionary flight visits a different site and conducts detailed site assessment, resource evaluation, resource extraction demonstration (water and oxygen), and science activities. The data obtained provide the basis for selecting the permanent Mars outpost site. Science activities are similar for each site and include studies of the geology, climate, and resources and a search for past and present water environments and life. Human performance and biomedicine are also examined.

A one-way cargo flight departs Earth in 2024, arriving at Mars in 2025 with the permanent constructible habitat, its associated airlock and utility subsystems, and the necessary emplacement and construction equipment to deploy it. This habitat is capable of supporting a crew of four for 600 days. Other payload delivered includes an additional rover and a vehicle launch and landing facility capable of supporting the Mars excursion vehicle for up to 600 days.

A piloted flight departs Earth in 2026 and arrives at Mars in 2027, where the crew constructs, activates, and occupies the permanent habitat. The crew remains at Mars for 600 days. The emplacement phase continues beyond 2027 as additional flights are made to the outpost. Although this study extends only to 2025, it is assumed that consolidation and operation of the Mars outpost will follow.

In order to support the buildup of Space Station Freedom and the launch of the lunar transportation vehicles, propellant, and cargo, a heavy-lift launch vehicle with two different size payload shrouds will be used. Between 2000 and 2002, the vehicle with the smaller shroud will be used to launch augmentation hardware to Space Station Freedom to provide readiness for the test flight of the lunar transfer and excursion vehicles in 2002. The vehicle with the larger shroud must be ready to launch the lunar transfer and excursion vehicles on that initial test flight in 2002, and for subsequent flights. The smaller shroud vehicle will be used to launch to Space Station Freedom the filled cryogenic propellant tanks for the transfer vehicle for all lunar flights. Capability to process reusable transportation vehicles begins with the first piloted lunar flight in 2004.

Freedom support for the Mars flights includes significant vehicle assembly, integration, checkout, launch, and recovery upon Earth return of the Earth crew capture vehicle. Beginning in 2011, the Space Station Freedom lunar mission configuration will be augmented using the smaller shroud of a heavy-lift launch vehicle beginning in 2011 to support a test flight of the Mars aerobrake in 2013, and subsequently to support the initiation of Mars missions in 2015. Beginning in 2014, the Mars transportation vehicle elements for the Mars aerobrake test flight will be launched to Freedom, using a larger heavy-lift vehicle and the capability of lifting 140 metric tons to Freedom. This vehicle will launch all subsequent Mars transportation vehicles.

The telecommunications network must support lunar data return beginning in 2002 and must include a Mars data link to Earth. In addition, two Mars telecommunications satellites will be established in Mars orbit in 2014 to provide communications access between Earth and the Mars outpost.

Infrastructure

Section 5

SECTION 5

Infrastructure

Three major infrastructure elements will enable and sustain the Human Exploration Initiative, providing vital support to lunar and Mars outposts throughout their emplacement, consolidation, and operation phases. The first element of this infrastructure is a fleet of vehicles that will launch exploration mission vehicles, cargo, and crews to the second element, Space Station Freedom, which will serve as an assembly, staging, and training base. The third infrastructure element will provide the telecommunications, navigation, and information management services basic to all space ventures.

Earth-to-Orbit Transportation

The Directive on National Space Policy signed by President Reagan on January 5, 1988, and the National Space Launch Program Report to Congress signed by President Bush on April 10, 1989, established the basis for assessing the Nation's launch vehicle infrastructure. In response to the policies and time-phased strategies defined in these documents, reliable access to space will be provided through a mixed fleet of launch vehicles that includes the Space Shuttle, existing expendable launch vehicles, and planned heavy-lift launch vehicles. This fleet will enable the Nation to meet existing and projected program needs and to accommodate the expanded requirements of human exploration of the Moon and Mars.

Many types of launch activities are included in currently planned missions: assembly, logistics, and crew rotation for Space Station Freedom and space platforms; servicing of satellites and Spacelab; and delivery of communications, science, planetary, and observatory satellites. The current Space Shuttle and a family of expendable launch vehicles, some of which already exist, and others of which will be operational soon, can support these activities. This infrastructure can also provide the capability to perform robotic lunar and Mars exploration missions and to assemble Space Station Freedom and establish it as a transportation node for the Human Exploration Initiative. Augmentation with heavy-lift launch systems will provide the Earth-to-orbit launch capability necessary to support human missions to the Moon and Mars.

Launch Requirements for the Human Exploration Initiative

The full set of robotic missions that will precede piloted flights to the Moon and Mars can be supported by expendable launch vehicles. When the lunar and Mars outpost missions begin, all vehicles, propellant, cargo, and crew must be launched from Earth to Space Station Freedom. The mass delivery requirements for the lunar missions will more than double current launch requirements. When Mars missions begin, the mass delivery requirements will more than double again. Launch to orbit of individual payload elements heavier than 30 metric tons, required for lunar and Mars missions, is beyond the capability of existing launch vehicles. The current fleet must be augmented by a heavy-lift launch vehicle for lunar missions and a larger heavy-lift launch vehicle for Mars missions.

Lunar mission elements, packaged to enhance launch efficiency and to minimize assembly operations at Freedom, will require an Earth-to-orbit lift capability of approximately 60 metric tons, including adequate payload margin. Delivery to Freedom of the aerobrake center assembly and the lunar excursion vehicle necessitates a launch vehicle payload shroud to accommodate a payload envelope 7.6 meters in diameter and 27.4 meters long. The lunar transfer vehicle main propellant tanks can be launched with a payload envelope 4.6 meters in diameter and 25 meters long.

Earth-to-Orbit Transportation

- Existing Space Shuttle and expendable launch vehicle fleet will support robotic missions; Space Shuttle will be used for crew transport to Space Station Freedom.
- For establishing the lunar outpost, an Earth-to-orbit lift capability of approximately 60 metric tons is required. The only vehicle in this class being considered before 1999 is the Shuttle-C; after that time, use of the new Advanced Launch System vehicles is possible.
- For establishing the Mars outpost, an Earth-to-orbit lift capability of approximately 140 metric tons is required. A larger Shuttle-derived heavy-lift vehicle and an Advanced Launch System vehicle are being considered for this purpose.
- For either Shuttle-derived or Advanced Launch System heavy-lift vehicles, some degree of enhancement of ground launch and production facilities will be necessary.

The payload mass to be launched to Freedom in support of the lunar outpost can range from 110 to 200 metric tons, depending on such mission variables as lunar transfer vehicle expendability or reusability and whether the mission is cargo or piloted. Mass for piloted flights includes cargo in addition to the crew. Approximately 75 percent of the mass delivered to low Earth orbit is lunar transfer vehicle propellant.

A launch vehicle capability of 140 metric tons is needed to ferry Mars mission vehicles, cargo, crew, and propellants to Freedom. Multiple flights of a large heavy-lift launch vehicle will be required to deliver Mars transfer vehicle elements and propellants weighing 550 to 850 metric tons, depending on the mission type and year. Propellant for trans-Mars injection and subsequent trans-Earth injection constitutes the greater part of the total mass. Each fully loaded trans-Mars injection stage propellant tank has a mass of 135 metric tons. Vehicle elements such as the aerobrake and the trans-Mars injection stage core (engines, thrust structure, and center tank), to be delivered separately and assembled at Freedom, require a shroud to accommodate a payload envelope 12.5 meters in diameter and 30 meters long.

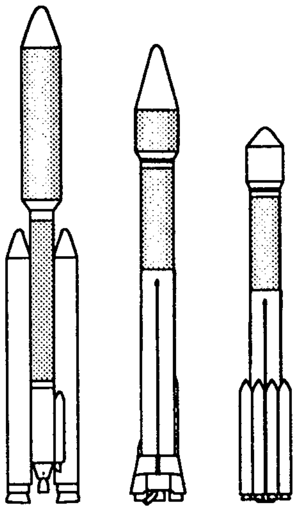
Existing System Capabilities and Potential

The current fleet of expendable launch vehicles and Space Shuttle can support initial efforts in the journey to the Moon and Mars. With enhancement, they can continue to be used in some subsequent operations.

The Space Shuttle is a multipurpose system capable of delivering both crew and cargo to low Earth orbit, retrieving payloads and returning them to Earth, providing on-orbit servicing, and supporting laboratories in space. The Space Shuttle is currently the Nation's sole means of providing human access to space, with the ability to transport five crew members to orbit. The Space Shuttle can accommodate the current manned mission requirements with a planned flight rate of 14 per year.

For lunar and Mars outpost missions, the Space Shuttle will transport crews and limited cargo to low Earth orbit. It will also support related on-orbit servicing missions in conjunction with Freedom and a space-based orbital maneuvering vehicle.

Advances in technology will allow opportunities to improve cost-effective operations, reliability, and safety; provide additional margins; and counter obsolescence. Many of these improvements can be incorporated at the subsystem level, whereas others will be incorporated during production of new orbiters and modification of existing orbiters. The first major program element upgrade is underway with the development of the advanced solid rocket motor. This upgrade will increase the current Space Shuttle 17.3-metric-ton lift capability by about 20 percent and will improve reliability and safety as well. To reduce cost and increase reliability, the Space Shuttle main engine could be upgraded using the technology being demonstrated in the Advanced Launch System propulsion development effort.



Launch Vehicle	Titan IV	Atlas II	Delta II
Payload to Low Earth Orbit (in metric tons)	17.7-22.3	6.7-8.8	3.9-5.0
Availability Date:	Jan 89	1991	Jan 89

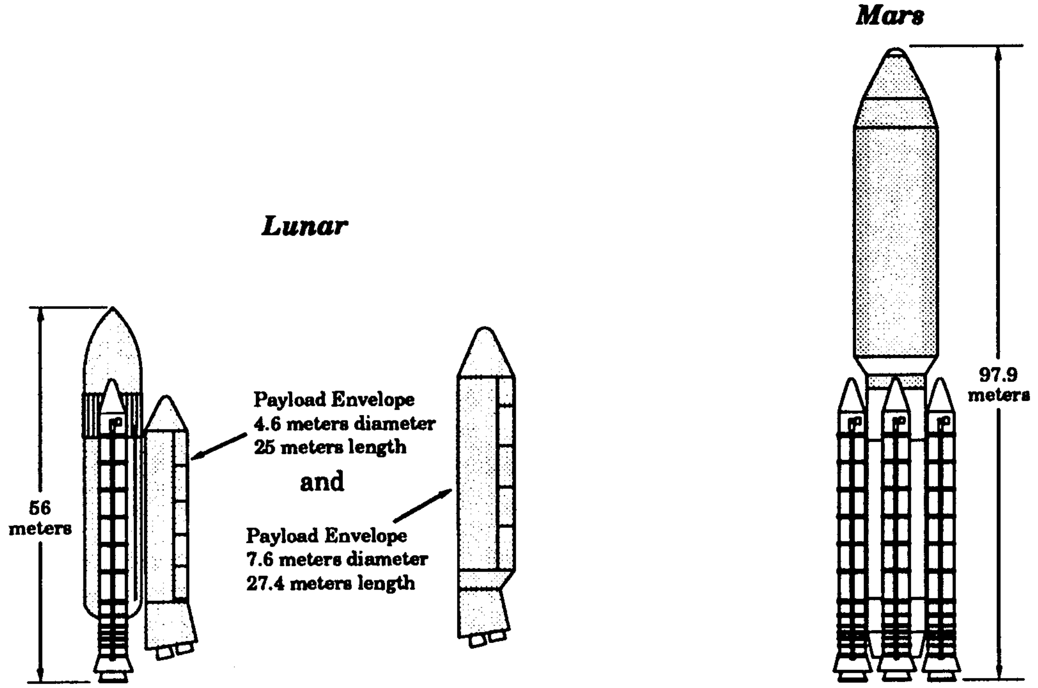
Figure 5-1 Expendable Launch Vehicles

Three families of expendable launch vehicles, illustrated in Figure 5-1, are available to augment the Space Shuttle. The capabilities of these vehicle families have been upgraded over the last few years to meet increasing national needs. The Delta II, Atlas II, and Titan IV families, using existing upper stages or those in development, can accomplish all currently planned robotic missions. The most capable upper stage currently available is the Centaur, a cryogenic stage that can be launched on either an Atlas or a Titan expendable launch vehicle. The largest version of Centaur in development can deliver 4.8 metric tons of payload to geosynchronous Earth orbit using a Titan IV booster. With structural enhancements to the Centaur to accommodate larger payloads, the Titan IV with the Centaur upper stage can support all the robotic lunar and Mars missions that are required before the human missions begin. However, some of these missions would be enhanced by a capability for launching larger payloads, which could be provided by a heavy-lift launch vehicle.

New Launch Vehicle Development

By the middle to late 1990s, a heavy-lift Earth-to-orbit launch capability will be required to support the Human Exploration Initiative. The only heavy-lift concept being considered for use before 1999 is Shuttle-C, an unmanned Shuttle-derived cargo vehicle in which the Shuttle orbiter is replaced by a cargo carrier. Such a vehicle could support assembly of Freedom and its growth to a lunar transportation node until 1999, when the new Advanced Launch System currently being defined in a joint effort by NASA and the Department of Defense may be available. From that point on, Shuttle-C, the Advanced Launch System, or a mixed fleet of both can support Freedom growth and lunar mission requirements. New, larger heavy-lift vehicles will be needed to launch the payloads, space vehicles, and propellants for the Mars missions, because the mass to be put into Earth orbit is much greater than that of any previous mission. This capability can be provided by a large Shuttle-derived launch vehicle or a future version of the Advanced Launch System vehicle. The heavy-lift vehicle will be required to deliver cargo to the vicinity of Space Station Freedom, where an orbital maneuvering vehicle based at Freedom will be used to transfer cargo to Freedom's vehicle servicing facility.

The Shuttle-C, designed to reliably deliver heavy payloads to orbit, is not a new design, but one that expands upon the current Space Shuttle program infrastructure. It uses existing and modified Shuttle-qualified systems, including main engines, solid rocket boosters, and a slightly modified external tank with enhanced structural interfaces. To minimize the number of Shuttle-C launches for lunar missions, the 4.6- and 7.6-meter-diameter payload envelope shrouds will be used with an otherwise common Shuttle-C configuration (Figure 5-2). Lunar missions can be supported by three Shuttle-C launches for the early



Net Payload 71 metric tons	Net Payload 61 metric tons
Boosters	2 Advanced solid rocket boosters
Core Stage	Standard external tank
Core Propulsion	3 Space Shuttle main engines

Net Payload	140 metric tons
Boosters	4 Advanced solid rocket boosters
Core Stage	New 10 meters diameter
Core Propulsion	Recoverable propulsion/avionics w/5 Space Shuttle main engines
Payload Envelope	12.5 meters diameter 30 meters length

Figure 5-2 Shuttle-Derived Heavy-Lift Launch Vehicles

missions and two launches for later missions with lower cargo requirements. Using the smaller shroud, Shuttle-C has a lift capability of 71 metric tons, which maximizes delivery of propellant and high-density payloads; with the larger configuration, it has a lift capability of 61 metric tons. This configuration is required to launch the large-diameter lunar excursion vehicle and aerobrake elements.

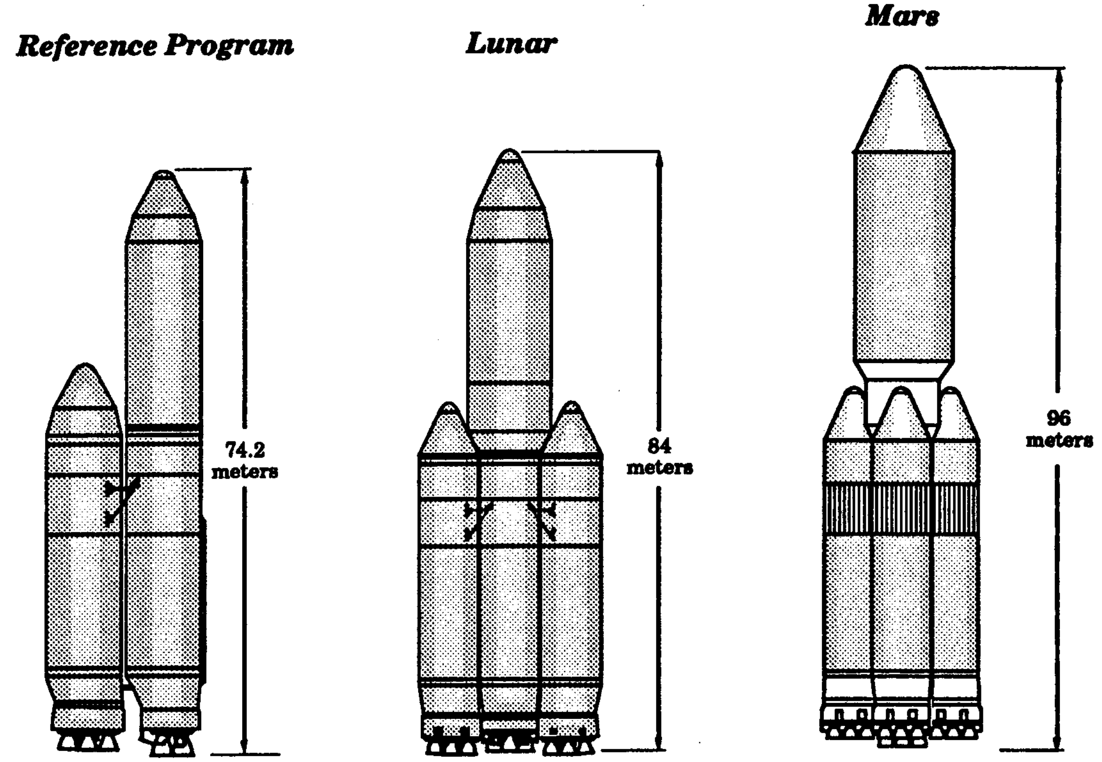
Transportation of Mars mission components from Earth to orbit calls for a launch vehicle with a greater payload volume and lift capability than that required for the lunar missions. A larger Shuttle-derived heavy-lift launch vehicle (Figure 5-2) can deliver 140 metric tons to Freedom with a payload envelope 12.5 meters in diameter and 30 meters in length. Four solid rockets are used as first stage boosters. Five Space Shuttle main engines in a recoverable propulsion/avionics module are used on a 10-meter-diameter core stage. After main engine cutoff, the core stage separates from the payload, and a small kick-stage transfers and circularizes the payload at the required orbit. The propulsion/avionics module separates from the core vehicle and returns to Earth for reuse. Each Mars mission requires from five to seven of the new Shuttle-derived heavy-lift launch vehicles, depending on mission type and year.

The Advanced Launch System family of unmanned launch vehicles is being designed to deliver to orbit a broad range of cargo size and mass. Primary design objectives are low cost per flight, high reliability, and high operability. The most significant requirements that human lunar and Mars missions will add to the Advanced Launch System reference program are elements to provide circularization and stabilization and the early introduction of a two-booster vehicle.

The two-booster vehicle (Figure 5-3), which can launch 98.2 metric tons, is required to efficiently package the lunar mission elements to minimize heavy-lift launches to the Moon. Elements for each lunar mission can be delivered by two Advanced Launch System flights. In addition to the Advanced Launch System vehicle, a transfer stage is required to circularize the payloads into Freedom's orbit.

Mars missions are supported by adding a three-booster vehicle (Figure 5-3) to the configuration used for lunar missions. The 12.5-meter-diameter payload envelope of this vehicle will accommodate the large mission elements required. As in the Shuttle-derived heavy-lift launch vehicle case, five to seven Advanced Launch System heavy-lift launch vehicle flights are required for Mars missions.

NASA is planning an assured crew return vehicle to support Space Station Freedom. Vehicle definition studies are scheduled for 1990 and 1991 to support initiation of design and development in fiscal year 1992. Assessments are being



Net Payload	52.3 metric tons
Boosters	1 LOX/LH$_2$ w/6 STME's
Core Stage	LOX/LH$_2$
Core Propulsion	3 STME's
Payload Envelope	7.6-m diameter 30-m length

Net Payload	98.2 metric tons
Boosters	2 LOX/LH$_2$ w/6 STME's ea.
Core Stage	LOX/LH$_2$
Core Propulsion	3 STME's
Payload Envelope	10-m diameter 30-m length

Net Payload	140 metric tons
Boosters	3 LOX/LH$_2$ w/6 STME's ea.
Core Stage	LOX/LH$_2$
Core Propulsion	3 STME's
Payload Envelope	12.5-m diameter 30-m length

m = meters
LOX = Liquid Oxygen
LH$_2$ = Liquid Hydrogen
STMEs = Space Transportation main engines

Figure 5-3 Advanced Launch System-Derived Heavy-Lift Launch Vehicles

made of the most cost-effective approach to combine assured crew return vehicle concepts with existing expendable launch vehicles or new Advanced Launch System boosters. Other options being considered are an Advanced Manned Launch System and the National AeroSpace Plane.

Ground Launch Support

Current facilities at the John F. Kennedy Space Center can support up to 14 Shuttle launches a year, which is adequate for existing program requirements. Facilities at Cape Canaveral Air Force Station can support launches of ten Delta, eight Atlas, and eight Titan vehicles each year. However, Centaur ground processing facilities limit Titan IV/Centaur launches to three per year. These support capabilities are sufficient for existing programs; however, total national launch requirements must be assessed to determine facility modifications needed to support Titan IV/Centaur launches of the robotic missions that precede human exploration. A possible solution would be to use the lunar heavy-lift launch vehicle in lieu of two Titan IV vehicles for the more demanding robotic missions for which dual payloads are launched in some years.

Facility and processing requirements for Shuttle-derived vehicles will be determined by flight rates and the selected vehicle configurations. Several modified and new facilities are required for vehicles that will deliver lunar mission elements to low Earth orbit. Shuttle-C launches require a cargo element transporter, a cargo element processing facility, modifications to the high-level access platforms in the vehicle assembly building, enhancements to the launch processing system, and new cryogenic handling and storage capabilities at the launch pads for the tanker missions. The 7.6-meter-diameter Shuttle-C shroud is incompatible with the lower level access platforms in the currently active vehicle assembly building high bays and with the rotating service structure at the pad. A new advanced rocket booster stacking facility and improved solid rocket booster processing capabilities will be needed to support approximately 17 flights a year. With the addition of a fourth mobile launch platform, the combined annual launch rate could reach 21, a limit set by the capabilities of the two existing launch pads. A new launch pad will be required either for total flight rates above 21, or later, when the new Mars heavy-lift vehicle is introduced. The larger heavy-lift launch vehicle for Mars missions will also require other substantial launch site enhancements, including a new launch pad, a further increase in solid rocket booster pre- and post-flight operational capabilities, reactivation of vehicle assembly building high bay 4, relocation of external tank processing into a new horizontal processing facility, a core-stage processing facility, a Mars payload processing and integration facility, two new-design mobile launch platforms, and a new crawler-transporter to deliver the vehicle to the pad.

A totally new ground launch infrastructure that consolidates operations is planned for the Advanced Launch System. Manufacturing and final assembly facilities will be located near the launch site to meet rapid turnaround requirements. Dual pads and streamlined vehicle and payload processing operations will permit approximately 20 flights a year. Because design of these facilities is still in a preliminary phase, the requirements to support lunar missions can be included in final designs and initial construction.

Investment in additional ground infrastructure such as additional payload encapsulation, vehicle integration cells, and mobile launch platforms would be needed for the larger Advanced Launch System required for the Mars missions. Combined with existing Advanced Launch System commitments, the Mars missions will bring launch rates to a level approaching 30 a year.

Higher launch rates and the attrition of flight hardware for Space Shuttle and Shuttle-derived vehicles will require enhancements to existing production and refurbishment capabilities for main engines, advanced solid rocket motors, and the Shuttle-C cargo element. External tank production facilities are capable of handling higher launch rates for the exploration missions.

The ability of expendable launch vehicle production facilities to support these missions must be evaluated within the context of total national needs. Titan IV and Centaur production facilities potentially require the most modifications.

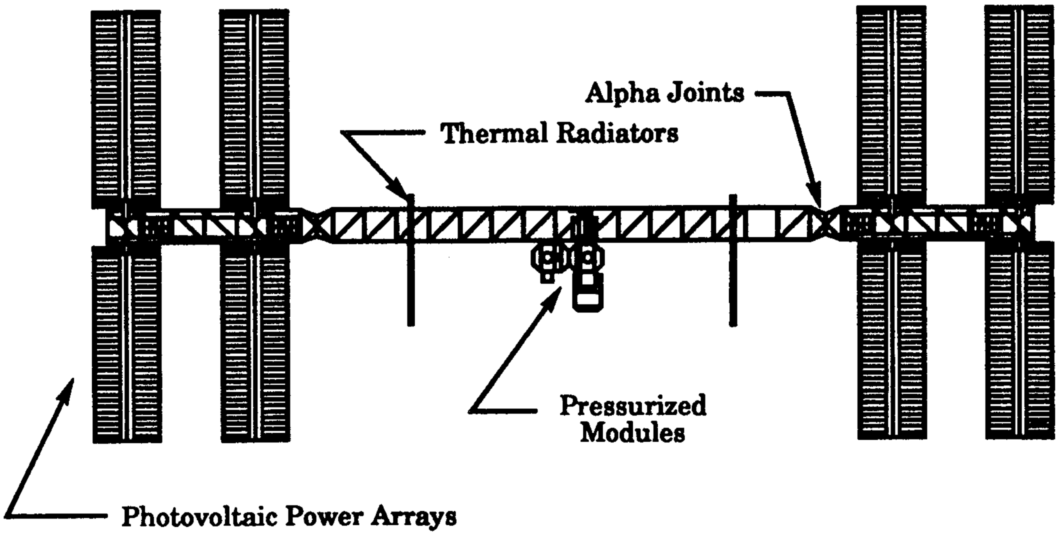
The Advanced Launch System production facility requirements to support the Human Exploration Initiative can be assessed as part of ongoing planning for these facilities.

Space Station Freedom

In its initial configuration, termed Assembly Complete, Space Station Freedom will be a versatile, multifunctional science and technology facility that will provide accommodations for continuous human presence in low Earth orbit. It will support research in a wide variety of disciplines, including microgravity, materials processing, medicine, Earth observation, life sciences, astronomy, and space physics. Freedom will also be used to develop and advance a broad range of space technologies such as automation and robotics, advanced structures and materials, power generation, space electronics, and communications. Major elements of the initial configuration are illustrated and summarized in Figure 5-4.

A significant feature of Space Station Freedom's design is its capability to add pressurized laboratory and habitation modules, power generation equipment, truss extensions, and specialized facilities. This capacity to evolve, essential to Freedom's role as an exploration support base, allows enhancement of the baseline research facility and provides the means to add new functions such as assembly, servicing, and repair of spacecraft and satellites.

Space Station Freedom performs two critical functions in the Human Exploration Initiative. First, it will serve as a transportation node for assembling, testing, processing, servicing, launching, and recovering lunar and Mars vehicles. It will also supply crew support, data management and communications systems, and logistics services to accomplish these activities.



Element	Description
Modules	• 3 laboratory (1 U.S., 1 European, 1 Japanese), 1 habitation
Truss Structure	• Transverse boom 145 meters in length
Power & Thermal	• 75 kilowatt power generation and heat rejection capability
Crew	• 8 permanent
Attached Payload Accommodations	• Accommodations for 2 attached payloads on transverse boom including power and high data rate service
Remote Manipulator (Canadian), Mobile Transporter	• 1 providing access to all faces of the transverse boom

Figure 5-4 Space Station Freedom Assembly Complete Configuration

Space Station Freedom

To serve as a transportation node for human exploration missions, Freedom will evolve from assembly complete through four additional configurations:

- The first configuration will support the lunar transfer vehicle verification flight. The truss structure will be augmented to include lower keels and a lower boom. Power will be increased from 75 kilowatts to 125 kilowatts, and two permanent crew members will be added. A service track assembly for the lunar transfer vehicle will also be added.
- The second configuration will support expendable lunar transfer vehicle operations. A second habitation module will be added to accommodate the transient lunar mission crew of four. An enclosed lunar transfer vehicle hangar will be added to the service track assembly to protect the vehicle from orbital debris damage during its stay.
- The third configuration will support reusable lunar transfer vehicle operations. Two permanent crew members will be added to support increased life sciences research, lunar transfer vehicle servicing operations, and maintenance of Freedom. Additional solar dynamic power units will bring total power generation capability to 175 kilowatts. A second remote manipulator will be added.
- The fourth configuration will support lunar and Mars operations. Upper keels and booms as well as a support structure for on-orbit assembly and checkout of the vehicle elements will be added. A Mars vehicle assembly facility will be added.

Freedom will also support ongoing research and development in:

- In-space operations
- Life sciences
- In-space assembly of spacecraft
- High-energy aerobrake testing and simulation of human missions to Mars

Second, Freedom will serve as an on-orbit laboratory for conducting research and developing technology required to implement the Initiative. Freedom is the ideal location for such demonstrations because no terrestrial laboratory can adequately simulate the characteristics of the space environment. Research will determine acceptable long-term microgravity countermeasures and obtain data for the design of self-sufficient life support systems. Freedom can advance technology by serving as a test-bed for new lunar and Mars system developments. The hardware, software, and other technologies used to assemble and operate Freedom can be applied to exploration vehicles and systems.

Assumptions basic to Freedom's accommodation of the Human Exploration Initiative requirements are that it will be fully augmented to support the required transportation node functions; that the resource allocation for this support (including power, crew, and laboratory workspace) will be provided from United States resource allocations; and that Freedom will continue to accommodate concurrent multidisciplinary research. The international partners will receive their fixed allocation of Freedom resources as agreed upon in the Memoranda of Understanding.

Four major Human Exploration Initiative milestones are significant to Space Station Freedom's role as a transportation node and a research and technology test-bed. The first is the verification flight of the lunar transfer vehicle. The second major milestone is expendable lunar transfer vehicle operations; the third is the beginning of reusable lunar transfer vehicle operations in support of the lunar outpost; and the fourth is the onset of orbital operations in support of Mars missions.

Space Station Freedom must evolve through four configurations (Figure 5-5) to support these four milestones. The major characteristics of Freedom as it progresses through these four configurations are summarized in Table 5-1.

The best way to achieve this progression is to incorporate capabilities for future system changes into the initial design. One design item critical to support the Initiative is the provision for additional power generation equipment on the alpha joints, which are rotating mounts on both ends of the main truss that allow the outboard solar collectors to track the Sun. Another critical item is the design of power distribution and control systems to permit future use of a hybrid system.

Freedom must also support "non-exploration" users, including NASA experimenters, commercial users, university investigators, and the international partners. Accommodating these users while simultaneously supporting the Human Exploration Initiative is an important national priority. In developing the evolutionary growth configurations for Freedom, these activities were evalu-

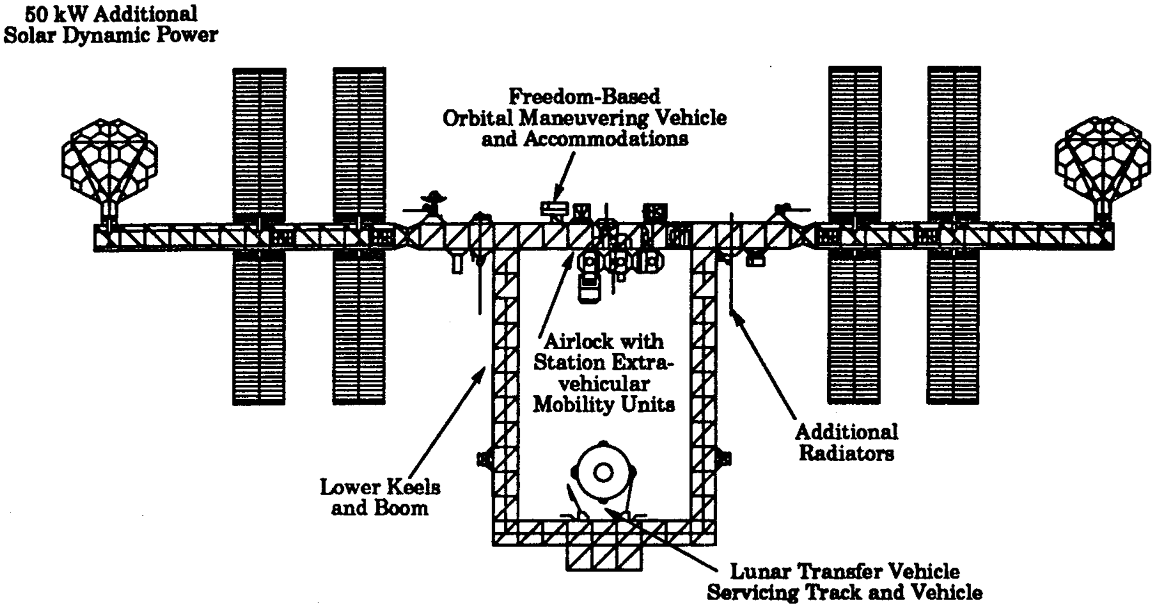
Table 5-1
Space Station Freedom Growth Elements for Human Exploration

Space Station Freedom Element	Lunar Transfer Vehicle Verification Flight	Expendable Lunar Transfer Vehicle Operations	Reusable Lunar Transfer Vehicle Operations	Lunar & Mars Operations
Modules	3 Laboratory (1 U.S., 1 European, 1 Japanese) 1 Habitation	3 Laboratory (1 U.S., 1 European, 1 Japanese) 2 Habitation	Same	Same
Truss Structure	Transverse Boom, Lower Keels & Lower Boom	Same	Same	Transverse Boom, Lower and Upper Keels and Booms, Mars Vehicle Support Structure
Power & Thermal	125 kilowatts	125 kilowatts	175 kilowatts	175 kilowatts
Crew	10 Permanent	10 Permanent, 4 Transient Lunar	12 Permanent, 4 Transient Lunar	12 Permanent, 4 Transient Lunar or Mars
Vehicle Processing	Service Track Assembly for Lunar Vehicle	Enclosed Lunar Transfer Vehicle Hangar	Same	Enclosed Lunar Transfer Vehicle Hangar, Mars Vehicle Assembly Facility
Remote Manipulator (Canadian), Mobile Transporter	1 Remote Manipulator, 1 Mobile Transporter	Same	2 Remote Manipulators, 1 Mobile Transporter	2 Remote Manipulators, 2 Mobile Transporters

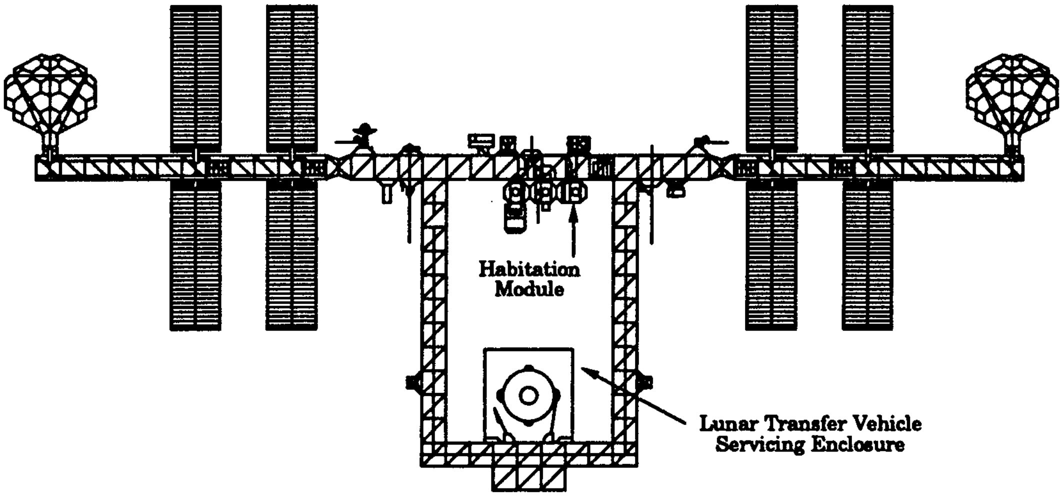
ated and incorporated into the design to ensure that the multidisciplinary research characteristics of Space Station Freedom would be maintained to the greatest extent possible.

The first milestone for Freedom in its transportation node function is a configuration that can support the lunar transfer vehicle verification flight, an end-to-end verification test of the vehicle, which will deliver a limited payload to the lunar surface. To support this test, Freedom must accommodate lunar transfer vehicle hardware elements and the lunar excursion vehicle, both of which will be delivered by heavy-lift launches. Freedom must also accommodate a space-based orbital maneuvering vehicle, which will be used to transfer flight hardware payload elements from the heavy-lift launch vehicle to the Space Station Freedom lunar transfer vehicle servicing facility. Other large equipment will be needed to support propulsion tank mating, aerobrake assembly, vehicle processing, and prelaunch checkout of the integrated vehicle. Freedom's capabilities must be augmented by truss structure extensions, additional power and crew, and other unique facilities.

One of these facilities is a service track assembly that will provide a fixture for

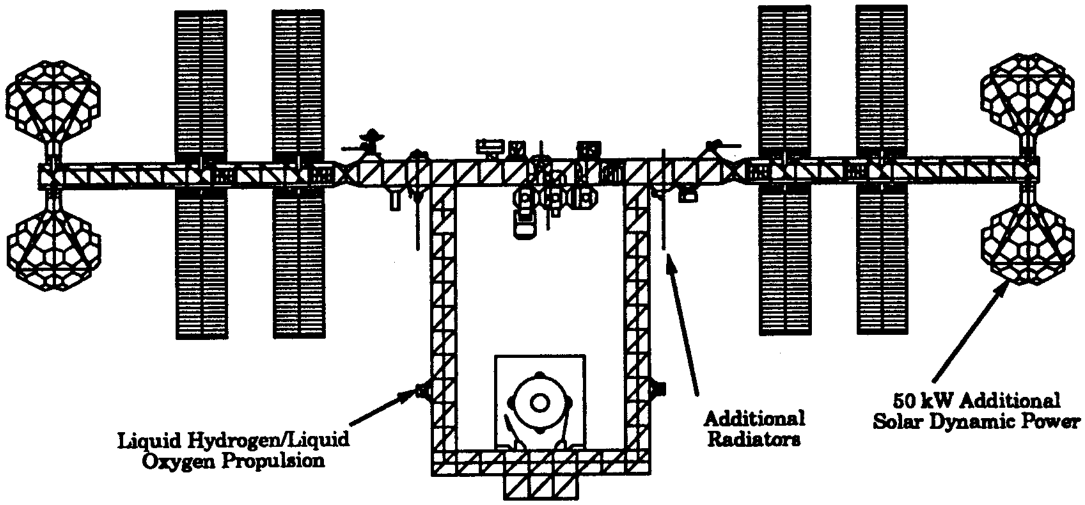


a) Lunar Transfer Vehicle Verification Flight Configuration

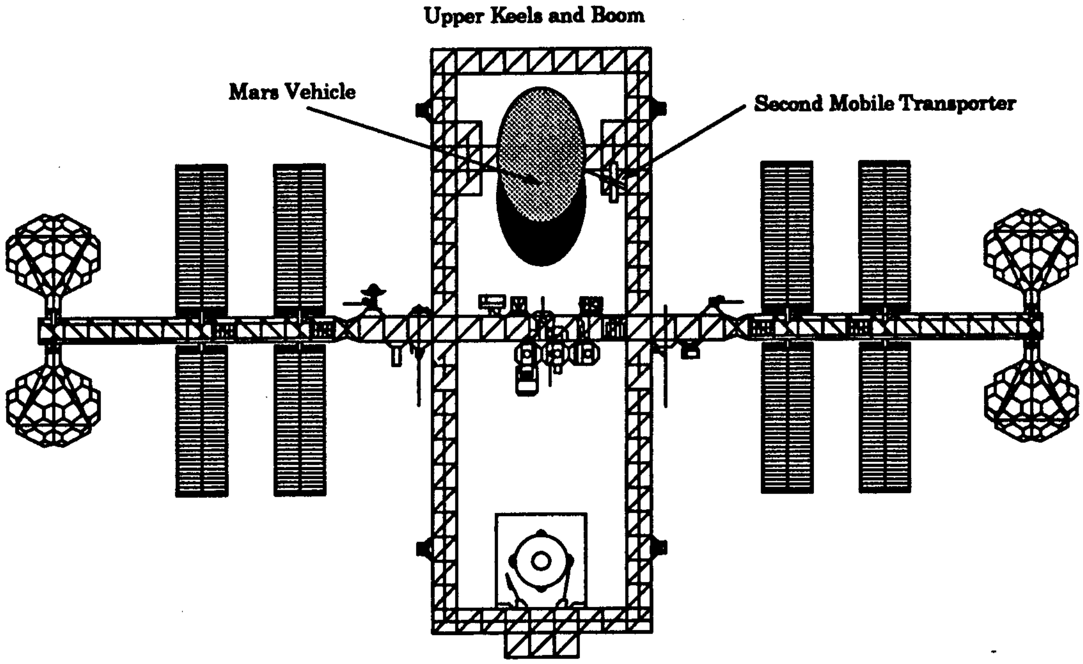


b) Expendable Lunar Transfer Vehicle Operations Configuration

Figure 5-5 Transportation Node Configurations for Space Station Freedom Evolution



c) **Reusable Lunar Transfer Vehicle Operations Configuration**



d) **Lunar and Mars Operations Configuration**

Figure 5-5 Concluded

mounting and manipulating the vehicle and its components, a storage area for vehicle processing equipment, and a track to guide remote manipulators to all portions of the vehicle. The initial configuration of Freedom does not include adequate space for mounting the service track assembly and processing the vehicle. To provide this location as well as areas for experiments and technology development, the truss structure will be augmented to include lower keels (two 12-truss segment extensions projecting down from the original structure) and a lower boom (a seven-truss segment connecting the keels at their base).

Crew-time requirements for processing the first lunar transfer vehicle, in addition to supporting maintenance, life sciences, technology development, concurrent science, and international projects, call for two additional crew members. They may be housed in the existing habitation module or in one of the resource nodes (connecting points that provide passage between modules) eliminating the need for a second habitation module.

By the time of the lunar transfer vehicle verification flight, power requirements on Freedom will have risen to approximately 100 kilowatts to support the lunar transfer vehicle assembly and checkout and the increased level of life sciences research. To provide this power, the main transverse boom will be extended on either side by six truss segments to allow mounting of solar dynamic power units that will increase power generation capability to an average of 125 kilowatts.

Other augmentations required to support the lunar transfer vehicle verification flight include a data management system to provide high data rate communication for vehicle processing; a thermal control system for cooling the lunar transfer vehicle processing area; unpressurized payload support equipment for lunar transfer vehicle assembly tasks, technology development, and concurrent science; a communications and tracking system, which will provide cameras for monitoring vehicle processing areas; and a guidance, navigation, and control system to support traffic management of the Space Shuttle, the lunar transfer vehicle, and other spacecraft in the proximity of Space Station Freedom.

Following the verification flight, Space Station Freedom will support the second milestone, processing of expendable lunar transfer vehicles. The processing time for lunar transfer vehicles is less than 6 months. Two flights per year can, therefore, be supported at Freedom with a single vehicle processing area. This configuration will also support an increase in life sciences research in preparation for the Mars missions, as well as on-orbit servicing operations technology development to prepare for the reusable vehicle operations.

Additions to Freedom for this configuration include a debris protection enclosure for the lunar transfer vehicle service track assembly. The enclosure is required because of the higher probability of orbital debris damage during longer stay times at Freedom for preflight and postflight operations. An additional habitation module will be required before the first piloted mission to accommodate the transient mission crew of four. Two members of the vehicle processing crew added during the previous phase will move to the second habitation module. The additional elements and activities during this phase will increase Freedom's power requirements; however, the power demand remains within the power generation capability of 125 kilowatts.

Reusable lunar transfer vehicle operations will follow the expendable flights, leading to increased processing demands on Freedom. The configuration must be enhanced to meet these requirements (Figure 5-5). Additional crew members will be needed to support increased life sciences research, lunar transfer vehicle servicing operations, and maintenance of Freedom. These crew members, along with the four transient mission crew members, will be housed in the second habitation module. The resultant increase in power requirements beyond 125 kilowatts will necessitate additional solar dynamic power units, bringing the total power generation capability to 175 kilowatts.

As exploration moves into the Mars emplacement phase, the components of the Mars mission vehicle, with the exception of the large propulsive stages, will be assembled and checked out at Freedom. These activities will be concurrent with ongoing lunar outpost support. Upon assembly of the high-energy aerobrake, Mars aerobrake, Mars transfer vehicle, and Mars excursion vehicle, a fully integrated checkout will be performed, followed by deployment from Freedom for staging with the propulsive elements. Since much of the Mars transfer vehicle's stay in low Earth orbit is spent away from Freedom, debris protection must be provided on the vehicle itself.

To process the Mars transfer vehicle, Freedom will require the addition of upper keels, an upper boom, and a support structure for on-orbit assembly and checkout of the vehicle elements. Lunar and Mars mission scheduling calls for sequential lunar transfer vehicle and Mars transfer vehicle processing operations; simultaneous vehicle processing is not required. Therefore, no additional Space Station Freedom crew support is needed. Temporary accommodations will be provided for four transient Mars crew members within the second habitation module.

In addition to its role as a transportation node, Freedom will also serve as a research and technology development test-bed. The initial phase of research and development support, which focuses on in-space operations and life sciences research, begins during Space Station Freedom assembly and continues until the lunar transfer vehicle verification flight.

In-space assembly techniques will be tested in preparation for the verification flight milestone. Assembly involves mating major spacecraft components delivered on multiple Earth-to-orbit launches, and deploying or assembling large vehicle elements, such as aerobrakes, that cannot be launched preassembled.

Also preliminary to this milestone, life sciences research will concentrate on procedures to guarantee safe and productive crew operations during extended orbital habitation. This program of biomedical monitoring and countermeasures will lead to Freedom crew stay times of 180 days.

Between the lunar transfer vehicle verification flight and the reusable lunar transfer vehicle operations phase, in-space operations research and development will focus on verifying methods for processing space transfer vehicles for flight, refurbishment, and reuse. This on-orbit processing includes integrating payloads with the transfer vehicle, fueling, inspection, testing, and flight readiness verification. Life sciences research and development in this period will concentrate on effective countermeasures to microgravity exposure for the extended durations associated with human trips to Mars.

Before the Mars mission orbital operations milestone, life sciences research on Freedom will be emphasized to confirm the effectiveness of microgravity countermeasures in order to design a zero-gravity Mars transfer vehicle. In-space operations research in this phase will focus on high-energy aerobrake testing and simulation of human Mars missions. Experience gained in processing lunar transfer vehicles will serve as a basis for Mars transfer vehicle operations.

Telecommunications, Navigation, and Information Management

The enabling support functions of telecommunications, navigation, and information management provide the capacity to monitor and control mission elements, acquire telemetered data from engineering and science measurements, provide radiometric data for navigation and video data for operations and science activities, and provide a capacity to communicate, receive, distribute, and process information. These functions must be provided efficiently, with human-related reliability, for both the lunar and Mars missions of the Human Exploration Initiative without detriment to other user support.

NASA currently provides operational support for data acquisition, data processing, communications, and control to approximately 20 unmanned missions in Earth orbit and deep space. This support is provided by ground networks, a space network, communications facilities and services, and data-handling facilities.

Telecommunications, Navigation, and Information Management

This vital support function will be based on a system with the following key characteristics:

- Builds on and evolves from existing systems
- Provides near-continuous link access between lunar and Mars mission nodes
- Accommodates largely unattended in situ support and information transfer
- Transmits real-time Mars video data to Earth
- Incorporates emergency modes and fail-soft design
- Allows for reasonable technology growth

The ground networks include the Deep Space Network of three multi-antenna complexes positioned around Earth at intervals of approximately 120 degrees longitude. The Space Network is a constellation of three orbiting Tracking and Data Relay Satellites and a ground terminal. The communications facilities and services and data handling facilities consist of operational and administrative networks, a variety of project operations control centers, and many data processing centers.

The proposed telecommunications, navigation, and information management architectures for the Human Exploration Initiative include the Earth-based acquisition and control network, lunar and Mars telecommunications relay networks, navigation support, the data acquisition and control network for robotic missions, and human mission operations support.

The system will provide the means to monitor and control distributed mission elements and to acquire system data from remote locations at high data rates at a high level of reliability. Since support must be provided for all vehicles and planetary surface system elements, the design must address end-to-end requirements.

Several challenges will critically affect the system's architecture: incorporating highly unattended operations for many of the local Mars telecommunications and navigation functions, achieving a high Mars-to-Earth data rate, providing robust system connectivity for manned links, and providing an information management discipline, including standards, for use in transferring data between system nodes.

Current human mission operations functions are highly operator-intensive, but the expected complexity of planned Mars local mission operations could make attended monitor and control techniques unaffordable. Because of the long round-trip transmission time (40 minutes) to Earth control centers, many real-time operational decisions must be made at Mars. Such local decision-making must be assisted by expert systems, and the links to distribute information rapidly to local terminals must operate largely unattended. The necessary elements of this design will require several years to develop, evolve, and validate, and they will be tested at the initial lunar outpost.

Methods of achieving high data rates focus on higher frequencies (Ka-band at 32 GHz) and effective data compression algorithms. Ka-band, which improves current X-band capability by at least a factor of five, is planned for the lunar outpost, Mars outpost, and the robotic Mars missions.

The requirement for more than 90 percent link connectivity from Earth to manned terminals on Mars and between terminals on Mars dictates the use of telecommunications relay satellites, which also permit the use of lower power and much smaller antennas at surface terminals and in transportation vehicles.

Developing an end-to-end approach for data transfer between distributed nodes on Earth, at Mars, at the Moon, and on vehicles in transit will have high priority. Standards (such as those for communications formats, data structures, data types, coding, access keys, and priority designations) for data transmission and storage will be used by all mission and support elements.

Telecommunications and Navigation Support

The Human Exploration Initiative requires evolutionary development of support capabilities, beginning with support of robotic missions, then addressing the lunar outpost missions, and concluding with full capability for the human Mars missions. The system will be designed to respond to mission events through a variety of data types and links that can be rescheduled in real time. On-line, unattended fault detection and service restoration are required. Link access between local manned terminals and to Earth must be available at least 90 percent of the time. During scheduled coverage, the link must be available at least 98 percent of the time.

Data required for the lunar missions include high- and low-rate video, voice, science and engineering telemetry, and commands for transmission on the link between the Moon and Earth. The user-derived preliminary data rate of 10 megabits per second for Moon-Earth links is needed primarily to handle compressed, high-rate video transmissions. If an increase in the Moon-to-Earth data rate is not foreseen, X-band can be used for lunar downlinks, but higher rates will require Ka-band.

The lunar mission navigation system will receive data from Earth-based radiometrics and local ranging fixes from lunar telecommunications relay satellites. The relay satellites require navigation accuracies sufficient for orbit determination, station keeping, and signal acquisition predictions.

The Mars missions also require high- and low-rate video data, voice data, science and engineering telemetry, and commands for transmission to and from Earth. These types of data, plus telerobotics data, are also required for transmission between terminals at Mars. In addition, telemetered radiometric data from in situ vehicles will be required for various navigation tasks. The user-derived preliminary data rates are 10 megabits per second for the Mars-Earth downlink and uplink for each relay satellite and the Mars transportation vehicle, again primarily to handle compressed, high-rate video transmissions. Unattended acquisition and operation of links between orbiters and surface terminals, which use high-gain narrow-beamwidth antennas, will be necessary, and providing such a system will be challenging.

Earth support of Mars tracking and data acquisition differs from that for the Moon in three significant ways. First, the two-way transmission time between Earth and Mars is up to 40 minutes. Second, since Mars rotates with a 24.6 hour period, surface facilities cannot "view" Earth for 12 to 14 hours of each day. Third, because of the long communications distance, the link performance is constrained by the signal-to-noise ratio, which means that trade-offs between operating frequency, antenna size, spacecraft transmitter power, ground antenna size, and system temperature require careful engineering consideration.

The key navigation need for Mars missions is radiometric support to provide the piloted vehicle with the trajectory accuracy needed for critical aerocapture maneuvers. Guidance provided by current Earth-based navigation systems, combined with local Mars-centered data, achieves the necessary accuracy and represents a reasonable balance between onboard and Earth-based navigation system capabilities.

System Architecture and Configuration

Figure 5-6 illustrates the key elements of the baseline lunar and Mars telecommunications systems. Low Earth orbit service will be provided by the space-based Advanced Tracking and Data Relay Satellite System, which will also support Earth launches and landings and navigation to and from Space Station Freedom. Beyond low Earth orbit, service will be provided by an expanded Earth-based Deep Space Network. Mission interfaces for lunar and Mars exploration will exist at four different locations: in transportation vehicles, on Space Station Freedom, at lunar and Mars surface terminals, and on Earth.

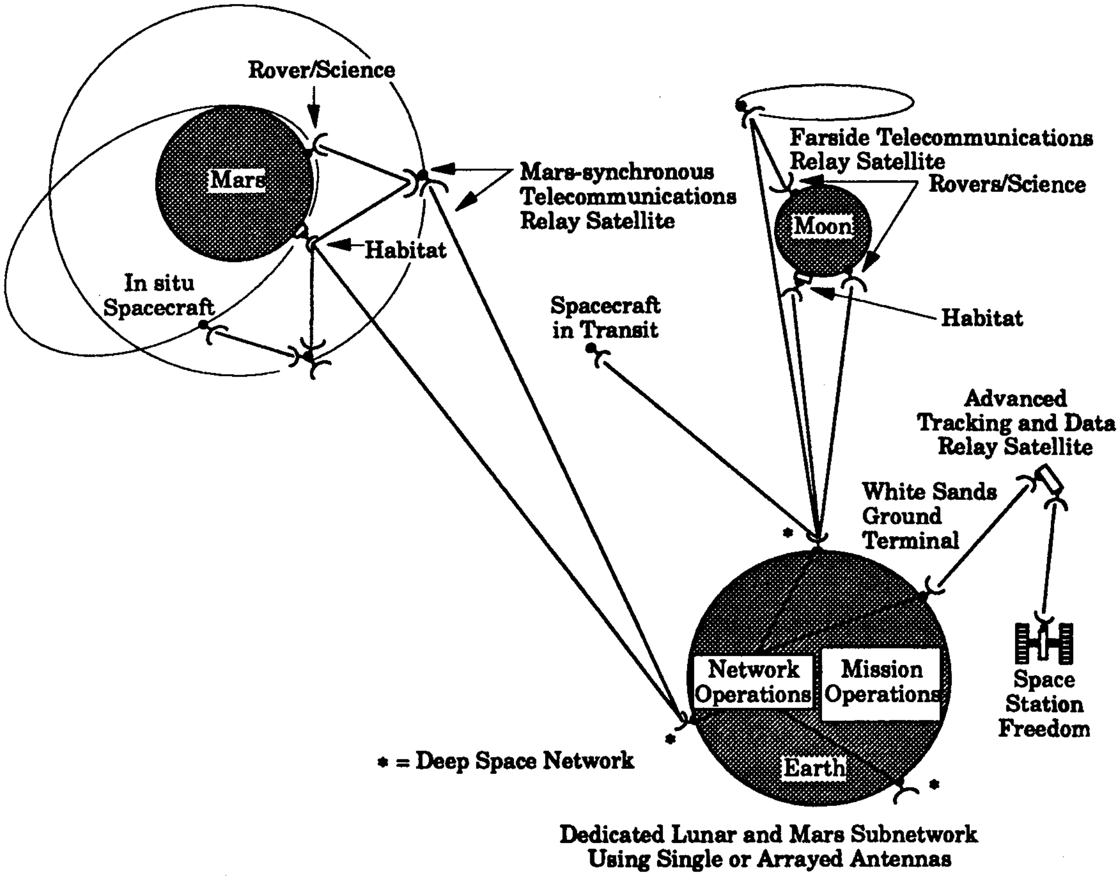


Figure 5-6 Telecommunications Architecture for the Human Exploration Initiative

The entire system will be required to function as one distributed end-to-end entity. Maximum use of data system standards will be necessary. Unattended expert systems will manage and move data and messages, using automatic path selection, message switching, and data buffering.

The robotic missions of the Initiative will require enhancement of the current Deep Space Network to provide nearly continuous support starting in 1995 at the Moon and in 1998 at Mars, continuing until the piloted missions begin. For planning purposes, present development plans to replace the oldest 34-meter antennas and prepare for installation of Ka-band capabilities are assumed to be completed on schedule.

Commitments of the Deep Space Network to science and applications flights will be honored, and support for the robotic missions will be provided incrementally as the mission sequence proceeds. Existing capabilities will support the Lunar Observer, but requirements will increase substantially as Mars missions begin.

The Mars Global Network mission will deploy multiple landers over large areas of Mars; their primary path for communication to Earth will be the spacecraft bus that carries them to Mars. Before their arrival at Mars, a third 34-meter subnetwork will be added to the Deep Space Network to provide continuous support. The equipment and facilities of the Deep Space Network's signal processing and network operations control center will also require upgrading to support this subnetwork and the associated multi-downlink operation. Overall support requirements at Mars will further increase during the next century as additional missions are initiated and completed.

Two telecommunications relays for Mars robotic missions will be launched with the Mars Site Reconnaissance Orbiter to support that orbiter and subsequent rovers.

The Human Exploration Initiative will be supported by a dedicated Earth subnetwork with ground stations at existing Deep Space Network complexes. For Mars support, multiple antenna arrays will supply the required downlink performance and provide for multiple simultaneous uplinks. Each Deep Space Network ground station will support the Mars missions with arrays of up to four 34-meter Ka-band antennas. The subnetwork will be designed for human-rated reliability and for lunar-Mars cross-support.

At the lunar outpost, users will communicate with Earth through two paths: to the outpost terminal by a hardwire or a line-of-sight ultrahigh-frequency link, and then to Earth, or through a direct link to Earth. Lunar transit vehicles will also be able to communicate directly to Earth. These Moon-to-Earth links will be supported by up to two 34-meter antennas installed at each complex of the Deep Space Network. Up to four data channels per antenna can be supported.

On the lunar farside, dispersed elements will be linked to the surface system terminal by hard-wired interfaces, and then via the relay satellite to Earth. Farside elements beyond the line of sight of the surface system terminal will use radio links through the relay satellite to Earth. The Mars surface systems will be supported in a similar manner, but will depend more on telecommunications relays to link with Earth.

A centralized, dedicated support facility will control and monitor the Earth-based tracking and data acquisition network and assess the quality of the science, engineering, monitor and control, and radiometric data handled. The capability will exist to simultaneously support seven separate processing data strings with redundancy for both lunar and Mars elements. Unattended operations techniques will be developed using expert systems. As these techniques mature, they will be implemented to upgrade the lunar operations system and will eventually be incorporated into the Mars operations system. Expert systems may reduce the number of operators required for operations and data quality assessment, permit rapid detection of data path failures, and provide automatic rerouting to available channels.

An additional monitor and control center for telecommunications relay satellite operations will use telemetry to monitor spacecraft subsystem condition and consumables and will generate commands to change modes and position and maintain performance. Initially, this center will support robotic Mars mission telecommunications relay operations beginning in 2003; in that phase, it will also serve as a test-bed for later operations support of lunar and Mars telecommunications relay satellites.

To enable unattended telecommunications at Mars, a system will be designed for all elements at Mars for signal acquisition, data transfer, and remote mission operations support. The system will be initiated on the Moon using an operator-attended capability. Advanced systems will be developed during the early phases of the lunar outpost, beginning with an Earth-based operator-attended capability. Unattended systems will be developed during the early lunar exploration program. Operators can monitor the systems in parallel with automated operations and intervene whenever necessary. Lunar signal acquisition and data transfer operations would eventually evolve to an unattended mode design for Mars operational use.

A lunar telecommunications relay satellite may be positioned in a halo orbit 60,000 kilometers behind the lunar farside to provide coverage for orbiting vehicles, farside surface terminals, and possibly the critical orbit insertion of piloted vehicles.

Telecommunications relay satellites at Mars are necessary not only to maintain communications with Earth, but also to communicate from the surface to vehicles in orbit and between those vehicles. Two such satellites will be placed in stationary orbit about Mars a year before the first piloted mission arrives. A relay satellite network significantly improves the connectivity and the performance of both Mars-to-Earth and local Mars links. The relay network will provide redundant and backup communications links, as well as emergency links to Earth. Another function of Mars relay satellites will be to support a ranging link to provide important Mars-centered navigation range data to an approaching spacecraft a few days before the critical aerocapture maneuver.

The Earth-based support system for the Human Exploration Initiative provides navigation and acquisition pointing and frequency-prediction parameters for the lunar and Mars telecommunications relay satellites, acquisition predictions for Earth stations, and backup navigation support for the mission elements.

The existing Earth-based navigation system will be upgraded for planetary exploration applications. Required accuracies can be achieved by ranging and Doppler techniques supplemented by very long baseline interferometry tracking techniques.

The mission navigation center on Earth will process radiometric data from Earth tracking stations, spacecraft-acquired optical data, and relative range or Doppler data from spacecraft to spacecraft or other elements in the system. Planetary surface beacon locations will be precision-calibrated using very long baseline interferometry.

Circuit-connect terminals would be included at the Deep Space Network complexes and NASA communications network nodes to enable use of network circuits as needed. Communications between the Deep Space Network complexes and mission control centers must accommodate lunar, Mars, and space transfer vehicles, and other scientific programs.

Compatibility test areas will be provided to test and validate the interface between mission and telecommunications elements. Mobile stations and permanent test areas, including five vans, one integration compatibility test area, and one launch compatibility test area, are required. The test systems will emulate telecommunications relay satellites, ground stations, data processing elements, and network monitor and control functions and interfaces during mission development, integration, and launch preflight operations.

Meeting Human Needs in Space

Section 6

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SECTION 6

Meeting Human Needs in Space

The human element is a critical aspect of the Human Exploration Initiative, and protecting and sustaining the lives of space explorers is of the utmost importance. The success of this bold and exciting enterprise means accommodating human needs in environments that are hostile and exceptionally different from Earth, at distances never encountered in human history, for durations never achieved by any space program. Fundamental differences between space and Earth – the lack of gravity, inadequate atmospheres, deep cold, and radiation hazards – challenge technological ability to protect, nurture, and sustain the crew members who will be the pioneers of the solar system.

The health and safety of crew members while they travel to and from the Moon and Mars and inhabit planetary surfaces are key near-term concerns. The explorers must be protected from the space radiation environment and from the physiological effects of reduced gravity. To maintain the fitness and productivity of the crew, medical care must be provided during long stays in very isolated and distant places.

Solutions to these concerns are at the heart of the very feasibility of traveling to Mars and living for extended periods on the Moon and Mars. A ground-based and flight research program must provide an understanding of the physiological basis for human responses, develop appropriate treatments and countermeasures, and decide how best to support crew members.

Simulating the environment that will be inhabited by crews on the Moon and Mars is an important facet of the research program. Much of the work can be done on the ground, but many studies will require access to space facilities. For short-duration simulations and tests, the Space Shuttle and Spacelab will be used. Space Station Freedom will be a test facility for research that demands long exposures to the reduced gravity loading conditions in spacecraft and on planetary surfaces. In preparation for Mars missions, research on the Moon will be vital.

In many cases, alternative solutions exist to problems faced by humans. For example, countermeasures can be developed for physiological degradation due to reduced gravity loading on long-duration missions, advanced propulsion systems can be developed to shorten travel time, or vehicles providing an artificial gravity environment can be developed. As the challenges of sustaining humans in space are resolved, advances in fundamental science, medicine, and technology will follow.

Radiation Protection

Earth's magnetic field protects our planet from radiation emitted by solar flares and shields it from a large fraction of galactic cosmic rays. When space missions travel beyond that magnetic shield, the radiation received is different in type and intensity from that received on Earth and in low Earth orbit, and the effects of the radiation on living cells are different. The radiation dose beyond Earth orbit could exceed projected exposure limits for astronauts, and without adequate protection, crew exposure to high radiation dosages in solar flare events could cause devastating effects, including radiation sickness and even death. The long-term chronic effects of exposure to galactic cosmic rays could include genetic damage, cataract formation, and cancer.

Radiation protection goals for the Human Exploration Initiative fall into three categories: determination of career dose limits and development of countermeasures that can reduce the adverse effects of radiation exposure, provision of sufficient radiation shielding in planetary habitats and in the Mars transfer vehicle to protect both crews and sensitive equipment from the normal galactic cosmic-radiation background, thereby extending the length of time that crews can safely remain in these environments, and provision of warning systems and "storm shelters" to protect crews against the transitory but extreme levels of radiation encountered during solar flares.

As in the past, NASA will rely on The National Council on Radiation Protection and Measurements guidelines, which recommend short-term and career radiation-exposure limits for astronauts. However, these limits are based on the characteristics of radiation present in low Earth orbit, where Earth's magnetic field and atmosphere provide protection from solar flares and galactic cosmic radiation. A Mars mission would exceed the current annual dose limit guideline. Revised radiation exposure standards for human exploration missions outside Earth's protective magnetic field will have to be developed. The standards must take into account, in the context of the inherent risk of exploration missions, the risks associated with the specific types of space radiation, such as solar particle events and galactic cosmic radiation, and their biological effects outside low Earth orbit. Even after exploration guidelines are established, NASA will provide a system of radiation protection that adheres to the ALARA principle (As Low as Reasonably Achievable), which recognizes that, although an acceptable upper limit of exposure is set, the residual risks should be minimized even further where it is reasonable to do so.

Determination of allowable doses will require better information on the effects of high-energy galactic cosmic rays on living matter. Space radiation experiments will be conducted during the 1990s using a reusable, polar-orbiting biosatellite (currently in the definition phase) with living biological specimens, including plants, rodents, cell and tissue cultures, and other small organisms. These experiments will provide information on the biological effects in zero gravity of the unique spectrum of the space radiation environment. These effects can also be studied, in part, using artificial radiation sources at the Brookhaven National Laboratory, Lawrence Berkeley Laboratory, and other radiation research centers. The ground-based research program will generate new information on the biological effects of high-energy heavy ions and secondary particles, and will develop and test dosimetry technology.

Solar flare particles require different shielding strategies than galactic cosmic radiation. Because of the high energy of galactic cosmic radiation, extremely thick shields would be required, so it is generally not feasible to use shielding. Protection afforded by propellant and water tanks may prove useful. For modest shielding thicknesses, the secondary radiation spectrum produced by the interaction of the galactic cosmic radiation with the shielding material may be more harmful to living tissues than the primary dose. On planetary surfaces, the planet shields against half the cosmic radiation received in space. The martian atmosphere, particularly at lower elevations, provides substantial additional radiation protection. In addition, habitats can be covered thickly enough with local materials to shield against cosmic rays and the secondary radiation they produce. Nevertheless, individual radiation doses will need to be monitored, and the galactic cosmic radiation dose will probably be the ultimate limiting factor for human exploration. At the lunar outpost, current plans envision occasional prolonged periods outside the habitat for construction and scientific activities. Any crew member's activity outside the habitat may be limited by exposure to background radiation levels for long periods of time in relatively unshielded suits.

The most acute source of space ionizing radiation for Moon and Mars explorers is a solar particle event, which accompanies some solar flares. The amount of radiation can be so large that the dose the explorers would receive significantly exceeds all limits, and can result in rapid death. However, to protect the explorers for limited periods, "storm shelters" can be constructed in the most heavily shielded areas of the spacecraft and habitats, and can be provisioned with sufficient consumables to maintain humans for the maximum estimated duration of a solar particle event (from a few hours to several days). The storm shelter and more protected areas of the Mars spacecraft could be occupied by the crew on a rotational basis during transit to provide added protection from galactic cosmic radiation.

To develop the best radiation shielding strategies for the lunar and Mars habitats and the transportation vehicles, robotic missions will help to determine the nominal background radiation encountered during transits to and from the

Moon and Mars, as well as on the planetary surfaces, and will measure radiation doses received during solar particle events. These radiation environments will then be modeled and simulated using ground-based radiation research facilities to determine the effectiveness of various shielding materials in protecting living tissues. The results of these studies will influence habitat and vehicle designs.

A system for alerting the crew is essential to planning extravehicular activity traverses, which would not be scheduled for periods in which a flare was expected. Warning must be received in sufficient time to allow the crew to return to the habitat or storm shelter before the buildup of radiation from an unanticipated flare puts the crew at risk. Solar flares are currently unpredictable to the extent that warning times at a spacecraft may be as short as 30 minutes. Improved predictions will require long-term observations of the magnetic field of the Sun and its relationship to solar flares, and specific warning systems will need to be developed.

A plan for providing solar alert/prediction services is based on three evolutionary space mission elements: an orbiting solar laboratory, a solar monitor, and a global set of solar monitors. The orbiting solar laboratory will carry a 1-meter-class solar telescope with several diagnostic instruments to monitor the onset of flares in the next cycle of solar activity. On the basis of experience with the orbiting solar laboratory, a solar monitor will be developed and placed at the Earth-Sun libration point. This monitor would be able to continuously see the Sun and would provide solar flare warnings to the lunar outpost.

When human missions to Mars are under way, a set of four identical orbiting solar monitoring stations around the Sun will be necessary, because flares that can threaten the crew on Mars may not emerge from parts of the Sun seen by a single spacecraft. However, crews on Mars missions should also have at their disposal a simple solar X-ray imaging telescope to provide flare prediction/alert capability.

Reduced Gravity Countermeasures

Microgravity exposure reduces the forces normally imposed on the body on Earth by a factor of 1 million. Previous spaceflight experience has shown that significant physiological changes occur during exposure to such reduced gravity loading; most notably, bone mineral loss, muscle atrophy, and cardiac deconditioning, all of which become more severe as stay-time in space increases. Although it is generally believed that these effects can be minimized if crews take certain preventive measures while in space, the problem of developing effective countermeasures to reduced gravity loading is significant.

So far, both the U.S. and the U.S.S.R. have relied heavily on exercise regimes, usually vigorous and protracted, to provide the desired countermeasures. At the present time, it is not known whether exercise will be capable of maintaining crew health for very long missions. Additionally, astronauts will have difficulty maintaining the required exercise program (2 to 4 hours a day) for the protracted periods envisioned for most exploration missions. If an astronaut were to suffer an accident or a serious illness and be unable to exercise, more severe deconditioning would result.

The major concern relates to the long transit times to Mars and to the demands placed on the crews immediately upon arrival at the martian surface. The baseline transit time to Mars is 300 days in zero gravity, followed by an estimated aerobraking environment of several times Earth gravity. In the case of a flyby abort, the astronauts would remain in reduced gravity for 3 years, which far exceeds either U.S. or U.S.S.R. experience. Exercise, nutrition, and pharmaceutical countermeasures show promise in controlling the adverse physiological effects of long-duration exposure to reduced gravity loading. Also, three alternative Mars transit options exist: shorten the outbound and return transit times by using advanced propulsion systems, employ artificial gravity countermeasures within the spacecraft either by providing an on-board centrifuge or by spinning the spacecraft itself, or accept the higher risk involved and proceed with the mission using the best available countermeasures. A zero-gravity transit has the advantage of more habitable volume (i.e., ceilings and floors) available for use by the crew, whereas artificial gravity has the advantage of providing Earth-like conditions.

A zero-gravity countermeasures program will test and evaluate a series of strategies on the Space Shuttle and Extended Duration Orbiter during the early 1990s; subsequently, primary tests will be conducted on Space Station Freedom. Within 5 years of initiating the countermeasures program on Space Station Freedom, crew stay-time in orbit will increase from 90 days to 120 days, then to 180 days, and finally to more than 300 days to simulate the Mars transit. If significant physiological deconditioning occurs, crew members will be returned to Earth early, and a modified countermeasures protocol will be followed with the next crew members. During the countermeasures program, crew members serving as test subjects will perform normal operations in support of Space Station Freedom. Countermeasures developed to mitigate the most severe deconditioning effects of microgravity will be used at the lunar outpost and on Mars to maintain crew health and performance in these reduced gravity environments.

Zero-gravity countermeasures may not be sufficient to maintain crew health and performance for a Mars mission. Adverse physiological changes due to reduced gravity loading may be prevented by exposure to some level of artificial gravity, but the specific level of gravity and the duration of the exposure that is necessary to prevent deconditioning are not yet known. Some level of artificial gravity should amplify the effectiveness of exercise countermeasures. Although artificial gravity should reduce or eliminate the worst deconditioning effects of living in zero gravity, rotating environments frequently cause undesirable side effects, including disorientation, nausea, fatigue, and disturbances in mood and sleep patterns. Significant research must be done to determine appropriate rotation rates and durations for any artificial gravity countermeasures.

The decision on whether artificial gravity must be employed to adequately support crews on their transits to and from Mars, as well as the decision on the necessary gravity level and rotation rate, has significant implications for vehicle design and operations. Life sciences requirements for artificial gravity must be developed using an integrated approach combining physiological studies and engineering feasibility. Preliminary physiological requirements can be developed using ground facilities to simulate weightlessness, fractional gravity, and rotational effects. For example, slowly rotating rooms can be used to examine the chronic physiological effects of continuous rotation.

The results of these studies will determine which strategies are necessary to maintain crew health during long-duration exposure to different gravity environments. Research conducted on the lunar surface will provide important information about the effects of the Moon's one-sixth gravity on humans. This will be an early data point in determining whether fractional gravity levels can

Meeting Human Needs in Space

Requirements:

- Ensure health of crew members by developing countermeasures to extended exposure to reduced gravity environments
- Protect crew members from the effects of long-term exposure to radiation
- Provide the means to predict and assure the stability and productivity of small groups living in extended isolation
- Ensure reliable life support for multi-year missions

Strategy:

- Evaluate the effects of exposure to reduced gravity and radiation using the Extended Duration Orbiter, Space Station Freedom, and biosatellites
- Use Space Station Freedom to develop, test, and evaluate countermeasures
- Use the lunar outpost for a test-bed and research base for life and medical support, human factors and behavior and performance, habitats, and countermeasures

assist in maintaining human health and performance. A decision will be made early in the next century on whether the Mars transfer vehicle can be designed for zero gravity, or whether it must be an artificial-gravity design.

Medical Care

Specific capabilities are critical for monitoring and maintaining crew health and for sustaining a high level of performance and productivity both in transit and on the surface of a planet. Health systems will be required to provide appropriate medical care, environmental monitoring and regulation, and optimization of human performance. The approach to health and performance systems is to evolve toward increasingly higher levels of self-sufficiency during the consecutive phases of emplacement, consolidation, and operation of the lunar and Mars outposts.

The crews members on exploration missions will be few in number, situated in remote locations, and unable to return immediately to Earth in the event of a medical emergency. Therefore, on-site medical care will be needed to accommodate major and minor illnesses and injuries and to provide critical surgical capability. The design of space medical care systems will adhere to acceptable U.S. standards.

Providing medical care in remote locations is a challenge that has traditionally been met with immediate services for stabilizing illness or injury and the ability to transport a patient to a medical facility that provides an optimum level of care. Experience in remote Earth and spaceflight settings has shown that medical care is essential in returning crew members to normal activities, averting serious illness, and preventing unnecessary medical transport operations.

The Shuttle Orbiter Medical System provides the capability for inflight treatment of minor illness and injury. For lunar transfer vehicles, lunar excursion vehicles, and pressurized lunar surface rovers, which are away from a central facility for periods of only a few days, an expansion and modification of this system will be utilized.

Space Station Freedom will have a compact medical care unit, the Health Maintenance Facility, which will support diagnosis, monitoring, transmission of patient status to the ground, and treatment of medical, minor surgical, and dental conditions. Medical care systems for lunar and Mars outposts and for the Mars transfer vehicle will build on and expand the capabilities of the Health Maintenance Facility to include inpatient, outpatient, and dental care as well as medical care during the return of critically ill or injured crew members to a facility that would provide more intensive support. They will also provide enhanced Earth-based support systems, in-space support, medical computer-aided artificial intelligence systems, and Earth-to-remote locations telemedicine capabilities using state-of-the-art telecommunication systems for consultation in diagnosis and treatment. As time spent on planetary surfaces increases, medical care capability will also expand to provide diagnosis, laboratory analytical capabilities, anesthesia, surgery, and pharmaceutical support. Hyperbaric facilities to treat occurrences of "the bends" will be needed for all spacecraft and habitats from which extravehicular activity is conducted.

One unique issue related to medical support on Mars is that the martian surface material itself may present a health hazard to the crew. Analysis for toxic and irritating substances and for any potential biological hazard must be done prior to human exploration; the Mars sample return mission is planned to directly address this issue.

Research and advanced development to extend the shelf-life of certain pharmaceuticals and blood products are required, as are the development and test of operational procedures in reduced-gravity and zero-gravity environments. The capabilities will be demonstrated using Moon and Mars advanced development health maintenance facility test-beds.

Supporting Human Life

Maintaining a safe environment for human habitation goes beyond the minimum required to sustain life through the provision of adequate air, food, water, and waste handling systems. The habitable environment must provide appropriate medical monitoring and care, be monitored for radiation exposure, and provide shielding appropriate to mission operations. The environment must be continuously monitored and controlled for the presence of toxoids, either microbial or physico-chemical, and it must maintain appropriate temperature, humidity, and atmospheric composition. The buildup of minor toxic substances in a tightly closed environment (the "tight building" syndrome) is a major design concern, and control mechanisms must incorporate provisions for effective removal and simple routine maintenance. Analytical methods need to be developed to predict or simulate the toxic buildup rates and projected levels and sources for extended lunar and Mars missions.

It is a major challenge to provide a reliable, cost-efficient life-sustaining environment in locations that are naturally devoid of food, air, water, and nutrients. Without these commodities, there can be no exploration, no reaching out, no discovery. Life support systems for exploration will provide these commodities in all phases of the exploration missions: traveling in space transfer vehicles, living in surface habitats, and working on planetary surfaces. These systems must have capabilities for air revitalization, water purification, food supply, waste processing, environmental monitoring and contamination control, thermal and humidity control, and fire suppression.

Perhaps the biggest challenge will be the development of regenerative life support systems, which could eventually provide food as well as recycle wastes, with a subsequent reduction in the quantity of supplies that must be transported from Earth. However, little is known about the operational characteristics and risks associated with long-term operation of regenerative life support systems, which have not been tested on humans in situations closely simulating the space environment. System performance must meet a variety of standards ranging from nutritional requirements to environmental quality.

Current intravehicular life support systems provide a habitable environment in space, but they are costly. Food is stored, air is recycled, and most water must be resupplied from Earth. By mass, water is the most important commodity. Humans require a minimum of about 6 kilograms of water, air, and food each day. In addition, if the crew is to bathe, wash dishes, flush toilets, and wash clothes, the need increases to about 20 kilograms per day. The Space Station Freedom program is developing systems that will use recycling technology to supply a portion of the potable water and part of the hygiene and wash water for the crew. Later, regenerative oxygen revitalization and more complete drinking water recycling will be added. For the Mars transfer vehicle, development of a more highly regenerative system, a natural evolution from the Space Station Freedom systems, is possible. For planetary surface facilities, most of the development work can be ground-based; however, testing and verification of performance in the surface facilities will be critical and may pace the rate of expansion of lunar and Mars outposts.

Guidelines for the design of life support systems for Human Exploration Initiative activities are: use closed-loop systems wherever practicable to reduce logistics requirements; use open-loop systems wherever power, mass, volume, and operational requirements dictate, or where development timelines preclude the use of a closed-loop system; and, for habitats and long-duration transfer vehicles, provide for life support system growth and evolution as technology progresses.

If the success of the exploration missions depends on the ability of humans to work on and explore planetary surfaces, then this success will depend on productive extravehicular activity conducted at great distances from Earth's support systems. During these missions, astronauts will be exposed to a range of gravity conditions and a diversity of environments. With the normally intense activity expected on the exploration missions, issues of productivity, usability, durability, and maintainability of extravehicular activity systems become acute. Operational and medical considerations will include prebreathing procedures, life sustaining system capability, environmental health, radiation protection, and emergency-mode operations. Allowing humans to make the transition simply and effectively between activities inside and outside vehicles will both enhance productivity and increase overall mission safety. Extravehicular activity systems must be provided for the Moon, Mars, and space operations in orbit and in transit.

Repeated, productive surface activity for 4 or more hours each day for up to 6 days a week is a requirement. Planetary surface systems, including suits, will have to be maintained by the crew, and must be resistant to contamination by surface materials such as dust. Extravehicular activity systems must provide a safe, non-toxic environment, with food and water supplies that are nutritious, esthetically pleasing, and free of contamination. In addition, several operational considerations are important to the effective use of suits or other individual mobility devices. The first consideration is to minimize the time needed to go from inside the spacecraft out to the planetary environment; of particular importance is the difference between habitat pressure and the pressure of the extravehicular activity system. The greater the difference, the more time must be spent adjusting to the generally lower outside pressure, in order to avoid the bends. The second consideration is to maximize time available for productive activity outside the spacecraft; suit mass and the ability to supply food and remove waste are particularly important. It is important to minimize restrictions on human capability by providing adequate thermal control, greater suit mobility – in particular in the gloves, torso, and boots – and enhanced communications capability for explorers and home base interactions. A third overall requirement is the maintainability of the system, allowing reuse without extensive overhaul.

Current capabilities in planetary surface extravehicular activity systems are derived from Apollo systems, which provide an excellent starting point for future missions. For long stays on planetary surfaces, however, these systems do not meet the stated mission requirements in most areas. Apollo technology equipment is not maintainable, and it is too massive to use on Mars, where the gravitational level is 0.38 that of Earth's. The Space Shuttle and Space Station Freedom systems are even more massive and were designed for only limited use in microgravity environments. New systems will be required and will evolve from enhanced space suits similar to those now in use; in addition, development of teleoperated tools that will allow an astronaut within a closed mobile chamber to manipulate devices outside the chamber may be incorporated and could blur the line between suits and habitats.

In the area of microgravity extravehicular activity, there have been significant advancements, though maintenance and refurbishment requirements are still too high for the Space Shuttle suit. Space Station Freedom suit development will greatly improve glove technology beyond that of Apollo, but higher suit pressures continue to be a major challenge. Existing portable life support systems are large and require extensive logistical support. However, the in-space needs of the exploration missions may be satisfied by the advanced system being developed for Space Station Freedom.

Suit development is an area that will require focused research and technology efforts emphasizing lightweight and durable materials, glove design, dust contamination protective measures and techniques, lower torso mobility systems for walking, ancillary mobility systems for surface transportation, long-term reusability and lightweight, compact, portable life support system technologies.

Behavior, Performance, and Human Factors

Space environments, like other isolated and confined environments, induce stress; additionally, there are physiologically induced stresses. If not appropriately managed, combined environmental and physiological stress is likely to result in behavior and performance deterioration during long-duration space missions. Humans have never embarked upon spaceflight missions approaching the scale of exploration now envisioned; the best analogs so far may be Antarctic expeditions and undersea experiences. Although no Earth-based analogs are perfect, such analogs provide insight into some of the unique attributes present in space exploration–alteration of day-night cycles, telecommunications to outpost operations, absence of other living creatures, self-sufficiency, and profound isolation–that affect crew dynamics and performance on space exploration missions. Using the analog environments and specialized ground simulation facilities as test-beds, and building on data obtained from Space Station Freedom and the lunar outpost, strategies will be developed to support the increasingly complex and demanding Mars missions.

The exploration missions must be carefully examined from a space human factors perspective. The key issue is the effect that prolonged exposure to the spaceflight environment has on individual psychological and behavioral functioning and on crew effectiveness and performance. Psychological, social, perceptual, and behavioral conditions affect crew performance, productivity, and safety. Spacecraft architecture and outfitting are particularly relevant because they can either enhance or reduce effective performance. Decisions made in all these areas drive habitat design, and it is clear that for long-term, extended missions, crew accommodation volumes will need to be larger than those on Space Station Freedom.

Crew composition will be based on personal and interpersonal characteristics that promote smooth-functioning and productive groups, as well as on the skill mix needed to sustain complex operations. Studies addressing these areas and the influence of task and authority structures and introduction of new members and unfamiliar crews, need to be conducted to determine effects on crew performance and productivity. Positive interactions and communications between the ground and the crew during all segments of the exploration missions are essential. In addition, task assignments for lengthy missions must be perceived by the crew members as productive and significant. Performance time-lines must be developed that are realistic in utilization of crew time and skills. Based on the studies, crew training, task assignments, and support strategies will be developed, implemented, and monitored.

Crew composition, training, and skill retention will be studied in ground-based laboratories, simulations, and analog test-beds. A ground-based lunar simulator will be developed to evaluate concepts, procedures, and equipment to gain an understanding of human factors and psychosocial issues related to crew performance and lunar habitat design and operation. A Mars transfer vehicle simulator will also be developed and will incorporate data obtained at Space Station Freedom and from lunar outpost operations. One of the major issues for long-duration missions is cross-training, which is necessary because of the limited or non-existent capability for return to Earth in the event that a crew member becomes incapacitated. The small number of crew members compared to the large range of tasks to be performed requires a high degree of proficiency in multiple specialty areas and the retention of that skill when opportunities to practice it are limited. In addition, since crew members may dedicate entire careers to one mission, career development and training take on greater importance.

The studies discussed above will result in the definition of effective design and functional standards, environmental and operational requirements, individual and group stability parameters, and authority and command structures. The results will ensure that the crew members are physically and mentally able to perform the required tasks and that the systems, equipment, spacecraft, habitat, rovers, vehicles, tools, and operations are designed to promote safe and effective performance.

Science Opportunities and Strategy

Section 7

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Science Opportunities and Strategies

The Human Exploration Initiative will significantly advance science as robots and astronauts explore the Moon and Mars and use their surfaces for observatories and laboratories. The act of exploration will provide new insights into the natural history of the bodies visited and prepare our explorers to use them for practical purposes. But one of the major contributions of the Initiative will be learning truths that can be extended beyond the Moon and Mars themselves to help us to understand the past and look into the future. Studies of the early history of Mars, its subsequent evolution, and its possibility of indigenous life, and of the Moon and its relationship to Earth, will help us to understand the past. With this broad understanding of the past, we will be in a better position to look into the future of our own planet, the solar system, and the universe. Described below are some fundamental scientific themes that can be uniquely addressed by the Human Exploration Initiative, and around which a science strategy can be built.

Five Fundamental Themes

How were Earth and the Moon born, and what was their shared early history?

Earth's internal differentiation into a core, mantle, and crust and its subsequent history of volcanism and plate tectonics were controlled by its initial composition and thermal state. The initial composition is related to Earth's position relative to the Sun. The initial thermal state depended on dynamic factors: the inner solar system may have been a relatively violent place toward the end of its formation, with a large number of Moon-sized or larger bodies that commonly collided; or it may have been a quieter place with a few large bodies and few Moon-sized bodies. What were the early processes that led to its differentiation and, especially, to the formation of Earth's core with its magnetic field? What, also, is the relationship of the formation of Earth to that of the Moon? Most of the evidence for this period has been lost on Earth, which has undergone 4.5 billion years of mountain building, erosion, metamorphism, and recycling of surface materials. Only by studying other solar system bodies, particularly the Moon and Mars, can we shed light on this question.

Whether they formed in a quiet or violent early solar system, the Moon and Earth are inextricably linked, and comparing Earth, the Moon, and Mars from a global perspective will be important to our understanding of them and the early solar system. Studying the Moon provides a unique baseline by which we can understand the development of crusts on the other terrestrial planets, including Mars. In addition, meteoroid impacts in the first half billion years of solar system history have modified the surfaces of the Moon, Mars, and Earth. On Earth, most of the direct evidence has been lost, but the Moon preserves the record of later bombardment by comets and asteroids, and these kinds of events may have changed the course of life's evolution on Earth.

Resolving these questions requires human presence to do in situ field geology and subsurface geophysics, using tools traditional to the field geologist: observation, sampling, analysis, and integration, using instruments to probe the interior and thoroughly explore the surface. Special emphasis must be placed on exploring areas that preserve evidence of interior composition and on searching for volcanic rocks that have carried fragments from the deep interior to the surface. Global mapping is required to extend surface details to a planet-wide context.

Did life ever start on Mars?

Mars today is inhospitable to life as we know it because its atmosphere is thin, and water is not stable in its liquid form (it does exist, but as vapor in the atmosphere and ice on the surface and in the subsurface). The thin martian atmosphere also permits harmful radiation to reach the surface of Mars with essentially unabated intensity. Abundant evidence exists that water once coursed through channels and came to rest in ponds and lakes, which are now all dry.

Life existed on Earth 3.5 billion years ago, and it must have started earlier. Conditions on Earth were similar to those on Mars at that time — warm and wet, with a carbon dioxide and nitrogen atmosphere, high rates of volcanism, and impact by meteoroids.

By systematically exploring the surface of Mars, seeking geological evidence on the extent and duration of the wet period on Mars, and examining rocks and sediment for evidence of organic compounds or fossils, we can assess the possibility that life developed there, and we can answer many other questions about the planet's evolution and history. The capability to explore, probe, sample, and analyze the variety of rocks and soils on the planet will allow us to understand its interior structure, composition, age, and surface processes for comparison to the other planets of the solar system as we develop an understanding of the life cycle of planets.

What is the relationship between the Sun, planetary atmospheres, and climate?

Earth's climate is the result of a complex interplay between energy from the Sun and the characteristics of the magnetosphere, atmosphere, oceans, permanent ice fields, and land surfaces. Humanity has reached the stage at which its actions can also influence Earth's habitability. In the next century, Earth faces the prospect of planet-wide environmental change, including climate warming, sea level change, deforestation, desertification, ozone depletion, acid deposition, and reduction in biodiversity. To prepare to meet this challenge, an understanding must be developed of how Earth works as a system, and the ability to predict and manage change must also be developed. Observations of Earth from the global perspective of space will be essential for comprehensive, long-term, continuous monitoring of the entire planet, for diagnosing Earth's state, and for providing an early warning system for change.

The study of other planets is also important, because they hold information on the longer-term variations of the Sun and on the processes that control or moderate global changes. The Moon serves as a unique site for synoptic viewing of Earth's magnetosphere, which can provide long-term information about the distribution of solar energy and the consequent warming and cooling of Earth's upper atmosphere.

Evidence for liquid (i.e., water) on Mars indicates that its climate was warmer and wetter in its early stages. Since the early Sun is thought to have been less luminous, it is widely believed that this warmer, wetter climate may have resulted from an atmospheric greenhouse effect that overcompensated for the weaker Sun. Study of the nature and effect of greenhouse phenomena has obvious significance for Earth, which now may be experiencing global warming due to a greenhouse effect.

The current martian atmosphere has a low atmospheric pressure, and surface temperatures range from well above the freezing point of water near the equator to low enough to condense carbon dioxide at its winter pole. How long have these conditions prevailed, and can the climatic conditions be extrapolated into the past? What is the relation of the upper atmosphere to conditions at the surface? Dust storms commonly arise locally and may grow to global scale within a few days, dramatically changing the circulation and temperature of the atmosphere. What are the physical processes that control the initiation of these storms and their evolution to the global scale? There is evidence that Mars currently is losing atmospheric constituents. What are the mechanisms that contribute to this loss?

These questions can be uniquely addressed by the detailed exploration of the Moon and Mars, and by conducting long-term observations of the Sun, Earth, and martian atmosphere.

Are there worlds around other stars?

The least-explored astrophysical domain is the solar system-sized regions around other stars. This is the realm of planets–but are there any? This is the unique zone for other life in the universe–but is it empty? Only a large, powerful observatory, such as we would be able to build on the Moon, can study this frontier in great detail.

Scientists believe that a chain of common astrophysical events produced our solar system: gravitational collapse of interstellar clouds, nucleation of a protostar, flattening of a disk of gas and dust, and accumulation of planets that differentiate and may yield life, as Earth did. We have never found other planets, because no current telescopes are capable of that challenge. A large telescope on the Moon could search for and, more important, characterize planets around hundreds of nearby stars to address the habitability of extrasolar planets and possibly detect, indirectly, the presence of life.

What is the fate of the universe?

A major, long-standing quest of the human intellect has been to understand the origin and fate of the universe. We know now that the present intricate and beautiful structure of the universe on the large scale, as well as the fundamental laws of physics on the smallest scale of elementary particles, was established in the early universe. However, if the universe originated in a "big bang" event and is now closed or nearly so, we can account for only about 90 percent of its mass in what we have already observed. Detailed observations of galaxies, galactic halos, cold matter, and other properties of galactic structures formed over the history of the universe are needed to better understand this missing mass. A complete understanding of the mass of the universe will allow a determination of whether the universe will forever expand, or whether it will ultimately contract to a central nucleus. The space-based Great Observatories, the foundation of the Nation's space astronomy program in the coming decade, will permit astronomers to study in unprecedented detail the character of the very early universe by looking at events that occurred when the universe was only 10 to 20 percent of its current size. Looking back further in time, by looking at more distant sources, will be made possible by the following generation of lunar observatories.

The behavior of the Sun will be an important scientific field in the Human Exploration Initiative, for its own sake and also because solar flares and their emissions of energetic charged particles are significant hazards to humans in space. However, the Sun's astronomical significance lies in calibrating and understanding the nature of stars, which the next generation of observational instruments will be able to study in detail. As instruments approach the resolution necessary to detect extrasolar planets, stars can be studied in more detail.

Science Opportunities and Strategies

Exciting and productive opportunities exist to advance science through both the robotic and human exploration phases of the Initiative. The robotic missions to the Moon and Mars will significantly enhance our scientific understanding of these solar system neighbors. When human explorers arrive on the scene, the opportunities will multiply. Studies of the early history of Mars, its subsequent evolution, and its possibility of indigent life, and of the Moon and its relationship to Earth, will help us to understand the past. With this broad understanding of the past, we will be in a better position to look into the future of our own planet, the solar system, and the universe.

The fundamental scientific themes that can be uniquely addressed by the Human Exploration Initiative are:

- How were Earth and the Moon born, and what was their shared early history?
- Did life ever start on Mars?
- What is the relationship between the Sun, planetary atmospheres, and climate?
- Are there worlds around other stars?
- What is the fate of the universe?

A Scientific Strategy for the Moon and Mars

The themes and questions identified above can be addressed by the Human Exploration Initiative through the study of the Moon and Mars, and through the establishment of laboratories and observatories on the Moon. The advancement of exploration and science skills of human explorers and the machines that assist them will require learning and experience in the new environments. Outstanding opportunities and strategies for conducting the scientific program are addressed below, and establishing priorities among detailed scientific objectives will be an important facet of planning for the Human Exploration Initiative.

Exploration of and from the Moon

Lunar studies made possible by the long-term presence of humans will allow us to probe many questions that are crucial to the theme: *How were Earth and the Moon born, and what was their shared early history?* Studies of lunar surface materials can also contribute to resolving issues in the theme, *What is the relationship between the Sun, planetary atmospheres, and climate?*

The U. S. Apollo and U. S. S. R. Luna missions in 1969 through 1976 conducted the first detailed surface investigations of the Moon. Because of that set of investigations, the Moon has become a cornerstone in planetary science, used as a basis for comparison when new information is obtained on the origin and evolution of the planets.

To both understand the Moon and prepare for human exploration, the next stage in lunar exploration is the Lunar Observer, a polar orbiting spacecraft capable of obtaining global information about the Moon's surface chemistry, mineral composition, magnetic properties, gravity field, topography, and the possible presence of frozen volatiles at the lunar poles. It will also provide improved global imagery as well as high-resolution imagery of selected sites. Aimed at improving global models of the Moon's origin and history, this mission also is essential for locating optimum sites for future scientific studies and for globally characterizing the material resources of the Moon.

Among the first objectives of human explorers at a permanent lunar outpost will be the scientific investigation and characterization of the outpost's physical environment. One of the exciting opportunities for the geosciences is that the presence of humans, able to select new samples and respond to observations with new experiments, will bring lunar science to a traditional scientific mode of activity so successful for geoscience on Earth. Like terrestrial geologists, scientists on the Moon will rely on remotely sensed data to characterize the places that they should visit in the field, then interpolate and extrapolate their field observations to form models consistent with other data. Samples collected either robotically or by the explorers will be examined at the outpost, and preliminary assessments will be made of their character and importance. Based on the preliminary analysis, additional samples may be returned to Earth for detailed studies.

Accessing important geological features is essential to the continued advance of scientific understanding, and a site should be selected to optimize its science return over a period of tens of years of operation. Geoscientists on the Moon will initially have the capability of exploring the local vicinity of the outpost site in detail, and as the outpost capability matures, scientists will have a global range of operation.

Throughout the Human Exploration Initiative, automated rovers, teleoperated from Earth or from the Moon, will be essential to the science strategy. These rovers will be capable of observing (by television), analyzing (through a range of detectors), and collecting samples to return to the outpost. In addition, they will be capable of emplacing remote instrument packages. They could range hundreds of kilometers from the early outpost, but they should have global capability in later phases. At first they would be teleoperated, but as experience and technology advance, telepresence (giving the remote operator the feeling of being on the vehicle) can be developed. The evolution of the robotic capability will also be important for Mars exploration.

The emplacement of a global geophysical network by robots and astronauts has high priority for lunar missions. The network would contain seismometers to probe the Moon's local and deep internal structure to attempt to determine whether the Moon has a core. Additional heat flow measurements are necessary to determine the thermal characteristics of the Moon. The network can also conduct lunar electrodynamic studies, sensing the lunar atmosphere and lunar dust movement. Plasma, magnetic field, electric field, and energetic particle sensors can fully characterize the various radiation and electrical responses of the Moon to the natural inputs from the Sun, the interplanetary medium, and Earth's magnetosphere.

Investigations carried out from the Moon are at the heart of the strategy for the themes *"Are there worlds around other stars?"* and *"What is the fate of the universe?"* and will contribute to the study of the Sun needed to address the theme *"What is the relationship between the Sun, planetary atmospheres, and climate?"*

The Moon is a massive natural space station, well-suited as a site for a 21st Century observatory. The Moon is airless, so the entire electromagnetic spectrum can be studied; its surface is virtually free of vibration from internal seismic energy, allowing instruments to be precisely positioned and aimed; and on its farside, the body of the Moon shields observatories from natural and anthropogenic emissions from Earth. Because of its low gravity and the absence of winds, large instruments can be constructed, allowing improvements in radiation-gathering power. Because the Moon rotates slowly, continuous observations could be made over periods of days of dynamic phenomena that occur on other planets, the Sun, and the stars. The Moon is at an appropriate distance from Earth to allow synoptic viewing of Earth's magnetosphere, and its monthly transit of Earth's magnetotail makes it possible to study the boundary regions of the magnetotail in detail. Human intervention is important, because some of the facilities will be complicated to construct and install, and instruments can be changed as detector technology or scientific objectives change.

Astronomical observatories on the Moon would take advantage of the unique lunar environmental conditions to extend capabilities beyond those achieved by the Hubble Space Telescope and other Great Observatories planned for the 1990s. The earlier emphasis on the outpost will be on two types of instruments: powerful optical (ultraviolet, visible, infrared) telescopes, and arrays of smaller telescopes, interferometrically linked to synthesize a single large phantom aperture. Each type can be approached in an evolutionary way, beginning with small instruments or modules that can grow as the capability for emplacing and operating them grows.

The Moon offers its greatest astronomical advantage for a class of instruments called optical interferometers, which are arrays of telescopes and a beam-combining station all joined by a precision laser position-measuring system. The purpose of the measuring system is to ensure that light from a star field travels identical distances through each of the telescopes to the beam combiner. The paths must be kept equal to within fractions of a micron over distances of hundreds of meters. If this criterion is met, the pattern received by the beam combining station can be converted by a computer into an image of the star field. The resolution of detail in the resulting image would be as fine as would be expected from a single telescope with an aperture as big as the separation of the individual telescopes of the array.

The airless, stable lunar surface with its low seismic activity makes the Moon an ideal base for interferometers. These modular instruments can be transported to the Moon in pieces, and their scientific value increases as more modules become operational. They are, therefore, ideal for an evolutionary lunar outpost program. A lunar optical array at ultraviolet, visible, and infrared wavelengths will study fundamental astrophysical phenomena, from the central engines of quasars and active galaxies, which generate huge amounts of energy by processes not understood, to the terminal explosions of massive stars. By making the telescope an element of the interferometer array, the sensitivity of the entire array could be increased dramatically.

Just as the ultraviolet, visible, and near-infrared interferometric array will provide a window on hot astrophysical sources, an associated submillimeter wavelength array will open a window on the cooler material of the universe generally associated with the formation of stars and planetary systems. With the submillimeter array, we will synthesize high resolution images of stellar systems at birth and learn how the disks and jets believed to be connected with star formation are tied to the processes by which planetary systems appear.

The Moon would allow the study of the universe in a region of the electromagnetic spectrum not accessible from Earth or Earth orbit. Low frequency radio waves from astronomical sources are blocked from ground-based telescopes by

Earth's ionosphere, and too much terrestrial interference, both natural and artificial, may exist to observe these waves using artificial satellites. An array of detectors on the farside of the Moon would provide both high resolution and shielding from Earth's noise. Since this is an unexplored wavelength region, it is not possible to accurately forecast its scientific importance; however, new information on quasars and interstellar plasmas would be expected. The basic elements of the array could be tested early in a lunar outpost program using a small array at a nearside location on the Moon.

The Moon can also be an excellent place from which to conduct planetary observations. In addition to the large telescopes and interferometers described above, the establishment of a 2- to 3-meter ultraviolet, visible, and infrared telescope can substantially contribute to studies of the terrestrial planets and the atmospheres and surfaces of the outer planets and their satellites. The capability to make hours-long observations would make possible the study of the progress of dust storms on Mars and volcanic emissions on the Jovian moon Io. The capability of using the Moon's limb to mask the Sun would open Mercury, Venus, and comets near the Sun to extended study.

Imaging Earth's magnetosphere from a lunar outpost can address a high priority new science effort in magnetospheric physics. Resonantly scattered sunlight and spectroscopic signatures of fast neutral atoms can render the plasmas that envelop Earth visible. Instrument sensitivities and designs are available that will allow the acquisition of these images of Earth's ring current, plasmasphere, and elements of the magnetotail every 5 minutes. This will allow the distribution of energy from the solar wind to Earth's upper atmosphere to be studied synoptically for the first time. The lunar outpost will provide an excellent platform for acquiring these observations because of the Moon's optimal distance from Earth and its capability of continuous observation.

In addition, two areas of high-priority cosmic ray physics research can be uniquely carried out on the Moon. The first is an experiment to determine the composition of cosmic rays with energies above 10^{15} electron volts. The experiment would consist of a sandwich of thin, plastic, active particle detectors brought from Earth interleaved between passive sections consisting of trays approximately 30 centimeters deep, filled with lunar soil, forming a cubical structure about 4 meters on a side. The passive sections cause cosmic ray interactions that are sensed by active detectors. The Moon is a unique site for such an experiment, as the lunar regolith can be used as the bulk of the passive (160 ton) detector. This large detector mass makes an Earth-orbiting satellite version of this experiment impractical.

The study of the physical processes responsible for forming chemical elements relies on detailed measurements of the relative abundances of all the elements and their isotopes in a variety of samples of matter. Galactic cosmic radiation, consisting of atomic nuclei that have been accelerated to relativistic speeds, is of unique importance because it carries to Earth fresh matter from supernovae and other galactic sites that could not otherwise be studied. The techniques rely on measuring nuclei having energies too low for entry into Earth's magnetic field, except over a small range of latitudes near the poles. Thus, the Space Shuttle and Space Station Freedom are not suitable platforms for these studies, and even a polar orbiting platform can provide only low efficiency for collecting the particles of interest. The Moon, lying outside Earth's magnetic field and having no appreciable atmosphere to stop these particles, provides an ideal site for large experiments to measure cosmic ray composition. Likewise, the Moon will be an excellent platform for measuring the composition of the solar wind, as a probe of the composition of our own Sun.

The lunar surface also offers opportunities for exobiology, which seeks to understand the origin, evolution, and distribution of life on Earth and throughout the universe. The Moon was shown by study of Apollo samples to be devoid of organic matter and any evidence of life, consistent with its history as a dry, atmosphereless body. However, for just that reason, the Moon is an excellent place to sample and analyze materials for traces of organic matter that may have been carried to the Moon by meteorites or comets, which can be used as tracers for the flux of these materials to the Moon and Earth over time. As our lunar exploration capabilities expand, analyses will be performed on samples from the polar regions and the deep subsurface for possible prebiotic molecules delivered by cometary impact.

The search for planetary systems around other stars is of high importance to the life sciences. If planets can be found, their characterization as possible abodes for life and evidence for the possible existence of life will be a foremost enterprise. In addition, NASA currently is undertaking a radio telescope search for signals emanating from advanced civilizations. In the period of the Human Exploration Initiative, this search may have to be continued from the Moon because Earth's radio environment is becoming increasingly noisy and will likely restrict the opportunities to conduct such investigations from Earth.

Gravity has shaped life on Earth through 2.5 billion evolutionary years. Internal and external biological organization responds to gravity's demands in countless subtle ways. So pervasive and constant is its influence, and so completely has life adapted to it and evolved utilizing its constant reference, that gravity's role in directing biological processes was largely ignored in life sciences research until the space program both underscored its importance and provided opportunities to experimentally explore the gravity continuum at less than Earth's normal gravitational force.

A life sciences research laboratory on the Moon would allow fundamental research in both animal and plant physiology, concentrating on the processes of reproduction, growth, development, and aging, using the combination of sensitive developmental stages and controlled gravitational exposures to elucidate response mechanisms. It would address fundamental questions concerning how living organisms perceive gravity, how gravity is involved in developmental and physiological regulation, and how gravity has affected evolutionary history.

The lunar biology laboratory would also provide a means of undertaking long duration experiments in radiation biology. The goals are to study the stability of cellular DNA to determine the effects of radiation on both gametogenesis and developmental processes, and to determine the frequency of malignant cell transformations subjected to high radiation from proton, neutron, or galactic cosmic ray bombardment.

The Moon's suitability as a platform and laboratory relies on unique characteristics of the lunar environment. However, the lunar environment is not necessarily stable if contaminants are introduced into it. The instruments left by Apollo recorded residual contaminants several months after the astronauts returned to Earth. As humans begin to inhabit the Moon, it will be important to monitor the lunar environment and determine the mechanisms by which human activity can degrade it. By starting early in the exploration program to learn about the effects of human habitation on the Moon's surface, it should be possible to preserve the lunar environment.

Exploration and Study of Mars

The exploration and study of Mars can uniquely address the theme *"Did life ever start on Mars?"* It can make unique contributions to our understanding of *"What is the relationship between the Sun, planetary atmospheres, and climate?"* and augment our understanding of *"How were Earth and the Moon born and what was their shared early history?"* by adding Mars to the list of terrestrial planets studied intensively.

Mars is a diverse planet with evidence of intense volcanic activity, weather associated with its thin atmosphere, indications of a past atmosphere that was denser and able to support liquid water at the planet's surface, and evidence that suggests water deposits as permafrost in higher latitudes. These observations indicate that Mars's geological history is intermediate between that of the Moon and the Earth, as befits its intermediate size, and suggest that life could have existed in the past. It is much less likely that life, if it started, could have persisted in the present cold, dry environment. Geoscience, climatology, and exobiology merge in their interests to study the planet intensively.

A science strategy for the exploration of Mars has been recommended for many years by the National Academy of Sciences' Space Science Board and other scientific advisory bodies. The strategy requires capabilities that systematically address the wide range of science issues, including global mapping from Mars orbit to determine the distribution of rocks at the surface and study geophysical and atmospheric properties; emplacing a network of geophysical stations to probe the interior structure and obtain long-term global weather data; returning samples to Earth for detailed study in order to understand chemical composition, mineralogical makeup, evidence for biological activity in the past, age of major features, and nature of weathering processes; and regionally exploring the planet's surface to extend the compositional information, interpolate between local observations and the global data base, and investigate unique locations for evidence of past life or water-related processes.

Two types of information not heretofore considered essential to the robotic scientific strategy for Mars are important if we are to send humans there. The first type will make human operations safer or improve the capability to design systems to operate in the Mars environment. This includes data on atmospheric structure (for the design of entry vehicles), on surface hazards to landing and mobility (mainly through high resolution imagery), on trafficability of the surface, and on the presence of materials that could be toxic or debilitating to human activity. The second type, valuable to the long-term habitation and utility of an outpost on Mars, could include clues to the location of water, ice, or other resources, data on the capability of the soil to support the growth of plants, or information that allows an outpost site to be selected that will enable an optimum long-term scientific investigation program.

A complete sequence of robotic missions, described in Section 3, is proposed for the Human Exploration Initiative to meet both the fundamental science objective of understanding Mars and the informational needs of human exploration. The mission elements utilize robotic systems prior to sending humans to Mars, then take advantage of the humans to further explore and investigate the scientific problems as they learn to live and work on Mars.

The strategy for Mars exploration utilizes robots in the form of planetary orbiters, landers, rovers, and sample return missions to build the base of understanding of the planet and locate the best sites to advance science and exploration in the human phase. Each of the robotic missions would be multidisciplinary, addressing at the appropriate scale, and at an appropriate place in the strategy, the questions of geoscience, climatology, and exobiology.

Throughout the robotic exploration phase, our geological, biological, and climatological models of Mars will improve. A major result of that improvement will be our understanding of landing targets that will optimize additional important scientific observations by humans who will collect specific samples and emplace geophysical stations. Such observations will confirm or reject hypotheses developed in the robotic phase and initiate an era of more intensive scientific exploration concurrent with the first human habitation of the planet's surface.

Humans will make valuable contributions to the Mars science objectives because of their capability to extrapolate their observations, interpret subtle clues, assimilate information, and revise their exploration strategy in real time. No scientist currently believes that the discovery of past life will be straightforward. The probability that the question will be resolved by robotic experiments is small; the data, whether positive or negative, will need to be confirmed by direct human observation.

Evolution of human capability at a Mars outpost will parallel that for the lunar case. In early stages, it is likely that the mobility of humans will be limited, but dependable and versatile long-range robotic rovers should already have been developed. As the outpost grows, the range of the human explorers should grow as well, eventually providing global access.

Relationships to Current Programs

Advancing science through space research missions and the use of space platforms to improve the quality of life on Earth are central to NASA's mission. The way in which we Americans view our Earth, our solar system and universe, and our opportunities for the future are directly related to the accomplishments of the NASA space science and applications programs. To an important extent, the Human Exploration Initiative is already underway in the science missions that have begun to elucidate conditions in space and on the Moon and Mars, through Earth- and space-based studies.

NASA's experience in planetary exploration is important to our understanding of Earth. Comparison of Earth to Venus and Mars, for example, has heightened our understanding of the greenhouse effect. The planetary exploration program, in addition, has demonstrated the power of simultaneous measurements by various sensors and the merging of data sets to obtain new insights into planetary phenomena.

In the coming years, a Mission to Planet Earth will allow us to examine, understand, and predict changes in Earth's environment. This knowledge will, in turn, help us to understand other planets as well.

The next few decades promise to be exciting and productive for space science. A program of human exploration of the Moon and Mars will renew additional opportunities held in abeyance since Apollo. The base program of space science in NASA is well prepared for a renaissance of human exploration.

Technology Assessment

Section 8

SECTION 8

Technology Assessment

One of the principal challenges of the Human Exploration Initiative is to build a program that is credible in costs and schedules for critical near-term technology development and at the same time is cognizant of the broader spectrum of technologies that enable longer-term program goals. Success in meeting this challenge depends upon a solid understanding of state-of-the-art engineering systems, as well as a feasible projection of what can confidently be achieved through focused research, technology development, and system-specific advanced development programs.

Figure 8-1 illustrates the strategy for developing technology to meet the objectives of all phases of the Human Exploration Initiative. Because adequate lead time is essential to technology development, focused research begins in the early 1990s and advances with program milestones. In this section, specific areas of high-priority technology development that will follow this strategy are discussed in detail, and summary sketches of other areas of technology development needed for the Initiative follow.

Technology Drivers

Prior to the landing of the first system for the lunar outpost, one or more orbital missions may be launched to survey the Moon for resources and to certify the landing site. The current reference mission to meet this need, the Lunar Observer, requires no notable new technology developments.

Concurrent with the Lunar Observer and the establishment of the lunar outpost, a series of robotic missions to Mars will develop the scientific, engineering, and technology foundation upon which subsequent human missions will be based. These missions require a variety of major technological developments. The long-lived Mars Global Network will need durable power supplies, impact-tolerant electronics and instruments, and the technology for deep subsurface penetration. The return of samples from specific sites on Mars mandates capabilities for autonomous landing, rendezvous, docking, and techniques for sample acquisition, analysis, and preservation. Extended-range rovers on Mars need mobile power, onboard and ground-based automated operations, and mobility. Use of aerocapture at Mars requires advances in aerothermodynamic modeling of the martian atmosphere, thermal protection systems for the aeroshell, and adaptive guidance, navigation, and control.

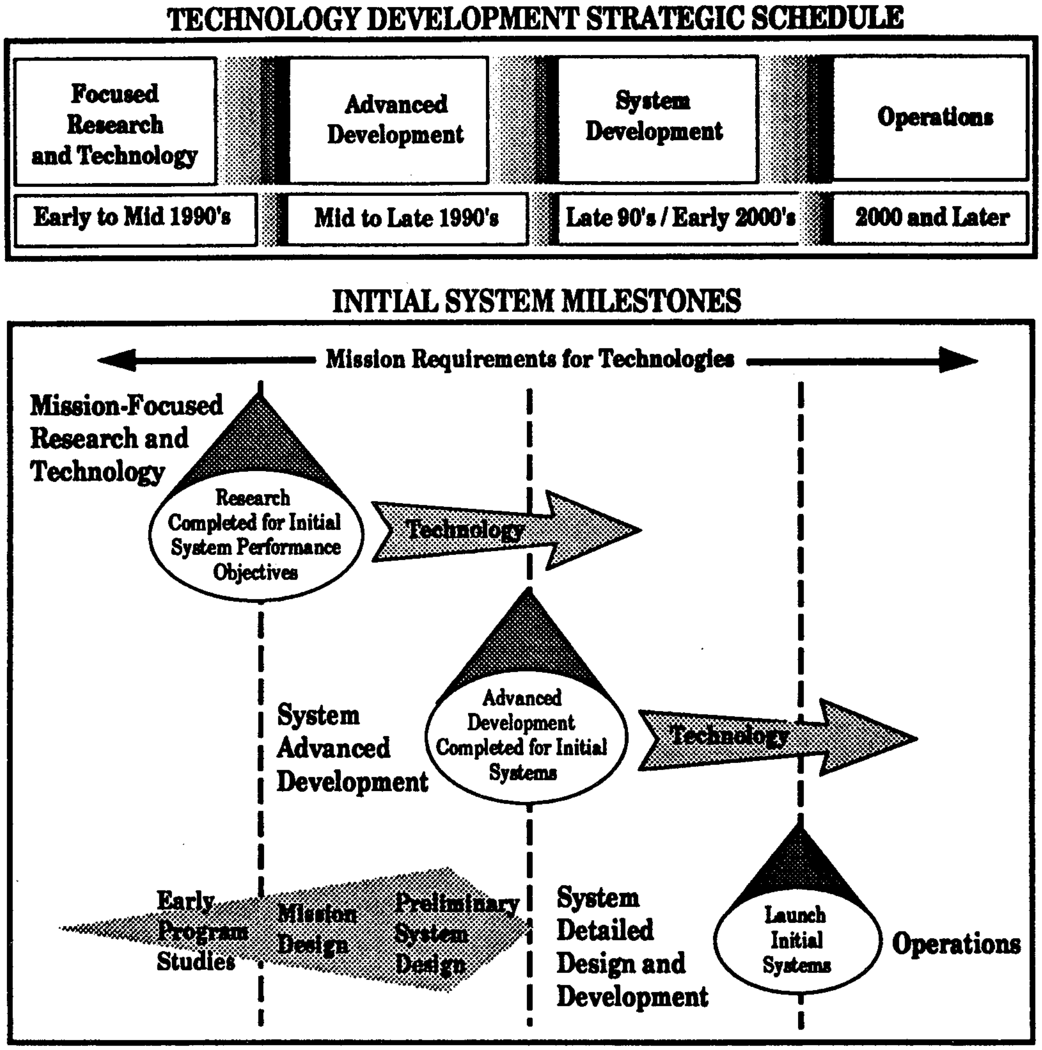

Figure 8-1 Exploration Technology Development Strategy

Our technological inheritance from the Apollo Program could permit short-term expeditions to the Moon without any significant advance in technology. However, establishing a long-term lunar outpost will require major advances in engineering capabilities in lunar surface systems, transportation, and low-Earth-orbit operations.

For lunar surface activities, several innovative systems must be implemented over more than a decade. These systems will require development of technologies for low-cost, highly reliable life support, extended extravehicular activity, and high capacity power generation at the lunar surface, including generation of power during the 354-hour lunar night. Transportation and in-space operations will involve a family of closely coupled systems: Earth-to-orbit transportation systems, Space Station Freedom elements, and space-based vehicles for transportation to the lunar surface. Space-based vehicles must be reliable and reusable with high-performance cryogenic engines and space-assembled, reusable aerobrakes. Techniques will be needed for in-space cryogenic propellant handling, storage, and transfer, and for vehicle assembly and processing at Space Station Freedom. Technology must also be developed for automation of the planning and execution of outpost operations, information processing, software engineering, and training techniques.

Human exploration and settlement of Mars will build directly on the technologies developed for and proven during the robotic phases of the Mars and lunar outpost missions. Sending humans to Mars will mandate developments in almost all areas of technology. In particular, major advances will be required in life support for the Mars transfer vehicle and Mars surface habitats, space transportation (large, reusable aerobrakes for the Mars transfer and excursion vehicles), in-space operations such as vehicle assembly and processing, and surface systems such as construction equipment.

A number of technology requirements apply to more than one mission element. These include substantial increases in ground and surface operations automation; in-space system autonomy; diverse applications of advanced electromechanical manipulator systems, using control approaches ranging from teleoperation, through telerobotics, to full robotics; and requirements for data and control system components and software that increase the fault tolerance of system operations, including automated fault detection, isolation, and resolution. Across all phases of the Human Exploration Initiative, human safety and health during long-duration missions will have high priority and will pace and direct technology development.

Assessment of Critical Technologies

A major challenge of human settlement of the Moon and Mars is the need to dramatically decrease the total mass that must be launched into low Earth orbit and transported to the lunar and Mars surfaces. Although additional factors, such as crew time, power, and servicing requirements, are very important, reducing launched mass is an overarching need for long-term self-sufficiency and acceptable operations costs. Critical technologies in regenerative life support, aerobraking, and advanced space-based cryogenic engines must be developed to substantially reduce the mass of near-term systems. Mid-term technologies critical to decreased mass are surface nuclear power, in situ resource utilization, and radiation shielding. In addition, although human expeditions to Mars can be conducted using cryogenic propulsion and aerobraking, nuclear propulsion presents a compelling prospect for tremendously reducing the mass or travel time required. Development in each of these seven technologies–regenerative life support, aerobraking, cryogenic engines, surface nuclear power systems, in situ resource utilization, radiation protection, and nuclear propulsion–needs to be accelerated. These areas are described in detail below.

Regenerative Life Support Systems

The piloted vehicles and pressurized surface systems planned for use on the Moon and Mars will require life support systems with varying degrees of capability. For the lunar outpost, short-term life support will be required for the lunar transfer and excursion vehicles. Long-term life support will be required for both emplaced and constructed lunar habitats, as well as for the Mars transfer vehicle.

The state of the art in technology for environmental control and life support is the physical-chemical open-loop system used on the Space Shuttle, which supports 7-day maximum flights followed by ground-based maintenance and resupply. This state of the art will be enhanced in the Space Station Freedom open-loop support system, which provides some closure of the water cycle and is designed for on-orbit resupply, repair, and maintenance approximately every 90 days.

Also, numerous factors of outpost operations preclude long-term reliance on Earth-based servicing; for example, the costs of transportation to a lunar outpost, the long duration of Earth-Mars transits (14 months nominal round-trip time, and 36 months for an abort mission), and the duration and remoteness of Mars surface operations (up to 600 days without resupply). Regenerative life support systems will provide enormous mass savings for exploration systems and operations. In situ recycling of life support resources, especially air and water, could reduce the launch mass by 20 kilograms for each crew member each day of the mission.

Research and technology development for both physical-chemical and bioregenerative life support systems is in progress. Because of the time required to achieve technology maturity, early lunar outpost elements will rely on physical-chemical life support systems derived almost entirely from Space Station Freedom systems. The initial lunar outpost habitat may be equipped with more technologically advanced systems. Concurrently, life support research and technology development for Mars-mission vehicles and surface systems can achieve required levels of maturity by about 2006.

Regenerative life support systems for constructible habitats, planned for use on both the Moon and Mars, can incorporate improved technologies that enable high levels of closure, high reliability, and in situ maintenance and repair. These improvements will reduce operations costs and mission risks.

To improve current and projected life support systems, technology development is needed in the critical areas of air revitalization, water purification and/or reclamation, waste management and processing, air and water quality control, and sensors and processors for reliable environmental monitoring and autonomous operations. All systems must be designed for high reliability, in situ maintainability, and a high degree of system autonomy. Complete closure of the life support system for long-duration human surface operations on the Moon and Mars will, of course, require local food production. Although not critical, complete closure is a major strategic program option. NASA is currently researching controlled ecological life support systems to determine their feasibility, and is beginning to plan for eventual integration of bioregenerative life support subsystems into physical-chemical life support systems.

Critical Technology Assessment

Technology Areas	Benefits
• Regenerative Life Support Systems	• Enables strategic self-sufficiency goals • Annual mass savings of 45 metric tons
• Aerobraking	• Essential for cost-effective space transportation • Annual mass savings of 60 metric tons
• Advanced Space Engine	• Essential for cost-effective space transportation • Annual mass savings of 30 metric tons
• Surface Nuclear Power	• Enables strategic self-sufficiency goal • Mass savings of 315 metric tons
• In Situ Resource Utilization	• Enables strategic self-sufficiency goal • Annual mass savings of 315 metric tons
• Radiation Protection	• Essential for strategic Mars goal
• Nuclear Thermal Rocket Propulsion	• Potentially reduces Mars trip time to 200 days • Mass savings of 360 metric tons

Aerobraking

Aerobraking is a technique whereby the atmosphere of a planet is used to decelerate a spacecraft and change its trajectory, instead of using costly propellants to achieve the same results. Aerobraking is needed for space transportation for the lunar outpost, robotic Mars missions, and human flights to Mars; thus, reusable aerobrakes might provide substantial total cost savings. An aerobrake is considered low- or high-energy depending on the incoming velocity of the spacecraft on which it is mounted and the resultant heat generated by deceleration; both present technology challenges. Knowledge relating to low-energy aerobraking comes from the Apollo program and current experience with Space Shuttle flights. The Space Shuttle program has produced a base of ceramic thermal protection technology and of computer modeling and computational fluid dynamic techniques for determining aerodynamic and aerothermodynamic characteristics. However, the combined Apollo and Shuttle experience covers only simple blunt configurations operating in a narrow corridor; these programs have yielded very limited data relative to in-space aerobraking. For high-energy aerobraking, Apollo-era ablative thermal protection materials represent the state of the art. These materials are inherently heavy and cannot meet desired design goals. Although not required, high-energy aerobraking, especially for the return to Earth from Mars, is a significant option that could further reduce the weight of the Human Exploration Initiative flight systems.

For lunar transfer vehicle designs currently under study, the use of an aerobrake for deceleration into low Earth orbit would reduce initial mass in low Earth orbit by approximately 20 percent for each flight. Thus, a fully loaded lunar transfer vehicle with crew would weigh approximately 30 metric tons less, saving approximately 60 metric tons per year during steady-state lunar outpost operations. The savings would be even greater — perhaps as high as 50 percent — for a lunar transfer vehicle that was fully reusable, had no drop tanks, and used a lighter aerobrake. For each Mars sample-return mission, initial mass in low Earth orbit can be reduced by approximately 45 percent by the use of aerocapture rather than all-propulsive orbit insertion at Mars. The aerobrake can also be used for entry into the Mars atmosphere, providing additional savings.

Efforts are already underway within NASA to develop the technologies needed for aerobraking. Within the Civil Space Technology Initiative, the Aeroassist Flight Experiment will provide in-space validation of computer models by the mid-1990s. An integrated technology program for interplanetary aerobraking (in particular, for high-energy aerobraking) is also in progress. Key areas for technology development include low-mass high-strength composite materials for aeroshell supporting structures; thermal protection materials for both the lunar transfer vehicle and robotic Mars mission aeroshells; adaptive onboard guidance, navigation, and control for robotic Mars applications; and analytical computer codes for the martian atmosphere. Technology readiness for an initial lunar transfer vehicle flight in 1999 or 2000 may be very difficult to achieve. However, readiness for post-2000 robotic Mars spacecraft and post-2010 piloted missions to Mars should be achievable.

Cryogenic Hydrogen-Oxygen Engines

A family of advanced cryogenic hydrogen-oxygen propulsion systems will be required for the Human Exploration Initiative. The most important of these is the moderate-thrust (90 kilonewton class) engine with a specific impulse of about 480 seconds for the lunar transfer vehicle and 460 seconds for the lunar excursion vehicle. Related technology developments in high-thrust (e.g., 900 kilonewtons) cryogenic engines and in integrated, cryogenic attitude-control thrusters will be needed for the Mars transfer and excursion vehicles. Critical design developments include space-basing, high thrust, throttling (for landers), reusability without servicing at Freedom or on the Moon, and small engine size for aerobrake compatibility.

The only upper-stage, expander-cycle cryogenic engine currently in operation is the RL-10. Although physically quite large, the RL-10 reliably provides only about 70 kilonewtons of thrust, with a specific impulse of approximately 444 seconds. However, with upgrades, the RL-10 could provide the capabilities essential to cost-effective lunar outpost operations. In addition, a long-term NASA program has been under way for several years to develop components for more advanced high-performance space-based cryogenic engines. Among these developments are high-speed turbomachinery, high heat transfer combustors, large-area-ratio nozzles, and engine-health monitoring systems.

The lunar transfer and excursion vehicle systems will use an advanced space engine to achieve greater specific impulse, space-basing, throttling capability, and long life with multiple starts. Advanced space engine technology improves on that for RL-10 engines by saving approximately 16 metric tons of initial mass in low Earth orbit (10 percent of total) for each lunar transfer vehicle delivery of a fixed payload to the Moon.

Building on its foundation of basic research and technology development in engine components, NASA has initiated a program to integrate early component-level technology into breadboard engines, including that for essential throttling and in situ engine-health monitoring capabilities. An accelerated program of major research and technology development and advanced system development could provide technology readiness for advanced space engine production and flight in 1999 or 2000.

Surface Nuclear Power Systems

The initial lunar outpost will require approximately 100 kilowatts of continuous electric power for operations (including habitat life support), research (such as in situ resource utilization experimentation), and maintenance of surface systems. As initial lunar outpost systems evolve toward more permanent installations, including full-scale lunar oxygen production, requirements for power will grow to several hundreds of kilowatts or more. Solar power systems (photovoltaic arrays and regenerative fuel cells) can provide the lower levels of power, but they require relatively frequent system maintenance and significantly more mass than space nuclear power systems, especially on the Moon with its long nights. A space nuclear power system would provide power in the 100-kilowatt range, limited total system mass, long life, and high reliability. For production of 100 kilowatts of power at the lunar outpost, a nuclear system would provide a savings of more than 300 metric tons in initial mass in low Earth orbit when compared with advanced photovoltaic arrays and regenerative fuel cell energy storage. Later, when the lunar outpost requires 1,000 kilowatts of power, use of photovoltaic and regenerative systems rather than nuclear systems would result in a penalty of more than 1,800 metric tons in initial mass in low Earth orbit.

Beginning with the early part of the consolidation phase of the lunar outpost program, nuclear reactors offer the only cost-effective approach to providing high levels of continuous power for the lunar outpost. In the far term, surface nuclear power may provide the long-lived, highly reliable power necessary for Mars surface systems.

The state of the art in space nuclear power systems is represented by radioisotope thermoelectric generators that typically provide about 250 watts of power. However, research programs in progress will lead to more powerful systems. The SP-100 program, sponsored and managed jointly by NASA, the Department of Defense, and the Department of Energy, will provide ground validation of a space reactor system and technologies yielding thermoelectric conversion efficiencies of approximately 3 to 4 percent. Those advances will make possible a space reactor power system that produces about 100 kilowatts of power and has a projected system lifetime of 7 to 10 years. Another NASA research and technology development program has the objective of producing more advanced subsystems for thermal-to-electric conversion. This program will produce more efficient solid state converters and a dynamic conversion subsystem (with a Stirling-cycle heat engine) that could generate power levels up to 1,000 kilowatts using the same SP-100 space reactor system with multiple dynamic conversion units.

Key areas for technology development in the SP-100 program include the space reactor system, thermal control systems, and thermal-to-electric conversion technologies including solid state thermoelectric converters and dynamic conversion systems such as Stirling engines, and thermal control systems. If the program continues on schedule, technology readiness for lunar surface applications should be achieved by the mid-1990s, permitting possible development and launch of a flight system by about 2003. For the initial human outpost on the Moon in 1999 or 2000, photovoltaic arrays and regenerative fuel cells employing high-pressure gaseous storage or cryogenic liquid storage of reactant gases will have to be used until a space nuclear power system becomes available in 2003 or 2004.

In Situ Resource Utilization

The use of nonterrestrial resources can provide substantial benefits to a variety of future space activities by dramatically reducing the amount of material that must be transported from Earth to a planetary surface. For example, through the processing of lunar rocks and soil, liquid oxygen could be produced for propulsion and life support, and the lunar soil could be a source of materials for construction and radiation shielding. In situ resource utilization will rely on technology development in resource processing and mining and beneficiation. Substantial application of robotics to mining and handling equipment and of automation to processing equipment will be critical, given the limited work force on the Moon and Mars. In situ resource utilization is a critical component of long-term, largely self-sufficient outpost operations.

Although resource processing has been the subject of considerable study, very little technology has been developed for nonterrestrial utilization of in situ resources. Lunar samples have been studied extensively, and several processes have been proposed for producing lunar oxygen and other materials, such as ceramics, metals, and construction components. The most promising of those processes are based on either chemical-thermal or electrolytic processes. However, little process engineering has been done to date, and no single process can be considered to be proven for long-term use in the lunar outpost.

No experience from the Apollo program or from Earth-based operations can be applied confidently to lunar mining or beneficiation systems. The only complex mechanical equipment operated on the Moon during Apollo was the lunar rover, a low-mass vehicle that had a minimal power supply, did only light work, and had a very brief required lifetime, with no servicing. Related Earth-based equipment is typically very massive, requires routine servicing, and employs high levels of mobile power. Some degree of automation is being implemented in terrestrial mining operations, but it is unclear whether systems for long-term lunar use can be derived directly from Earth-equipment experience. Beneficiation concepts, including electrostatic and magnetic separation, have undergone some laboratory experimentation. Early results suggest that low gravity and low electrical conductivity may actually improve process performance and reduce system mass and power requirements.

Nearly 85 percent of the propellant mass required for the Human Exploration Initiative Earth-Moon transportation system is oxygen, which is also the principal constituent of the lunar soil, at about 42 percent. Although precise specifications vary, a typical objective for lunar outpost in situ resource utilization is to produce approximately 50 metric tons of liquid oxygen per year, beginning in about 2010. This oxygen would be used in lieu of liquid oxygen brought from Earth for use in lunar-based transportation systems. Given a full-scale production plant with a mass of approximately 50 to 100 metric tons, the payback period in terms of simple mass to the lunar surface would be 1 to 2 years, depending on final production requirements. In situ resource use could achieve a total savings in initial mass in low Earth orbit of approximately 300 metric tons per year or approximately 3,000 metric tons for a 10-year period on the lunar outpost.

Processes for extracting martian resources are believed to be much simpler, because oxygen could be produced through straightforward reduction of the atmosphere, which is primarily carbon dioxide. Mining and beneficiation requirements for Mars have not yet been defined.

Major processing issues include system mass, power requirements, durability, and the quantity, purity, and consistency requirements for feedstock. At present, several small studies of in situ resource utilization are being conducted, and a major technology effort has been planned. It should be quite feasible to provide technology readiness for preliminary in situ resource utilization experiments on the lunar surface by 2000 to 2002, with development of an operational flight system by the end of the first decade of the 21st century. In the longer term, technology development will be focused on in situ resource utilization on Mars; however, in the immediate future, work related to Mars will be limited to fundamental research and studies.

Radiation Protection

The damaging effects of space radiation never reach humans on Earth; they are protected by the thick shield of Earth's magnetic field and atmosphere. However, human space flight beyond low Earth orbit will entail a high degree of risk from the radiation environment of space. For the lunar outpost, this risk can be substantially mitigated through the use of bagged lunar surface materials to attenuate radiation from space. However, for the Mars transfer vehicle, with its multi-month flights between Earth and Mars, there will be a significant requirement to accurately predict the dose received by crew members and to provide low-mass radiation shielding from solar flares and galactic cosmic rays.

The Apollo missions were only a few days long, and they did not involve major total exposures to space radiation. Human missions are currently confined to short-duration Space Shuttle missions in low Earth orbit, where radiation protection is a minimal concern due to the protective character of Earth's magnetic fields. It is well known that the primary sources of radiation exposure in space are galactic cosmic rays and solar particle events. However, due to a number of independent variables associated with these sources of radiation, there is considerable uncertainty about the total shielding mass required for long-duration human missions. Current health requirements limit the total yearly radiation dose from all sources to not more than 50 rem.

Although tons of soil may be used indefinitely to provide shielding for stationary objects on planetary surfaces, crews in transit between Earth and Mars must also be protected, and each pound of in-transit shielding entails an enormous penalty in initial mass in low Earth orbit. The current state of knowledge is such that the total required shielding mass of a Mars transfer vehicle to ensure crew health and safety could vary by as much as a factor of 10. Only through a more accurate understanding of the radiation present and of radiation protection techniques can the actual amount of shielding required to ensure the long-term health and safety of crew members be determined. Reducing the present large uncertainties in radiation shielding requirements could significantly reduce the amount of mass margin required for human expeditions to Mars.

There is a critical need to confidently predict, within 10 percent, the shielding capabilities of various materials and spacecraft components. In addition, research and technology development is needed for lightweight shielding techniques and materials that will ensure adequate protection for crews during Earth-Mars transits. NASA is planning a significant, focused program to build upon current low-level research efforts. This program should be readily capable of providing needed research results to support Mars transfer vehicle development for post-2010 flights and possible upgrades of initial lunar outpost systems.

Nuclear Propulsion

Detailed mission planning for human exploration has centered on the use of high-performance cryogenic engines and aerobraking technologies as the foundation for Earth-Moon and Earth-Mars transportation. However, nuclear propulsion is a major alternative for Earth-Mars transportation. Two specific technologies are nuclear thermal rockets and nuclear electric propulsion.

Nuclear thermal rocket technologies include solid-core nuclear thermal rockets, which have lower performance (specific impulse on the order of 900 seconds) and lower development risk, and gas core nuclear thermal rockets, which have much higher performance (1,500 to 6,000 seconds) and much higher development risk. During the Rover and NERVA solid-core nuclear thermal rocket programs from 1955 to 1973, twenty propulsion reactors were designed, built, and tested. Power and thrust levels ranged from 1,100 megawatts-thermal and 55,000 pounds-force, to 5,000 megawatts-thermal and 250,000 pounds-force. The NERVA program demonstrated a sustained engine burn endurance of more than 1 hour at rated conditions, and a restart capability in excess of 20 cycles in conjunction with powered operation. Solid-core nuclear thermal rockets have thus far completed breadboard validation and demonstration, but further component and system level tests will be required before the technology is ready for flight system development. Concepts for gas-core nuclear thermal rockets were formulated during the Rover and NERVA programs. Between 1958 and 1979, a variety of critical subcomponent tests and physics and process-oriented experiments were conducted on both solid and gas core concepts. A large investment in facilities will be required to achieve mature technology for both types of nuclear thermal rockets.

For human missions to Mars, solid-core nuclear thermal rocket technology can provide performance comparable to that of advanced cryogenic engines and aerobraking. However, for a fixed flight duration of approximately 565 days, gas core nuclear thermal rocket technology can provide a savings of almost 50 percent (more than 350 metric tons) in initial mass in low Earth orbit for a typical human mission to Mars. More important, for a fixed initial mass in low Earth orbit of approximately 800 metric tons, gas-core nuclear thermal rockets could reduce round-trip travel time approximately 65 percent, from 1–1/2 years to approximately 200 days. This could eliminate most concerns about long-term exposure of crews to zero gravity, and human missions to Mars could be flown within the current experience base.

No significant United States program is investigating the potential of nuclear thermal rocket propulsion for exploration missions. The feasibility of using solid-core and gas-core nuclear thermal rockets for human flights to Mars could be determined through a program beginning in 1991. The first step would be an assessment in the mid-1990s of basic feasibility for gas-core rockets, and then, depending upon the result of that assessment, a final breadboard-level proof of concept would be conducted in the late 1990s. Facilities for testing nuclear thermal rocket systems is a major issue that must be resolved in order to make development of this extremely effective technology possible.

Nuclear electric propulsion offers very high specific impulse (2,000 - 10,000 seconds) which results in a reduction in propellant mass requirements. By nature, low thrust electric propulsion systems offer increased mission flexibility compared to high thrust chemical propulsion systems (i.e., unconstrained by launch windows). At power levels of 5 megawatts, nuclear electric propulsion has the potential to reduce initial mass to low Earth orbit for Mars cargo missions by 50 - 60% compared to chemical/aerobrake systems. For the cargo missions, trip time to Mars will be relatively long compared to chemical propulsion systems. At considerably higher power levels (40 - 200 megawatts), nuclear electric propulsion can potentially reduce trip time for piloted mission applications.

Electric propulsion thruster systems have been developed up to 10 megawatts for flight use. High power electric propulsion thrusters (hundreds to thousands of megawatts) are under development in the Pathfinder program and would need to be continued. A high power vacuum facility would be required.

Megawatt level nuclear power systems with low specific mass will be required. The SP-100 reactor development program will demonstrate space reactor technology and can potentially be used for the 5 megawatt class systems when coupled with advanced dynamic energy conversion systems. For the higher power nuclear electric propulsion concepts (40 to 200 megawatts), a new reactor development program will be required, as well as development of energy conversion, heat rejection, and power management and distribution techniques to achieve low power system specific masses.

Other Technology Needs

The following subsections briefly sketch the remaining technology needs of the Human Exploration Initiative, organized according to broad functional areas. These technologies will significantly improve the state of the art, by reducing crew requirements and logistics, improving performance to required levels, and enabling advanced scientific payloads. Each subsection notes the priority technologies listed above in order to provide the context within which these remaining technologies have been assessed.

In-Space Operations

Advances in current and planned capabilities for a wide assortment of in-space operations will provide technologies for Earth-orbit staging and operations for large-scale human missions to the Moon and Mars, as well as for robotic Mars missions. Elements needing technology development include in-space assembly and construction, in-space vehicle processing and servicing, cryogenic fluid management, and autonomous rendezvous and docking. For example, key technologies needed for cryogenic fluid management include low-loss transfer, low boil-off, long-term transfer, reliquefaction of boiloff, and instruments to monitor and control the status of cryogens in space. Of these elements, the first three are very important to successful near-term implementation of the lunar outpost program; the fourth is essential to the cost-effective return of samples from Mars as part of the robotic missions. In-space assembly and processing capabilities initially developed for lunar exploration vehicles will be substantially advanced and upgraded before the launch of the first human mission to Mars.

Earth-to-Orbit Transportation

To meet long-term performance, cost, and schedule requirements of human expeditions to Mars, new technologies will be needed for both current and planned Earth-to-orbit heavy lift launch vehicle systems. Major development considerations will be safety, reliability, and resiliency, and operational and manufacturing efficiency to reduce operational costs. Technology development is needed in the areas of automated systems diagnostics, critical subsystem technologies (such as integrated thermal control systems, power generation systems, and adaptive guidance, navigation, and control), primary vehicle systems (for example, reduced-mass cryogenic tankage materials and structures and reduced-cost main engines), strap-on booster technologies (such as clean-burning solid rocket motors), and a variety of operational applications of automation and robotics (e.g., launch servicing and fluid handling). Future developments for Earth-to-orbit transportation systems will build on the foundation of continuing Space Shuttle improvements and on the technology developments being pursued within the Advanced Launch System program.

Space Transportation

Technology development for space transportation systems will provide improvements necessary to ensure efficient, reliable, and safe transportation to, and return from, the Moon and Mars. Elements on which technology development will be focused include low-energy and high-energy aerobraking for both lunar and interplanetary vehicles, cryogenic propulsion systems, vehicle structures and cryogenic-propellant tanks, autonomous landing systems, and nuclear electric and nuclear thermal rocket propulsion. Technology development for cryogenic propulsion systems may include moderate-thrust, cryogenic hydrogen-oxygen engines for both space transfer and lander descent and ascent, cryogenic hydrogen-oxygen attitude control thrusters, and high-thrust, cryogenic hydrogen-oxygen space transfer engines.

Critical near-term space-transportation technologies include those for the lunar outpost (multiple-use, low-energy aerobrake and moderate-thrust cryogenic engines) and for the robotic Mars missions (low-energy interplanetary aerobraking and autonomous landing). Technology development to reduce the mass of lunar vehicle propellant tanks may continue beyond the initial flights of those systems, with upgrades introduced as planned product improvements.

Surface Systems

Advanced surface systems will require diverse technological developments to provide the engineering data for long-term, operationally intensive missions on the Moon and Mars. Elements requiring technology development include surface nuclear power, surface solar power with chemical energy storage, in situ resource utilization, including both initial mining and beneficiation and subsequent resource processing, thermal control systems, surface transportation systems, and surface habitats and construction. Of these, surface nuclear power and in situ resource utilization are fundamental to any strategic program of exploration. In addition, advances in technology for surface transportation systems, including advances in mobility mechanisms, controlling software and processors, and mobile power systems, are essential to the robotic Mars missions.

Humans In Space

Building on a foundation of Space Shuttle and Space Station Freedom systems, development of technology for humans in space will provide the capabilities and understanding to ensure safe and productive long-term human missions, including both extended surface operations on the Moon and Mars and long-duration spaceflights. Elements in which Human Exploration Initiative technological development is needed include regenerative life support systems, extravehicular activity/suits, radiation protection, and space human factors (human-machine interfaces). Of these, substantial advances in the state of the art in the first three elements will be critical to both the health and safety of the crew and the overall success of the Initiative; advances in the fourth will improve overall crew performance and efficiency.

Lunar and Mars Science

The Human Exploration Initiative will encompass at least three fundamental classes of scientific objectives requiring technological advances: local planetary science, use of systems and sites to accommodate space physics and astrophysical instruments, and in situ experimentation that takes advantage of unique local physical conditions. For example, beginning in the early 2000s, astronomical observatories in a range of electromagnetic frequencies from the visible through the ultraviolet and the X-ray regions may be constructed and operated on the lunar surface. To enable new classes of scientific investigation, technological developments are required in sample acquisition, analysis, and preservation, science instruments, probes and penetrators, and astrophysical observatories. Of these, development in sample acquisition, analysis, and preservation is very important, because the success of the robotic Mars missions will depend upon scientific instrumentation for the collection, study, and occasional return to

Earth of Mars surface and subsurface samples. Technology development for astrophysical observatories will be an exciting, long-term process that supports a series of initial lunar observatories, evolving to challenging, large-scale optical interferometers.

Information Systems and Automation

In almost all of the systems being projected for the Human Exploration Initiative, advances in cross-cutting technological information systems and automation have the potential to substantially improve the performance, increase the reliability, and reduce the cost of the systems. Technology development can decrease delay rates and increase system on-line availability through fault-trend analysis and management. Development can also substantially decrease the operational effect of the need for space-based system maintenance through the application of highly automated system architectures. Technological advancements are needed in automation and robotics, high-rate communications, and data systems, processors, and recorders. Of these, advances in the automation and robotics element are the most important to the overall success of the Human Exploration Initiative, whereas development of advanced high-rate communications (in particular, Ka-Band technology) is required for human missions to Mars.

In-Space Technology Development

Although the majority of research, technology, development, and advanced development programs can and will be conducted in ground-based laboratories and facilities, in many cases technology development must be completed in space because no terrestrial facility can adequately simulate key physical and operational characteristics of the space environment. Each of the several technology development areas will involve some degree of in-space experimentation on Space Station Freedom. The most critical of these will be in-space operations, for which development and demonstration on Freedom will be needed of assembly and construction techniques that will be essential for lunar and Mars vehicles. These techniques include mating major space components (e.g., assembling segments of the lunar transfer vehicle aerobrake or integrating cryogenic tankage for that vehicle) and structural inspection and adjustment of vehicle components following each mission. Also, vehicle processing technologies, including inspection and integration of payloads and largely automated checkout and testing of integrated vehicle systems and payloads, will be tested on Freedom. Research and technology development may also be extended to Freedom in regard to testing processes and subsystems for both physical-chemical life support systems and biologically based regenerative life support systems needed for Mars transfer vehicles.

Other National Technology Development

The development of technology for the Human Exploration Initiative will be driven by the strategic plans of the Initiative itself. However, the program will also be coordinated with, and will utilize wherever advantageous, advances in engineering capabilities being achieved in other national technology development programs. Programs such as the National AeroSpace Plane and the Advanced Launch System will provide key technological advances in Earth-to-orbit transportation that could also have exciting applications elsewhere within the exploration activities, including advances in guidance, navigation, and control, vehicle materials and structures, and propellant tankage.

In addition, significant technological expertise resides in institutions and programs outside of NASA. The Defense Advanced Research Projects Agency is continually driving toward new and innovative applications of microelectronics, software, sensors, and other disciplines. One of that agency's programs, the Advanced Land Vehicle, has provided a substantial part of the technology foundation upon which NASA has built planetary rover development. Similarly, other Department of Defense organizations provide important capabilities and expertise. Innovation and excellence have always been hallmarks of the Department of Energy's national laboratories, which will be strong contributors of technology for the Human Exploration Initiative. For instance, the Los Alamos National Laboratory is collaborating with NASA in the development of energy technologies for exploration, including research in regenerative fuel cells and a major role in the SP-100 space nuclear power program. The development of technology for the Human Exploration Initiative will challenge the Nation's entire aerospace science and engineering community.

National and Institutional Impact

Section 9

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National and Institutional Impact

Resource Assessment

The Human Exploration Initiative will draw heavily on NASA's personnel, facilities, and equipment. This resource base, the NASA institutional core capability, is built on 75 years of research, development, and operational experience and hundreds of unique national facilities. From the National Advisory Committee on Aeronautics to the creation of NASA in 1958, to the present, the Agency has developed an unparalleled capability in civil space research and development and aeronautics.

The NASA institution is an important element in preserving U.S. leadership in space and aeronautics. The institution provides the scientists, engineers, and technicians required for the research, design, and development of a program, and it provides the laboratories, wind tunnels, launch pads and control rooms, and similar facilities needed to conduct a program. The institution also provides the equipment and logistical support that enable the work to take place.

The National Aeronautics and Space Administration is made up of approximately 24,000 civil service employees located at its headquarters and at eight multipurpose field installations. In addition, approximately 40,000 on- or near-site technical and support service contractors work in partnership with the civil servants in implementing the Agency's civil aeronautics and space programs.

More than 55 percent of the civil servants are engineers and scientists, over one-third of whom possess advanced degrees. Coupled with the 4,000 administrative professionals, and the 4,500 technician and clerical personnel, the scientists and engineers perform the core research and development and provide the management and technical expertise of the Agency. The scientists and engineers form the backbone of the Agency's abilities in flight systems, materials and structures, power and propulsion, measurement, instrumentation, computer systems, and space and Earth sciences. This amalgam of science, engineering, and project management expertise represents a major segment of the Nation's aeronautical and space research capability.

NASA will request a significant augmentation of civil servant positions to support the Human Exploration Initiative. These positions will provide the necessary technical expertise, program management, and administrative support to meet the objectives of the Initiative. The augmentation will also enhance the in-house work force, providing a strong balance between in-house and contracted efforts.

The second major component of NASA's institution, the facility infrastructure, consists of a unique array of research and development complexes, administrative areas, manufacturing facilities, and launch and payload processing facilities, with a replacement value of $14.2 billion. NASA core facilities are located at nine major installations across the continental United States with five component installations and three Deep Space Network sites that provide additional support. NASA's major facilities are varied and represent a national resource that is not duplicated in the non-Government sector. The major components of NASA facilities include Research and Development, which encompasses 22 large wind tunnels, 16 major test stands, 10 major computing facilities, and 21 large vacuum chambers; Manufacturing Facilities comprising 3,600,000 gross square feet of external tank and orbiter replacement assembly areas; and Launch and Launch-related Facilities, which include launch pads, orbiter preparation facilities, vehicle assembly buildings, and payload processing areas.

Many special purpose facilities required for the Initiative have been identified, along with upgrades or expansions of current facilities. Additional facility requirements will be developed as program plans mature.

The NASA institution also provides computational support in the programmatic areas of flight, applications, and basic research. NASA flight computational resources are used to support engineering and mission planning, evaluation, control, training, and simulation for the Space Shuttle. The applications areas require computational support for the development and operation of space probes and scientific satellites and for the study of scientific phenomena in space and on Earth. For basic research, theoretical computational analysis is required for avionics, acoustics, structures, aerothermodynamics, and atmospheric modeling. The Numerical Aerodynamic Simulator at the Ames Research Center integrates state-of-the-art supercomputers with advanced computational techniques in support of basic aeronautics and space research.

Information management, equipment, logistical support, and similar support activities will be refined as program planning continues.

Enhancing Management Systems

The President and Congress recognized in 1958 that a civilian space agency would need exceptional authorities to conduct novel and urgent missions. Therefore, the National Aeronautics and Space Act of 1958 contained many special provisions, including the authority to establish a certain number of excepted positions without regard to the Classification Act of 1949, authority to accept unconditional gifts, specialized patent provisions, authority to acquire real property, authority to enter into contracts on such terms and conditions as it deems necessary, and other unique authorities. In addition, Congress granted NASA "no year" appropriations (appropriations available for obligation until expended) and liberal reprogramming flexibility.

Much has changed since 1958. New legislative and regulatory requirements have eroded many of the flexibilities originally granted. This erosion, coupled with the complexity of a 30-year program of lunar and Mars exploration, once again necessitates a novel approach to administrative and management systems. Never before has a program of this magnitude, requiring such long-term development and operations, been undertaken. Accomplishment of the President's initiative will be significantly enhanced by restoring the flexibility of the Space Act of 1958 so that it may operate as originally intended. Although the Human Exploration Initiative can be accomplished within existing legal and regulatory structures, a severe penalty in schedules, resources, and efficiencies would be incurred.

The Human Exploration Initiative, unlike any other, also presents a unique opportunity to demonstrate the viability of streamlined administrative and management processes for long-term, complex, highly visible U.S. programs having significant international implications. The lessons learned will yield invaluable guidance transferable to other important U.S. programs.

Three areas of concern, if successfully accommodated, will offer the greatest opportunity to realize significant efficiencies and enhanced effectiveness: the acquisition system, the budget process, and human resource management systems. NASA has already begun to address these areas internally, but there are elements that are outside NASA's control. In each of these areas, NASA will focus on changes unique to the nature of the enterprise rather than across-the-board changes to laws of general application.

Acquisition System

The existing system is structured to accommodate every type of Federal procurement activity, from routine administrative procurements to state-of-the-art technology advancements and the development and operation of ultra-sophisticated space programs. Such a system of broad application is ill-suited to the needs of a research and development agency. In addition, the system has been encumbered with a variety of restrictions and limitations that actually impede a research and development agency. Since the early 1980s, the time necessary to complete a major procurement has increased by about one-third, and the volume of supporting documentation has grown by about one-half. New or modified tools are needed to accommodate technology programs and the 30-year development of complex, large systems.

Budget Process

In its early years, NASA received so-called "no-year" research and development appropriations, which enabled realistic planning and efficient utilization of resources. This flexibility was reduced through congressional imposition of a 2-year research and development appropriation. Broad transfer authority between appropriations has also been significantly reduced. These factors have contributed to planning instability and unpredictable program continuity. The uncertainties for long-term programs under these circumstances will severely affect the Human Exploration Initiative, as well as potential international cooperation.

Human Resources Management Systems

A critical element of the Human Exploration Initiative is the provision of adequate human resources. Efficient management of those resources will require flexibility to make adjustments in the work force without artificial ceilings and related restraints.

An added impediment is the antiquated Federal personnel system, which imposes severe constraints on recruitment, motivation, and retention of a quality work force. The system is unable to address shortages of scientists and engineers in critical disciplines and noncompetitive pay and benefits.

The projections for the future high-technology work force are not encouraging. The marketplace for recruiting high-quality scientific and technical personnel has become increasingly competitive in the last decade. The National Science Foundation projects that by the year 2000 there will be a shortage of 675,000 scientists and engineers in the United States, arising from anticipated increases in demand combined with decreases in the number of students trained. More than half of NASA's work force is composed of scientists and engineers, and that work force must increase substantially to support the challenges of the Human Exploration Initiative. If NASA is to attract and retain the caliber of talent necessary to achieve the Human Exploration Initiative, the agency must secure greater flexibility in setting competitive pay levels, streamlining the hiring process, managing career progression, and strengthening the tie between performance and recognition.

The multiplicity of ethics and post-employment restrictions currently applicable to Federal employment is also a problem in attracting senior managers. A new law or modification of the existing law may be necessary to attract top level officials who are discouraged from pursuing a career in the Federal Government.

Improvements in the acquisition system, budget process, and human resources management systems can be made at three levels: Congress, the Administration, and internally within NASA. A significant number of desired enhancements are within NASA's authority, and actions are underway to make changes internal to the Agency.

Recommended Actions

NASA will explore a legislative package in the near future to strengthen the acquisition process and human resources management system. In the acquisition area, the legislative proposal would address long-term contracting authority and the use of "soft" options to meet the demands of a long-lived program. The proposal would also identify procurement streamlining features such as the authority to competitively select contractors on the basis of initial proposals without discussions. Further, NASA will explore the feasibility of using a modified Uniform Commercial Code contracting approach for the Human Exploration Initiative.

In the area of human resources management, the legislative proposal would include provisions for flexible personnel compensation levels, recruitment and staffing incentives, enhanced performance appraisal, and a modified personnel benefits program.

NASA will also explore budget process changes including "no year" appropriations, long-term program authorizations, transfer authority between appropriations accounts, and flexible reprogramming authority.

In addition, NASA will explore an Executive Order or other appropriate Presidential directive to provide necessary authorities for the Human Exploration Initiative. The request may include exemption from the Office of Management and Budget Circular A-76 to permit management flexibility in determining the appropriate civil service and contractor skill mix. A class waiver to Office of Management and Budget Circular A-109 may be requested as appropriate for program and procurement planning for the Initiative. NASA may also seek a blanket delegation of procurement authority from the General Services Administration for the acquisition of automated data processing equipment for other than routine administrative or business application. The request may include exemption from non-statutory requirements of the Federal Acquisition Regulation, when required to facilitate execution of the Human Exploration Initiative. Finally, NASA may request removal of full-time equivalent ceilings to permit management of the work force composition and size in accordance with budget levels.

The scope and complexity of the Human Exploration Initiative will place substantial stress on current administrative and management systems. The timeliness, effectiveness, and efficiency of the Initiative will be significantly strengthened by taking the actions just described.

National and Institutional Impact

The Human Exploration Initiative will draw heavily on NASA's personnel, facilities, and equipment. An augmentation of civil service positions is necessary to provide the in-house work force to meet the objectives of the Initiative. In addition, many new facilities or upgrades to current facilities will be required over the life of the Initiative.

Although the Human Exploration Initiative can be accomplished within existing administrative and management authorities, the scope and complexity of the Initiative will challenge current systems. There is a need to restore the flexibilities originally embodied in the Space Act and to improve the timeliness, effectiveness and efficiency of the acquisition system, budget process, and human resources management systems.

The Human Exploration Initiative contains a hierarchy of possible approaches to international cooperation. Different approaches may be appropriate for different phases of the Initiative and for different partners.

International Participation

Potential international participation in the Human Exploration Initiative is the subject of a separate policy analysis being conducted under the direction of the National Space Council. That analysis will assess international capabilities, opportunities, issues, and options related specifically to the Human Exploration Initiative. This section provides information to support that activity by drawing upon NASA's extensive experience in conducting space missions with foreign partners.

The Experience Base

NASA has a 30-year history of cooperating with other nations on space projects. However, the present environment is considerably different from that of the past. Many U.S. allies are evolving from dependence to autonomy in space, with strong national commitments to develop indigenous space capabilities. In parallel, the Soviet Union has opened its programs for cooperation with Western nations. As a result of this changed international environment, NASA's current projects involve a mix of cooperation forms, including foreign participation in NASA missions, NASA participation in other nations' missions, coordination of independent national missions, and jointly defined programs.

Taking into account NASA's experience, particularly with long-term complex projects such as Space Station Freedom, and considering the growing competence and autonomy of its potential international partners, certain observations about large scale cooperative programs may be of value in the Human Exploration Initiative context.

First, it is important that prospective partners be included in the early definition of a program; exclusion from the definition process may make later acceptance of the program more difficult. This early consultation sounds out each partner's interest and level of commitment. It provides an opportunity for interaction, not only on the technical portion of the program, but also on program management and the possibilities of quid pro quos. Early consultation is also necessary to match planning, budget, and decision schedules.

Cooperation on large-scale, long-term, U.S.-led projects must increasingly provide foreign partners with operational roles as well as responsibility for developing hardware, especially if significant foreign investments are sought.

The U.S. must also be responsive to its foreign partners' needs for roles that display national identity and demonstrate indigenous technology within the context of the cooperative undertaking.

Technical commitments to the program must be matched by equally strong political commitments on the part of all parties. The larger and more expensive the program, the higher the level of political commitment and sustained engagement required. Sufficient time must be built into program plans to allow for the extended negotiations necessary at each stage.

A final observation is that management complexity can be controlled and technology transfer concerns mitigated by conducting cooperation across "clean interfaces" at the major element (e.g., laboratory module) level rather than at the system or subsystem level within elements.

Human Exploration Initiative Characteristics

Several characteristics of the Human Exploration Initiative are important to an assessment of cooperative possibilities. First, the Human Exploration Initiative is not a single program, but a series of programs extending over at least 30 years. Cooperative arrangements can thus be phased to reflect U.S. objectives, take into account partner capabilities and interests, and build upon experience as it accrues. Further, the Initiative contains a large number of major end-item elements that provide many opportunities for others to participate. These elements include launch vehicles, transfer vehicles, excursion vehicles, crew return vehicles, mission modules, habitats, rovers, unmanned robotic spacecraft, soil processing plants, servicing facilities, propellant depots, power plants, and servicers.

The Human Exploration Initiative contains a hierarchy of critical and non-critical paths, providing opportunities for managing risk while still providing interested partners with significant technical challenges, operating responsibilities, and investment opportunities. The first critical building block for human exploration programs, Space Station Freedom, is already an international program. The memoranda of understanding provide for a potential role by the Europeans, Japanese, and Canadians in any evolution of Freedom, such as that required by the Human Exploration Initiative. Specifically, the memoranda state: "The partners intend that the Space Station will evolve through the addition of capability and will strive to maximize the likelihood that such evolution will be effected through contributions from all the partners. To this end, it will be the object of the Parties to provide, where appropriate, the opportunity to the other partners to cooperate in their respective proposals for additions of evolutionary capability."

Finally, the planned program of sustained human exploration of the solar system will require a substantial increase in the NASA budget over time. For foreign partners to make significant contributions to the exploration program, they, like the United States, will have to make high-level political commitments involving major long-term outlays going significantly beyond currently approved or projected budgets.

Approaches to Cooperation

A number of approaches could be used to structure international cooperation for the Human Exploration Initiative and its robotic activities. For an undertaking of such long duration and with many individual elements, no single approach would be ideal for all partners, and the approach adopted with a given partner may very well change over time. The following approaches are generic in nature and may be mixed in practice.

One approach is that of separate but coordinated programs. From a pure management and control standpoint, this approach is attractive in that it minimizes technical and management interfaces, as well as dependence on external decision-making and performance. Such an approach offers additional program robustness while permitting the U.S. effort to go forward regardless of whether a partner's program proceeds; however, it offers very little cost savings. This approach may have immediate application for certain robotic exploration activities, given the U.S., Japanese, and Soviet interest in developing lunar orbiters and the U.S. and Soviet interest in a variety of unmanned Mars missions. If this approach were applied to human outposts on the Moon or Mars, it would imply that NASA's partners have an independent capability of reaching these destinations, a case that currently can be made only for the U.S.S.R.

Another approach is that of augmentation through cooperation, where international participation is sought in a U.S.-led project, but not for significant critical path items. This approach creates a modest increase in demands on management but can offer some cost savings. Historically, it has been NASA's most common approach to international cooperation.

A third approach is interdependence, where internationally provided elements are on the critical path, but the interfaces are relatively clear. This approach is one in which the partners must have great confidence in one another and be assured that the likelihood of interference or cancellation as a result of budgetary problems or political "fallout" is minimal. Cost savings could be substantial, depending on the nature of the international contributions. However, close oversight of critical items is clearly necessary, and, therefore, so is additional management overhead for such programs.

Finally, a fourth approach is the joint development and operation of an element. This is the most intensely "international" approach from a political perspective. It also presents the U.S. with the prospect of maximum management overhead and extremely complex technical interfaces. NASA has not traditionally entered into this type of cooperation for large projects. Moreover, it may not be appealing to other nations that are often equally concerned about national identity, technical autonomy, and technology transfers.

A variety of factors influence the approach taken to cooperation. These factors affect not only the United States but also the prospective partners' opinions about the appropriate approach. For example, different approaches may be best for different phases of the Human Exploration Initiative. Early collaboration on Space Station Freedom was deliberately structured in the form of parallel studies, in case any of the partners decided not to go forward with the program. However, once commitments to proceed were made, the approach was changed to place the activities under a single management structure, with the partners having additional responsibilities including design, development, and operations. In the case of exploration programs, one approach may be appropriate for robotic activities, another for the lunar outpost, and yet another for human exploration of Mars. Similarly, robotic missions could be used as testing grounds for cooperation on later human phases of the Initiative.

Also, different models may be appropriate for cooperation with different nations. National capabilities, technology transfer considerations, internal needs, and various foreign policy factors influence decisions on cooperative arrangements.

In making decisions about approaches to cooperation, the United States must develop a view on the extent of control to be shared among partners, both in terms of technical oversight and in decision-making authority. The prospective partners will have their own views regarding the level of control they wish to exercise in return for their participation.

Of prime importance in the current environment is the course of Space Station Freedom development. How collaboration on Space Station Freedom proceeds is being viewed abroad as a measure of U.S. reliability, with respect to both NASA's success in obtaining funding to proceed with development as planned and to its method of meeting its international obligations. The next few years of Space Station Freedom development will be critical in the formation of attitudes abroad, including attitudes within nations that are not partners in the program. This period coincides with the period of preparatory activities for the Human Exploration Initiative.

The Human Exploration Initiative offers the potential for a variety of cooperative approaches with a number of potential partners. Europe, Japan, Canada, the U.S.S.R., and perhaps other nations possess technical space capabilities that could potentially benefit the Human Exploration Initiative by adding robustness and/or reducing overall costs. Expanded cooperation with traditional allies and political adversaries can also serve important foreign policy goals. At the same time, international cooperation complicates management and diffuses overall control. Savings are never "dollar for dollar" and inefficiencies can result because of dependence on multiple decision-making and budget systems that do not use the same approach or follow the same schedule as those of the U.S. Also, there is always the potential for "fallout" from political instabilities unrelated to space cooperation. Scientific and technical cooperation on large endeavors can rarely be insulated from the overall political relationship existing between the nations involved. The National Space Council analysis will consider these and other factors in assessing the feasibility of further international participation in the Human Exploration Initiative.

Conclusion

The Human Exploration Initiative benefits the nation in a multitude of dimensions. The Initiative has the ability to reinvigorate the human spirit by responding to the imperative to explore new worlds. A wealth of new knowledge will flow from the exploration and science conducted within the Initiative. And international leadership and national pride will result from a successful, visible, long-term U.S. exploration program.

Each of these benefits is substantial and important to the vitality of the Nation. But, there are other benefits more tangible and near term. The Human Exploration Initiative provides a stimulus for science and engineering education; it strengthens our national technological capabilities; and it serves as a mechanism for national policy.

International cooperation considerations are discussed earlier and are the subject of a separate policy analysis conducted under the direction of the National Space Council. The many approaches to international cooperation provide opportunity to further national objectives today, as well as over the life of the Initiative.

The Human Exploration Initiative supports the maintenance of our domestic standard of living by strengthening U.S. competitiveness in an interdependent, global, trading economy. NASA plays a leading role among government agencies in developing a body of knowledge that has the potential to advance technology. NASA's research and development budget of $3.3 billion (1988) represents 13 percent of all civilian research and development in the government. NASA contributes to the Nation's base of technology through the transfer of research knowledge into the public and private sectors. The application and reapplication of this knowledge has a multiplicative effect, in which the general increase of efficiency and wealth from the advanced knowledge spreads throughout society.

Although the measure of contribution varies, there is general agreement among economists that NASA makes a major contribution to the economy. The Human Exploration Initiative will expand this contribution as advanced technologies such as automation and robotics, cryogenic propellants, life support systems, lightweight, easily assembled structures, aerobrakes, and other technologies are developed.

Another benefit increasingly important today is the stimulus the Human Exploration Initiative can provide to education. In order to help ensure that the Nation has an adequate, continuing supply of scientists, engineers, and other technical personnel to successfully implement the President's Human Exploration Initiative, an aggressive and targeted educational action plan is needed. The Nation faces a predicted shortage of some 675,000 scientists and engineers by the year 2000. Accordingly, as a part of its implementation of the Human Exploration Initiative, NASA will contribute to helping solve this national problem. NASA will redirect and enhance its existing aerospace education program into a new, comprehensive, educational program entitled "Scientific Literacy for the 21st Century."

This educational program will use the unique and highly motivational educational resources represented by NASA's space science and technology mission, its highly trained staff, and its special facilities. The educational outreach under "Scientific Literacy for the 21st Century" will supplement other national efforts to help increase scientific literacy among four high leverage groups:

teachers, students, universities, and the adult general public. An exciting series of specialized educational programs will be designed for each of the four groups, and all will incorporate the space science and technology concepts and activities associated with the Human Exploration Initiative.

Benefits

"From the voyages of Columbus, to the Oregon Trail, to the journey to the Moon itself, history proves that we have never lost by pressing the limits of our frontiers." - President George Bush

The Human Exploration Initiative will provide numerous down-to-Earth benefits.

- Respond to the human imperative to explore
- Provide a stimulus for science and engineering education
- Strengthen the national technological capabilities
- Expand the knowledge of our universe
- Foster international cooperation
- Support international leadership and national pride

Space is a magnet for learning, and the Human Exploration Initiative, in an educational context, will captivate new generations of students, who constitute the Nation's future scientific and technical work force.

The study and programmatic assessment described in the previous pages have shown that the Human Exploration Initiative is indeed a feasible approach to achieving the President's goal. Several reasonable alternatives exist, but a long-range commitment and significant resources will be required. However, the value of the program and the benefits to the Nation are immeasurable.

Some day it may be said that the residents of Earth had to leave their planet in order to find it. Indeed, from space, humans first got to see their own planet, floating in blackness above the barren moonscape like a blue and white marble. Perhaps more than anything else, this view of Earth dramatized our planet's uniqueness and its fragility.

The last half of the 20th Century and the first half of the 21st Century will almost certainly be remembered as the era when humans broke the bonds that bound them to Earth and set forth on a journey into space.

That journey will, in time, extend human presence throughout the solar system. Historians will note that the Moon became a familiar place to Earthlings very early in that period. They returned there to follow in the bootprints of Armstrong, Aldrin, and their Apollo colleagues, to mine the lunar rocks and other resources and to establish an outpost for further exploration and expansion of human activities, on Mars and beyond.

Historians will further note that the journey to expand the human presence into the solar system began in earnest on July 20, 1989, the 20th anniversary of the Apollo 11 lunar landing. On that day, President George Bush announced his proposal for a long-range, continuing commitment to a bold program of human exploration of the solar system.

Report Transmittal Letter from the Study Director to the NASA Administrator

NASA

National Aeronautics and
Space Administration

Washington, D.C.
20546

Reply to Attn of: A

Vice Admiral Richard H. Truly
Administrator
National Aeronautics and Space Administration
NASA Headquarters
Washington, DC 20546

Dear Admiral Truly:

I am providing you the report resulting from our 90-day study to examine elements of the President's Human Exploration Initiative. This report represents the effort of teams from across the Agency. Each Program Associate Administrator developed functional and discipline assessments for the Initiative and participated in the integration of the overall study. NASA centers and JPL participated in the program office assessments and contributed members to the study team. A technical study group integrated the inputs of the center representatives and conducted detailed analyses and trade studies. Finally, a report assembly team worked with all involved to produce the enclosed report. Throughout the study, reviews were conducted by the Associate Administrators and center directors as well as a review team made up of senior agency officials.

As described in the Preface, this report provides a data base for future Administration decision-making on the Human Exploration Initiative. It considers five reference approaches and addresses questions of program objectives, schedules, technologies, and resource requirements. In addition, the report provides information regarding the benefits of the Human Exploration Initiative, international participation considerations, and potential management enhancements. It is significant to note that the approaches are based on current and forecasted advances in technological capabilities. Should breakthroughs in any of several key technologies – including propulsion, life support, and power – cause these technologies to advance more rapidly than anticipated, increases in performance or reductions in cost could result.

We believe this report represents a good starting point for Council deliberations and we plan to continue our efforts as the Human Exploration Initiative develops. The data base will permit the development of implementation options for use in the policy formulation process. Beyond providing this data base, NASA is also working with the Space Council on separate assessments of a number of critical issues including alternative approaches to schedule and technology development, and international cooperation.

Throughout the effort to develop the report, I have had the opportunity to speak with a large number of people and I have been encouraged by the enthusiasm displayed and the thousands of hours so many people willingly contributed to the study. I am impressed not only with the capability available for the Human Exploration Initiative, but also with the dedication and excitement of individuals within the Agency as well as those outside the Agency.

I feel the message is clear from those who participated in the 90-day study. NASA stands ready to support the Nation's decision to complete Space Station Freedom, to return to the Moon, this time to stay, and then press onward to Mars.

Sincerely,

Aaron Cohen

Aaron Cohen

Enclosure