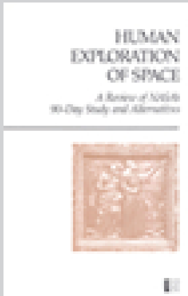

Human Exploration of Space: A Review of NASA's 90-Day Study and Alternatives

Committee on Human Exploration of Space, National Research Council

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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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In Memoriam

General Samuel C. Phillips, who had agreed to serve on the Committee on Human Exploration of Space and who had begun preparatory work for the study, died on January 31, 1990. He had a long and distinguished career that included directing the Apollo program from 1964 through the lunar landing in 1969, commanding the US Air Force Space and Missile Systems Organization, directing the National Security Agency, and heading the Air Force Systems Command. General Phillips later served as a Vice President for TRW. He performed many analyses of critical US space issues, and only recently was a valued member of a National Academy of Sciences/National Academy of Engineering study of US space policy. General Phillips' death is a great loss to the nation and to his colleagues who worked with him through the years.

Acknowledgments

The committee wishes to thank the many individuals from industry, academia, and federal agencies and laboratories who took the time either to meet with the committee or to make their views available in other ways. NASA Administrator Richard Truly, his associate administrators and staff, along with National Space Council Executive Secretary Mark Albrecht and his staff, were very frank and forthcoming with information concerning the President's human space exploration initiative.

In addition, the following individuals presented their ideas and technical concepts to the committee: Lowell Wood and his associates from the Lawrence Livermore National Laboratory, who briefed us on The Great Exploration; General Richard C. Henry of Brown & Root, who discussed the Workhorse Launch System; Maxwell W. Hunter, who made a presentation on the SSX, a single-stage-to-orbit launch system; Peter Wilhelm of the Naval Center for Space Technology, who explained the SEALAR concept, involving launching recoverable vehicles at sea; Michael D. Griffin, Deputy for Technology of the Strategic Defense Organization, who discussed project management techniques; and Lt. Colonel Roger Lenard, who described a nuclear propulsion concept. A full list of invitied presenters and guests is contained in Appendix B.

Thanks are in order as well to the staffs of the National Research Council (NRC) Space Studies Board and the Aeronautics and Space Engineering Board for their help and cooperation in putting together the study. Last, we would especially like to thank the study's Executive Director JoAnn Clayton for her thoughtful guidance at every stage and NRC Assistant Executive Officer for Special Projects Myron F. Uman for his wise counsel and constructive reviews of the draft report.

H. Guyford Stever, *Chairman*,
Committee on Human Exploration of Space

Summary

President George Bush on July 20, 1989, announced a US commitment for humans to return to the Moon and to journey to Mars; the Vice President in his capacity as Chairman of the National Space Council (NSC) was charged with making specific recommendations about how the President's initiative could best be achieved. The National Aeronautics and Space Administration (NASA) then prepared a document, based on earlier NASA analyses, to aid in the decision-making process. Subsequently, the Vice President requested that the National Research Council (NRC) assess the scope and content of the NASA document as well as alternative approaches and various technology issues. The Vice President presented the NRC with a challenging set of questions that resulted in this report.

In examining the NASA *Report of the 90-Day Study on Human Exploration of the Moon and Mars* and alternative concepts, the committee concluded that the appropriate framework in which to consider alternative approaches to meeting the President's initiative has at least four components. The committee's major findings and conclusions follow, presented in that framework.

MISSION CONCEPTS

Questions arise about the appropriate pace for the President's initiative; the scope of initial human exploration missions; and the level of long-term support that will be required for what could be an unprecedentedly long commitment to a national space goal. Development of policy,

advanced technologies, and mission concepts will probably be a continuing and iterative process. However, there is a need for guidance at an early date regarding the scope and pace of the early stages of the Human Exploration Initiative (HEI).

- As directed by the President, the space station is an integral first step in the HEI, but its present design may not meet all of the requirements for the HEI.
- The mission concepts in the NASA 90-Day Study prudently build on proven concepts and methodical research, development, and demonstration of new technology. The concepts are comprehensive and robust, implying relatively low risk.
- The Great Exploration, a concept developed by the Special Projects Office of the Lawrence Livermore National Laboratory, proposes to use available terrestrial equipment, accelerated administrative and procurement procedures, and a potentially feasible technology (inflatable modules) in an aggressive approach to reach Mars at the earliest possible time, but entails relatively high risk. The concept contains technical ideas that should be pursued, but the committee believes it underestimates the many practical and difficult engineering and operational challenges involved.
- It appears likely that the eventual choice of mission architecture will incorporate the ideas from a variety of concepts, some that now exist and others that will arise in the future. One concept, for example, would place the permanent human habitat in orbit, rather than on the surface of Mars. The variety of concepts should be regarded as a "menu" of opportunities.

HUMANS IN SPACE

Significant unanswered scientific questions exist concerning the feasibility of long-duration human spaceflight in a low-gravity environment. While it has been demonstrated that the human body adjusts remarkably well to the absence of gravity for short-duration flights, it has not been demonstrated that after long-duration spaceflight individuals can readjust rapidly to gravity without serious physiological consequences. The capability to send humans into space, maintain them in a physical condition that permits them to work productively, and return them to Earth in good health is central to the HEI.

- A program of scientific research on the effects of microgravity on human performance and welfare is critical for determining the mission architecture for the HEI.

• Development of technology for artificial gravity and countermeasures to mitigate zero-g exposure should proceed in parallel with studies of the physiological effects of microgravity.

• An emphasis on advanced human/machine systems can enhance the productivity of humans in space and increase their safety.

TECHNOLOGY DEVELOPMENT

Strategies are needed to develop and employ new technologies that will enable more rapid or cost-effective access to and habitation in space. Developing these strategies implies making trade-offs among alternative approaches. An important factor in these decisions is the level of human and technical risk that is acceptable. While major aerospace undertakings usually entail risks, recognizing them early in the planning stages of a major initiative may help identify choices that offer opportunities to manage the risks. A balanced technology development program with emphasis on critical long-term technologies can help to reduce risks and provide important options for the future.

Second to the need for scientific research and technology development to support humans in space is the need to advance national space transportation capabilities.

• A new generation of heavy lift launch vehicles is needed to transport massive cargoes to low Earth orbit (LEO).

• To transport humans to space, the nation must rely on the space shuttle for at least 10 years, and it is essential that the existing shuttle fleet be maintained in a fully operable condition. A new vehicle eventually will be required to transport humans and other precious cargo to LEO, emphasizing high reliability, robustness, and efficient ground operations.

• Nuclear rocket propulsion could make an important contribution to the HEI if it proves feasible and safe and can gain public acceptance.

• To meet the heavy demands for power on the Moon or Mars, nuclear electric power eventually will be essential.

SCIENCE GOALS

Another set of considerations concerns the expansion of knowledge. While the cardinal goals for the HEI may be related to leadership imperatives and to revitalizing the national research and development effort, important information can be gained about ourselves and our planet, about ongoing and past physical and biological processes, and about the history of the universe.

- Scientific research required to enable the initiative includes robotic precursor missions to learn more about the Moon and Mars as well as critical studies in the life sciences.
- Other research opportunities can be enabled by the HEI, for example, astronomical studies from a lunar base and geological studies of the Moon and Mars.
- Research that may become possible because of the HEI should be evaluated in the context of research strategies for the respective scientific disciplines, and with consideration of alternative ways of conducting the research. This analysis should be based on detailed scientific discussions and strategy development.
- Before defining scientific research for a lunar base, evaluations are needed on the effects of an inhabited lunar environment on scientific objectives and on instrumentation.

ADDITIONAL CONSIDERATIONS

The committee assumed that, independent of a program for human exploration of space, a vigorous base of civil space programs will exist, including astronomical research, solar and space physics, unmanned planetary exploration, and Earth remote sensing, supported in the near term by both expendable launch vehicles and by the space shuttle. In addition, technology will be developed, operational experience gained, and valuable scientific information obtained by the space programs of Europe, the USSR, and Japan, as well as by our own military space programs.

The climate for international cooperation is changing and is likely to continue to change. A detailed assessment is needed of the opportunities for international cooperation that may be available and the means to overcome technical and institutional barriers. It would be prudent to remain alert to future opportunities that may arise. At the same time, care must be taken that any enabling agreements are supported at the highest possible levels in the participating governments, with as much breadth as feasible, and that detailed technical agreements are not made final before all parties understand and agree on the requirements for the HEI or missions associated with it.

Finally, the nation is at a very early stage in the development of an HEI. None of the analyses to date—the NASA 90-Day Study, The Great Exploration, or, indeed, this report—should be regarded as providing anything other than a framework for further discussion, innovation, and debate. The HEI is an ambitious undertaking that requires development and implementation of new technology. Accurate cost estimates are only practical in circumstances where experience with the technology exists. Currently, the technologies and the HEI mission architectures are unknown.

While the nation has experience with estimating costs of some aspects of HEI, derived from experience with the costs of past space systems, at this time mission cost estimates should only be taken as suggesting the rough order of magnitude of the eventual costs.

Contents

Introduction

BACKGROUND

On July 20, 1989, the President of the United States affirmed a national space policy that emphasized the expansion of human presence and activity beyond Earth orbit. His vision included completing Space Station Freedom, returning permanently to the Moon, and eventually sending humans to explore Mars. In response to the President's declaration, the National Aeronautics and Space Administration undertook a review of the main elements of such a program, characterized as the Human Exploration Initiative (HEI). The review, entitled the *Report of the 90-Day Study on Human Exploration of the Moon and Mars*, was based on feasibility studies that NASA had conducted in the past. The report contains five "reference approaches" that are intended as a data base for planning, or as a starting point for future discussions involving technical, budgetary, or scheduling options. The primary audience for the report was the National Space Council, headed by the Vice President of the United States.

Subsequently, the Vice President invited members of several scientific and industrial communities in the US to participate in considering the best ways to address the national HEI. On December 4, 1989, the Vice President wrote to the Chairman of the National Research Council (NRC) asking for a review of the scope and content of the NASA report including the questions of whether the "report addresses the widest possible range of technically credible approaches to meeting the President's exploration goals," the reasonableness of NASA's technical assumptions, whether the report has overlooked possible innovative uses of existing technology or alternative ways to accomplish human space exploration, and whether the range of both desirable and enabling scientific objectives was appropriate. The committee was not asked to approve or endorse any aspect of the Human Exploration Initiative. (See Appendix A for the Vice President's request and the NRC response.)

PROCEDURE

In accordance with its practice and procedures, the NRC organized a committee of experts to prepare a report responsive to the request. The committee contains expertise ranging across many scientific and technical space disciplines. (Biographical data on committee members is found at the end of the report.) On January 4, 1990, several members, constituted as a steering committee, met in Boston to plan the undertaking. On January 17-21, 1990, the full committee and several invited technical and scientific advisors convened in Washington, D.C. The committee received a series of technical presentations on alternative mission scenarios and technical approaches from persons from private industry, universities, the Department of Defense, and national laboratories, and heard elaborations on the 90-Day Study and analyses from the NASA Administrator, several Associate Administrators, and other NASA representatives. In addition, the committee invited experts to brief them about four areas of space life sciences and also briefers to discuss the space nuclear power and propulsion programs run by NASA, the Department of Defense, and the Department of Energy. (A list of invited presenters and guests is contained in Appendix B.)

The committee considered a number of approaches to the HEI and its elements. These included the set of reference approaches addressed by NASA in its 90-Day Study and relevant programmatic information; an alternative approach called The Great Exploration, put forward by the Special Studies Program of the Lawrence Livermore National Laboratory; a concept that would utilize identical modules for a space station and the lunar and Mars missions; and several suggestions for improvement of launch and space propulsion capabilities. An extensive library was available to the committee, and key documents are listed in the bibliography.

Following two days of briefings on these matters, the committee spent two and a half days in discussion to begin preparation of the findings and conclusions in this document.

APPROACH

The committee regards the NASA 90-Day Study, currently available alternative mission scenarios, and the identified scientific and technical alternatives as starting points. It did not limit its deliberations to a review of the technical approaches in the NASA report and the alternative presentations, but extended its considerations to a number of interrelated nontechnical and institutional subjects, some of which are also addressed in the 90-Day Study.

The President's July 20 statement established a long-term objective of returning to the Moon and advancing humans to Mars. The President stated this policy in terms of an opportunity, not a race. (Excerpts from the July 20 statement and the subsequent National Space Policy document of November 2, 1989, are found in Appendix C.)

The pace at which the initiative should proceed, while clearly influenced by scientific and technical considerations, is inherently determined by social and political decision-making processes in which nontechnical constraints, such as the sustainable level of resource commitment and acceptable level of risk, are paramount. Within practical limits, technical analysts can develop alternative mission scenarios to achieve the stated goals under various sets of constraints, which provide ground rules for design. While scientists and engineers contribute to the policy debate, it is up to the political decision makers to establish the ground rules, which depend in turn on technical options.

To date the ground rules are unclear; as a consequence, technical analysts have presented mission scenarios based on differing assumptions. Many mission scenarios to establish bases on the Moon have been suggested, not only within NASA, but throughout the engineering and scientific communities of the US and the world. In its deliberations, the committee was exposed to only a few of these. Collectively, the committee is aware of many other possible scenarios, but lacked the time to examine them in detail. Some mission scenarios project a deliberate pace, extending current technology along foreseeable paths in order to minimize technical risk and maximize human safety. Other visions place higher emphasis on minimizing the time to get humans to Mars, incurring higher levels of technical and human risks. Clearly, there is need for guidance at an early date regarding the scope and pace of the early stages of the HEI.

In its reviews of alternative mission architectures and the underlying scientific and technical challenges, the committee also recognized a number of other issues inherent to achieving the President's goal. One was the challenge of educating, recruiting, training, and maintaining a technically competent work force. Another was the requirement for an appropriate industrial infrastructure to carry out the work. Still another was the managerial and administrative challenge of mounting a project of this nature, one that will certainly take many years to accomplish and presumably will result in a sustained program supporting the presence of humans in space.

I
Alternative Mission Concepts

The Committee on Human Exploration of Space examined NASA's approaches to the HEI and a number of alternatives. However, a wide range of possibilities for program architectures and mission configurations exists that is yet to be examined in detail. The scope of early HEI missions can be defined, but, given the scientific and engineering unknowns, it is too early in the process to focus upon a single, final plan for a permanent return to the Moon and voyages to Mars. The need to bring innovative ideas to the planning process is widely recognized.

THE SPACE STATION AS A FIRST STEP

The President's policy incorporates Space Station Freedom (SSF) as the first step to achieving the ultimate goals of Moon settlement and Mars exploration. Although it is technically feasible to go to the Moon and Mars without the intermediate step of establishing a permanent station in low Earth orbit (LEO), most of the mission architectures under consideration employ a station for assembly of vehicles for travel beyond Earth, for storing fuel and supplies, and as a human transfer facility. In the near term, a facility in LEO is essential for conducting research on human performance and well-being in zero or fractional gravity as well as long-term confinement in zero gravity. It also can serve as a testbed for the life support system that eventually will be needed on the Moon and Mars, and can house experiments with artificial gravity, should that become a requirement for the journey to Mars.

Thus, the first major step to be taken in human space exploration is establishment of a station in LEO. The current station could meet some, but not all, of the requirements of the HEI. Proceeding with the HEI, therefore, would require continued development of the station to meet the demands of the initiative, including the conduct of life science research and use of the station as a spaceport. In the long term, the compatibility of the many functions to be performed on the station may be a serious question.

A more precise interpretation of the goals surrounding the return to the Moon and the advance to Mars, as defined by the social and political decision-making process, will help to determine the nature, magnitude, and pace of the lunar and Mars ventures. The question even arises whether an additional station, complementary to the first and designed as a transportation node, will eventually become necessary to accommodate the later, more demanding missions.

THE NASA REPORT OF THE 90-DAY STUDY ON HUMAN EXPLORATION OF THE MOON AND MARS

The NASA Report of the 90-Day Study provided descriptions of five reference approaches:

Approach A is formulated to establish human presence on the Moon in 2001, and the Moon is used as a learning center to develop the capability to move on to Mars. An initial nuclear power unit and lunar oxygen production demonstration hardware are added in 2003 to reduce lunar logistics requirements. Research is planned in geologic and geophysic exploration, geophysical and particle physics, and astronomy, as well as in the life sciences. The first Mars expedition is a 30-day stay on the surface, followed by a 600-day visit beginning in 2018, during which many scientific experiments are foreseen. This scenario involves advancing completion of SSF to 1997, requiring a heavy lift launch vehicle.

Approach B is basically the same as Approach A, except that it advances the first human Mars landing to 2011 and limits the degree to which lunar experience could affect the design of the Mars transportation and surface systems. It delays lunar science activities, but advances those on Mars.

Approach C is akin to Approach A, except it advances to 2005 the date by which lunar oxygen is available, requiring earlier development of nuclear power system capabilities. By accelerating lunar activities, the knowledge learned can be applied to Mars missions.

Approach D is also based on Approach A, except that all milestones are delayed two to three years, with a return to the Moon in 2004. Approach D does not require accelerating SSF and permits incorporation of new technology developments in plans for Mars excursions.

Approach E envisions a scaled-down, human-tended lunar base, and does not require that SSF be advanced in time. It includes a 600-day Mars simulation activity on the Moon. A lunar outpost is established in 2004, and three human expeditions to different locations on Mars begin in 2016, preceeding establishment of a permanent base.

The reference approaches in the NASA 90-Day Study are largely variations on a theme and have certain common features: They depend on heavy lift vehicles to LEO and on SSF for assembly in LEO and as a transportation node. They employ unmanned robotic precursor missions, reusable transfer vehicles to lunar and Martian orbits, and excursion vehicles at surface bases. Each features sequential Moon and Mars programs, assumes zero gravity in transit to Mars and requires a decade or more of research on adaptability of humans to low or zero gravity, depends on aerobraking (using atmospheric drag to slow a vehicle for capture in the planetary gravity field), and requires new chemical propulsion engines using cryogenic fuels. Proceeding from initial habitats to constructible bases, these reference approaches all provide an extensive, reusable orbital transfer capability and infrastructure designed for permanent occupancy of the Moon and Mars.

The approaches described in the NASA study are relatively low in risks, in that each would proceed in methodical steps after earlier steps have been proven and after scientific and engineering questions inherent in the architecture (e.g., nuclear propulsion, aerobraking, Mars surface habitability) are answered. The study recognizes the need for substantial advances in technologies such as those relating to the life sciences and nuclear power and propulsion. The committee believes the reference missions provide a useful background of possible mission configurations against which new ideas and concepts can be compared, and against which various cost and schedule scenarios can be analyzed.

The architectures of the reference approaches, however, were built upon the presumed objective of returning to the Moon permanently and establishing bases on the surface of Mars. Therefore, the reference missions do not provide explicitly for an option that may entail less risk: a habitable station in orbit around Mars from which exploration initially could be conducted by telerobotics and later by human excursions to the surface. Considerable energy is required to transfer mass to Mars orbit from the surface, so it would be prudent to minimize the need for such transfer. In this context, it appears that a station in Mars orbit requires a less demanding infrastructure than a surface base and might serve a useful purpose in the early stages of human space exploration.

An important aspect of the NASA Mars reference approaches is the reliance on aerobraking, a technology that has not yet been demonstrated in the dilute Martian atmosphere. An aerobraking vehicle will require large surfaces, new materials, and precise controls to avoid descending too rapidly or deflecting from the atmosphere back into space. The final decision regarding aerobraking should await technology demonstration and further knowledge about the Martian atmosphere, as well as information regarding the weight trade-offs between successful aerobraking materials and fuel for propulsive braking, especially were nuclear propulsion to be available. Aerobraking has the potential for reducing the initial mass of a spacecraft by 20 to 50 percent, however, and demonstrations are needed to bring this technology to fruition.

Last, in these reference scenarios, extensive extravehicular activity (EVA) is implied for space construction and assembly. Human experience in space suggests that less EVA means safer missions, owing to the limited maneuverability and flexibility of astronauts in currently available space suits. Emphasis on teleoperations or more synergistic human/machine interactions can provide substitutes for extensive EVA. But to facilitate a wide range of human activities in space, it seems desirable to develop an improved space suit for necessary EVA tasks.

THE GREAT EXPLORATION

The most characteristic features of The Great Exploration concept are its success-oriented pace, the estimated low total costs projected by its proponents (permanent bases on the Moon and Mars by the year 2000 at an estimated cost of $10 billion to the launch of the Mars excursion vehicle), and the use of essentially identical, preassembled, inflatable structures for an Earth-orbiting space station, for propellant storage, and for structures for the Moon and Mars. The technology of space-based inflatables has been studied extensively, but has not been demonstrated in space. It also appears in the NASA study, in less critical applications. Clearly, prior to commitment to the use of such structures, there would be a need for advanced development and demonstration of space-based inflatables and of specific techniques for incorporating the necessary expandable hardware and fixtures in such structures. The potential advantage of inflatables is the reduced requirement for lifting mass to LEO, perhaps even reducing the requirements for a new heavy lift launch vehicle. However, if preassembled inflatable modules prove not to be useful for one or more of the applications envisioned in this mission architecture, modules of traditional, rigid construction would have to be substituted, presumably with considerable effect on the mission concept.

A number of critiques have been performed on The Great Exploration concept and its proponents have prepared responses. The committee's judgments have benefitted from this exchange of information and analyses.

However, it might be noted that the projected economies of time and cost proposed for The Great Exploration depend, in part, on using off-the-shelf technologies and "standard terrestrial machinery and equipment." The committee is not convinced that off-the-shelf, terrestrial technology will perform as required in the environment of space, the Moon, and Mars, nor that the technology meets requirements for reliability that should govern human-rated space systems. For example, the development of machines and apparatuses and their operation must take into consideration the adhesive and abrasive nature of the lunar soil, which is well known from earlier lunar landings. Further, The Great Exploration proposes no robotic precursor missions to learn more about the environments of the Moon or Mars or to identify safe or scientifically interesting landing sites. The committee believes The Great Exploration underestimates the many engineering and operational challenges involved in bringing its technical concepts to practical realization.

The Great Exploration strategies are self-described as intentionally "maximally time-compressed" and "reward- and risk-intensive" to achieve the ultimate goals as quickly as possible, on the premise that "there has never been a successful 25-30 year Federal technology program." Special priority procurement processes and waivers that are not otherwise available in unclassified civilian programs are required in order to meet the demanding schedule. Such procedures may not be acceptable in an open project, especially if there are international partners.

Nevertheless, the committee believes there may be technologies in this alternative to the NASA approaches that should be further investigated, for example, the use of space-based inflatables for at least some of the required functions and modules.

OTHER ARCHITECTURES FOR THE HUMAN EXPLORATION INITIATIVE

Many other approaches exist for accomplishing the HEI. A concept was presented that featured advanced bases on the lunar surface and in Mars orbit essentially identical to SSF core modules. Modules, assembled on SSF as complete bases, would be mated with expendable propulsion systems to be launched intact and unmanned from LEO. The concept relies on the existing space shuttle for transport to orbit of relatively lightweight, valuable cargo and personnel and on a heavy lift launch vehicle for fuel and major unit (modules, nodes, spacecraft) transport. Mars orbit is selected as a preferred base from which to explore the planet, in the belief that it would be a more predictable and controllable environment than one of the Martian moons, and less dangerous than the planet's surface. The principal obstacle to going to the surface is that the space station replica would not survive Mars atmospheric entry. Separate vehicles, also chemically propelled, are required for rapid transport of personnel.

In this concept the similarity of the space station, lunar, and Mars modules implies less development time and cost and indicates that Mars might be reached sooner for early exploration than if the Mars flights had to await technology validation by aerobraking research and development and nuclear propulsion demonstrations. The committee did not study this concept in great detail, but it appears that the principal unknown in this scenario concerns the stability of such modules in transit.

Among other early architectures that might be considered are the NASA baseline concept, with the initial Mars base in orbit rather than on the surface and the NASA baseline with separate cargo and crew transport systems, the latter with high-speed, staged chemical propulsion and even Earth launch of lunar and Mars missions. The committee is convinced that other alternatives will arise as concept development proceeds. The report of the National Commission on Space, *Pioneering the Space Frontier*, for example, contains stimulating discussions of future approaches to human exploration of space.

From the committee's brief exploration of these alternative concepts, it appears likely that the eventual choice of mission architecture will incorporate ideas from a variety of concepts, some that now exist and possibly some new ones. While the scenarios thus far described vary substantially in schedules, technologies, and in the need for research and development, all would benefit from advances in space transportation and in technologies critical to the support of humans in space. The committee found imaginative and worthwhile components in all of the presentations, and, at the same time, recognizes the value, at this time, of encouraging the search for new ideas.

II
Space Transportation: Launch Systems, Propulsion, and Power

The committee concurs with NASA's view and the general consensus that robust and reliable transport to LEO and beyond is essential to the success of HEI. Further, it believes that the currently available launch systems and their derivatives will not meet these criteria in the future. Improved capabilities are required for transport of humans and high-value cargo to and from LEO; transport of large unmanned components, propellants, and expendables to LEO; and orbital transfer to the Moon and Mars.

For reasons of cost and reliability, the transport of humans and other precious cargo will require a different launch system than those for the transport of more ordinary or bulk cargo. Because operations of the space shuttle will continue to be labor-intensive and expensive, because the system is not robust, and because the system probably will reach the end of its useful life sometime between 2000 and 2010, the committee believes that a successor to the shuttle eventually will be necessary for human transport to orbit. For at least the next 10 years, however, the nation will necessarily rely upon the shuttle for this role, and it is essential that the existing shuttle fleet be maintained in a fully operable state. As indicated in the NRC report, *Post Challenger Assessment of Space Shuttle Flight Rates and Utilization*, at least one additional replacement orbiter is likely to be required every 5 to 10 years to offset inevitable attrition of the present fleet. But orbiter replacements should not impede the emergence of a new capability for launch to LEO. Eventually, a plan for a graceful phasing out of the shuttle system should be prepared.

An important aspect of reducing costs, when considering the design of new launch systems, should be the efficiency of activities on the ground that are required to prepare vehicles and payloads for launch.

HUMAN TRANSPORTATION TO AND FROM ORBIT

The space shuttle system now appears to be operating satisfactorily, and there is reason to believe that with continued scrupulous adherence to proper manufacturing, maintenance, and operating procedures, it can continue to do so. It does, however, have a limited design life, like any high-performance system. It requires continuing refurbishment and in due course it will require major replenishment, or it will have to be supplanted. Continued access of humans to space will require that planning begin soon for a new human transportation system that will first supplement and then assume the shuttle's role in human transport to and from orbit, sometime between 2000 and 2010. The best available technologies should be used to produce a system that is robust, highly reliable, reasonably cost-effective, and that has minimum requirements for ground support and preparation for launch.

At present, the most likely configuration of the required system is a two-stage rocket powered vehicle, with a fly-back first stage, an orbiter with substantial cross range capability, and a thermal protection system or hot structure that allows reuse without major refurbishment. It may be that some of the technologies being developed in the National Aerospace Plane Program (NASP) will find application in this system.

UNMANNED LAUNCH SYSTEMS

In light of the evident requirements for lifting mass to LEO, a modern launch system with heavy lift capability will be essential. It does not exist in this country at this time. Therefore, a family of launch systems based perhaps on the interagency Advanced Launch System (ALS) or similar technologies should be defined and committed to development. The design of these systems, although not requiring a safety rating for humans, should still emphasize reliability and robustness over performance, as measured, for example, by the ratio of payload weight to gross weight. The level of reusability should be selected similarly to optimize the reliability and robustness of the systems and to minimize cost on the basis of realistic utilization rates. More reliable technologies can be used, at a given overall cost, if some of the critical components are recovered. It is the committee's view that if these criteria are met, substantial improvements in launch cost will accrue, relative to those for current systems.

The family of launch systems envisioned is likely to accommodate the upper range of payload masses projected by the Department of Defense, as well as the heavy lift requirements of the HEI. This can be done by clustering modular liquid propulsion systems with staging appropriate to the particular launch requirement. Key features of the required new launch systems will be the use of modern materials and technologies. The engines probably will operate at chamber pressures below those of the space shuttle main engine and will be manufactured using advanced technologies, such as precision casting, which lower costs while improving quality. Guidance and control will take advantage of modern electronic technology to provide fault tolerance and largely eliminate single point failures. Even with these improvements, it will be desirable to configure the vehicles so that missions can be completed after loss of one engine early in a launch. With the higher performance that will be available, such robustness should be affordable.

The committee favors this approach for three reasons: First, if developed to the criteria outlined, such liquid bipropellant systems will have a higher level of reliability than do the solid boosters utilized on the shuttle. The engines can be test fired prior to launch, an engine-out capability is feasible, and engine shutdown in flight is possible if a fault is detected. Second, pollution of the atmosphere by chlorides, as occurs with solid propellants, would be eliminated. This is likely to become an increasingly serious issue as launch rates rise in the buildup of the HEI. Finally, the committee believes liquid bipropellant systems have the potential for significantly lower recurring costs compared to solids. Thus, for the long term, the committee anticipates reliance on liquid rockets.

There are several alternatives to the above strategy. One considered by the committee is a flexible family of launchers that would use existing fully-developed solid propellant motors in clustered arrangements, providing up to four stages and a wide range of payloads to LEO or to higher orbits. Such launchers are certainly feasible. Their development costs would be lower than those of the ALS-class systems discussed above, and their recurring costs would probably be lower than the Titan, shuttle, or Shuttle-C. The committee has three concerns about this concept: First, with a large number of solid motors, this system is not likely to be as reliable as those using liquid rocket technology. Second, the recurring costs are likely to be substantially higher than for an all-liquid system, and, finally, the solid upper stages would present environmental problems with injection of chlorides at very high altitudes.

The committee notes, however, that the universal launch system complex being designed for this family of launchers, based on oil platform technology, has very attractive features such as modular construction of assembly buildings and a launch platform that can be elevated. An elevatable launch platform avoids the construction of flame ducts and can serve a variety of launch vehicles. These should be considered carefully if a new launch complex is needed. This concept could be applicable to manned or unmanned systems and could reduce costs for the entire launch complex.

Another alternative is single-stage-to-orbit rocket launch systems, which have been proposed many times. This option has been raised again in the present context in a configuration that conceptually would offer engine-out capability, a safe abort at any point in the launch, and full recoverability. The committee's brief review of this concept has led to the conclusion that it is founded on unrealizable assumptions regarding structural weight and propulsion system weight. Dramatic advances in single-stage structural technologies and in materials, even beyond those anticipated in current programs such as NASP, would be required to make this a viable concept.

A sea-launched, two-stage, fully recoverable system with pressure-fed engines has also been suggested, with the projection that the components could be reused up to 25 times. In any launch system, optimistic reuse projections can lead to attractive, but unrealistic, estimates of costs, and in the committee's judgment, such extensive reuse is improbable due to the effects of the marine environment. Ocean operations can pose more of a problem than an aid. Very large pressure-fed systems are also difficult to deal with and require very large nozzles. Further, this concept currently lacks a credible plan for recovery of the second stage, which would reach full orbital speed.

NUCLEAR THERMAL PROPULSION

Although the reference approaches in the NASA 90-Day Study rely on chemical propulsion, NASA has included nuclear thermal propulsion as an option to be considered for orbital transfer to Mars. Several possibilities have been mentioned within this general class of systems, all of which offer higher specific impulse than chemical rockets and employ hydrogen as the propellant.

The alternative nuclear propulsion technologies differ in the temperature to which the hydrogen is heated by the fissioning nuclear fuel; the pressure level in the thrust chamber (which along with the temperature determines the extent of dissociation of the hydrogen to atomic form); and the power density assumed to be achievable in the reactor. The temperature and pressure determine the specific impulse, while the power density largely determines the thrust-to-weight ratio of the propulsion system.

The baseline capability is taken to be the NERVA class technology, the technical feasibility of which was demonstrated in the late 1960s. In the NERVA program, a reactor was tested on the ground for periods longer than required for operation, at power densities that would yield thrust-to-weight ratios on the order of five, and at temperatures giving specific impulse as high as 850 seconds. This technology is available for full-scale development. It should be evaluated for injection to Mars in competition with hydrogen-oxygen chemical systems. The higher specific impulse of the nuclear rocket results in a smaller propellant expenditure for a given total impulse, but the propulsion system weight is higher, so that its attractiveness depends on the velocity change needed, and whether the system is reused. A major advantage of nuclear propulsion is its ability to enable transfer between Earth and Mars in one-half to one-third the time required with single-stage chemical propulsion systems. This advantage could be critical, pending the outcome of research on human performance in space for long periods. The use of nuclear technology in space faces formidable barriers of public acceptance, however, especially if employed in Earth orbit. Therefore, issues of safety are paramount in research and development.

An advanced reactor design has been partially evaluated experimentally that offers much higher power densities, hence much higher thrust-to-weight ratios, than the NERVA class technology. If proven feasible, this class of technology will make the nuclear rocket more attractive relative to chemical propellants. The risk involved in this technology development appear very high at present, but the committee urges a feasibility test be carried out to determine what thrust-to-weight ratio is practically achievable. It also recommends that the potential of the technology be reviewed by a senior group experienced in nuclear rocket technology.

The 90-Day Study mentions gaseous-core nuclear rockets as offering much higher specific impulse levels. A number of gaseous-core reactor concepts were carefully evaluated in the years between 1959 and 1970, but none was found to be technically feasible. Unless a new idea has appeared, which is always a possibility, the committee believes the gaseous-core nuclear rocket technology is too speculative at this time and should be dismissed as a possibility.

If careful systems studies, using thrust-to-weight ratios and specific impulse known to be feasible, show a significant advantage for nuclear rockets in trip time or in weight to orbit, an in-space demonstration of this technology should be done as soon as possible—taking into account requirements for crew, ground personnel, and public safety covering all phases of launch and flight, including mission abort. It will not be feasible to select the nuclear rocket as a baseline in a system architecture until such a demonstration has been conducted.

NUCLEAR ELECTRIC POWER

The committee believes that nuclear power eventually will be essential for lunar and Mars bases. The NASA reference approaches incorporate nuclear power; The Great Exploration does not.

At present, the only active technology program applicable to this need is the SP-100 thermoelectric space reactor, which has been pursued under a tri-agency program for several years. SP-100 was initiated in the absence of a definite mission requirement as a general purpose space power source. This program should be redefined in light of the requirements of the HEI and committed to development; nuclear thermionic research should continue to be pursued as well.

Consideration should be given to demonstration of the nuclear electric power system as the power source for an electric propulsion system, which may have application to science missions with large launch velocity requirements. (In fact, a number of outer planet missions have been suggested, including a Jovian system grand tour, that will require such advanced power sources.) Here, as with the nuclear rocket, considerations of safety must be incorporated into research, development, and demonstrations and factored into assessments of overall systems performance. The nuclear electric system might be demonstrated within these constraints by a mission in which the system is launched to a high orbit, say 600 miles, before it is operated. The orbit could then be raised by nuclear-electric propulsion to geosynchronous orbit or beyond.

If safety concerns can be successfully addressed, and feasibility demonstrated, the committee believes that use of nuclear power and propulsion can meet many needs in the human exploration of space.

III
Other Critical Technologies for the Human Exploration Initiative

Ongoing development of certain specific technologies is essential to the HEI and offers potentially high payoffs in capabilities and long-term cost savings. The committee assumes that HEI technology development will complement rather than displace the NASA program of basic research and technology development in such areas as materials and structures, sensors, air-breathing engines, and data processing.

THE NASA 90-DAY STUDY

The Technology Assessment section (Chapter 8) of the 90-Day Study lists seven technologies (regenerative life support systems, aerobraking, advanced space engine, surface nuclear power, in-situ resource utilization, radiation protection, and nuclear thermal rocket propulsion). It continues with "other technology needs, briefly sketched" under titles like "humans in space." Although the NASA Figure 8-1 envisions focused research that does not continue after five years, ongoing advanced technology research will clearly be characteristic of the HEI for many years.

The committee agrees that these technologies are important, but believes that strategies for development of technologies should take account of the lead times required and incorporate priorities according to whether the technologies are essential to the HEI, or serve to enhance capabilities. For example, provision of radiation protection, life support, and crew safety are survival imperatives for all human space-based modes, and must be addressed as major architectural considerations. Research on artificial gravity should be added to this list. On the other hand, aerobraking, in-situ resource utilization, and nuclear thermal rocket propulsion technologies may offer significant advantages in certain mission scenarios, but are not essential for human missions in general.

There are other specific new technologies, not in NASA's list of seven critical technologies, that can profoundly simplify and enhance operations in every mission scenario. Two clear examples are (1) advanced human/machine systems for tasks in space, in order to improve the efficiency of humans, and (2) far more capable information management systems for mission decision making. While the 90-Day Study recognizes advances in information systems and automation and robotics as being important to the success of the HEI, the emphasis should be on technologies that go one step farther, to greatly advanced computer-aided mechanical extensions of human performance, i.e., human/machine systems.

ARTIFICIAL GRAVITY

Artificial gravity was not included in the NASA list of critical technologies. With the current state of knowledge, a multiyear exposure to weightlessness, even with on-board exercise and countermeasures and an intermediate stay on the surface of Mars, presents unacceptable risks to the crew. Adaptation to microgravity makes return to a gravity environment dangerous and renders human performance on the surface of Mars problematical. The questions of whether artificial gravity will be required and, if so, how it will be provided are critical. The nation has no strategy for research to determine the need for or provide artificial gravity.

Several alternative approaches to addressing the problem can be considered. In one, an early commitment could be made to provide artificial gravity in the transfer vehicle to Mars. This option is not included in the 90-Day Study, but has been reviewed by NASA in the past and found to increase the mass of a Mars transit vehicle by no more than 20 percent, under the most conservative assumptions.

Another alternative is to determine the requirements for artificial gravity by testing humans in a variable-gravity research facility in LEO. Such a facility should permit research on human physiological deconditioning and countermeasures, including different artificial gravity radii and rotation rates, in order to determine the optimal combination of gravity levels and exposure times. Because of time considerations in human deconditioning phenomena, an operational research period lasting two to six years must be anticipated before definitive answers about artificial gravity can be expected.

Short of undertaking long-duration research on human performance in space, any research strategy for minimizing human risk of irreversible or incapacitating deconditioning should make maximum use of ground and space station facilities for relevant life science research. Ground bed-rest studies and incremental duration exposure of subjects in a space station must be integrated with animal research in orbit, including use of the SSF on-board centrifuge. In parallel with these tests, the effectiveness of several candidate countermeasures to deconditioning should be evaluated in controlled experiments. If the deconditioning is unacceptable and the simpler countermeasures are ineffective or onerous, full-scale space-based artificial gravity evaluation and facility development become imperative.

Another alternative approach, which is less thorough than the use of a variable-gravity research facility but which could be carried out in parallel with a lunar base development, is an investigation of the effectiveness of lunar gravity as a long-term countermeasure. This approach would provide deconditioning data at three levels: 0, 1/6, and 1 g. It would not, however, help with the question of gravity gradient or contribute to any of the engineering issues regarding a spinning spacecraft for Mars transit.This approach is the most limited and time consuming. It also carries with it the risk of negative results that would require the eventual, but delayed, artificial gravity investigations described above.

ADVANCED HUMAN/MACHINE SYSTEMS

Mechanical and computer-aided extensions of human (astronaut) managers can provide enhanced efficiency in inspection, assembly, maintenance, repair, and exploration tasks. The most powerful approaches to human exploration will integrate humans with machine systems to accomplish more than either can do alone. These approaches can range from low-level, hand-in-glove teleoperation, through higher-level object-motion commands, to planned task commands by a distant astronaut. Application of the many automation and robotic systems needed to integrate humans and machines can range from some of the early systems developed for space station management and operations, to precursor nonhuman missions, to advanced synergistic systems of humans and machines operating on another planet.

Advanced human/machine systems are not merely an enabling technology, but a requirement for practical HEI operations. Technical advances can extend profoundly the human role as master of highly flexible human surrogates, but obtaining such potential benefits will require more than complex robotry and automation. NASA presentations based on the 90-Day Study implicitly recognize this by grouping operations in functional categories. Systems that integrate automation and robotics with humans permeate the arenas of vehicle maneuvering; vehicle servicing in space; in-space and surface assembly and construction; planetary rovers; surface operations; extravehicular activity and exploration; sample acquisition, analysis, and preservation; and scientific probes and penetrators. Reduction of

EVA time alone probably will lead to increased efficiency and will increase safety.

Most of the technologies discussed above and in the NASA plan require long lead times. In many cases the basic research has barely begun. To make the HEI possible, the research foundation will have to be laid in the areas listed in the NASA report and in such fields as artificial gravity, more capable information systems, and human/machine systems.

The time at which these technologies are successfully developed is important to the pacing of the progression from the Moon to Mars.

IV
Space Science and the Human Exploration Initiative

The NASA 90-Day Study reflects an initial attempt to identify the scientific components of the HEI. It identifies five themes around which the science elements of the initiative are developed and states that the "fundamental scientific themes . . . can be uniquely addressed by the Human Exploration Initiative." Several specific examples are presented of scientific objectives in precursor flights to the Moon and Mars. The 90-Day Study provides evidence of NASA's intention that scientific research be an integral part of the HEI. Nevertheless, it is clear that much of the research in the NASA scientific themes does not require an HEI.

It is useful to divide the scientific research issues into three broad categories. First, there are scientific studies to enable the initiative—those that must be done before humans can travel to Mars, perform useful tasks, and return safely. Second are studies and experiments that can only be conducted as a result of the envisioned long-term human missions. Third are studies that may be undertaken in association with those missions, but could be carried out otherwise if necessary. Any scientific knowledge that might be obtained in association with long-term human missions should be evaluated in competition with other modes of gathering the same information (e.g., human-tended, telerobotics) and with other scientific research goals. This competitive category of scientific research should not be used as, nor considered to be, the primary justification for a national commitment to human exploration of space.

SCIENTIFIC KNOWLEDGE AS A PREREQUISITE FOR HUMAN EXPLORATION

The most important issues of prerequisite scientific knowledge concern those matters that are critical to human health and safety, including microgravity effects on physiologic functions, the effects of radiation, controlled environment life support systems, site-selection and contamination issues, and the psycho-social aspects of prolonged exposure in a confined habitat.

In every pioneering effort there are risks, known and unknown, that are intrinsic to the endeavor. Those responsible must make the fullest efforts to reduce the known risks to reasonable levels and make clear the levels of risk that remain. Potential hazards must be explored and countermeasures devised to reduce risk. Research is required to explore the range of risk and to devise reasonable countermeasures.

Life Sciences

Microgravity Issues

Data are incomplete regarding the effects of the microgravity environment on human physiology (including the cardiovascular, vestibular, and immune systems); more research is also necessary on adequate countermeasures. As noted in the NRC *Strategy for Space Biology and Medical Science*, "If this country is committed to the future of humans in space, particularly for long periods of time, it is essential that the large number of uncertainties about the effects of microgravity on humans and other living organisms be recognized and vigorously addressed." The 90-Day Study envisions research to develop countermeasures to the effects of very low gravity and to promote the basis for designing artificial gravity environments, if required. A rigorous research program would be based largely on facilities available in an Earth-orbiting station, designed to gain an understanding of the effects of a microgravity environment on humans. As NASA indicates, the results of this research will have significant implications for mission architectures and mission time profiles.

Radiation Issues

Radiation from solar and galactic sources poses serious potential hazards to human health. Predictions of solar flares and of solar flare particles remain uncertain, but successful predictions are not prerequisites to human spaceflight, if adequate shielding is provided. Research on prediction techniques, one of NASA's objectives, should be vigorously pursued in parallel with human exploration programs. The intent would be to provide the earliest possible warnings, with minimal false alarms, of impending solar flares and flare particles.

As the 90-Day Study indicates, it is important to learn more about the relative biological effects of radiation fluences, particularly high-Z galactic cosmic rays and solar flare electrons and protons, and their relationship to cancer and cataract induction, for example, in order to set meaningful guidelines for radiation protection. The question of appropriate shielding in flight, at an Earth-orbiting station, and on the Moon and Mars is complex and requires further study. For example, NASA suggests that for modest thicknesses of shielding, the secondary radiation arising from the interaction of galactic cosmic radiation may be more harmful to living tissue than the primary dose. Consideration should be given to undertaking early flights during solar minimum conditions.

Controlled Environment Life-Support Systems

The 90-Day Study recognizes the challenge of providing a reliable, cost-efficient life-sustaining environment in locations that are devoid of food, air, water, and nutrients. NASA's vision of the HEI uses closed-loop systems where practical to reduce logistic requirements and open-loop systems where limitations in technology or operational capabilities dictate.

It would be useful, but not mandatory, to have fully-closed life-support systems for brief visits to the Moon and to Mars. However, even for a brief visit, it is desirable to recycle water. For prolonged stays on the Moon and Mars, a completely closed regenerative system would be highly desirable to reduce requirements for resupply. Several terrestrial closed-loop experiments are under way and must be reviewed in the context of the HEI and refined until they are successful. The next step should be a test bed of a closed life-support system in microgravity on or near an Earth-orbiting station.

Contamination and Back Contamination

Evidence from the Viking missions to Mars suggests that terrestrial microorganisms have little or no probability of growth on that planet, but that does not rule out the possibility that life exists or may have existed there in the past. Although organic compounds and liquid water have not been detected on Mars, there is no basis for precluding their existence. There is, moreover, strong evidence that liquid water in large quantities existed in the Martian past. Furthermore, new discoveries about unusual biological niches on Earth, such as deep ocean thermal vents, illustrate the diversity of biological habitats.

International law requires that activities in space be conducted to avoid the harmful contamination of celestial bodies as well as introduction of changes in the Earth's environment by extraterrestrial matter. For example, a Mars robotic lander raises concerns about contamination of Mars (referred to as forward contamination), while a Mars sample return mission must deal with concerns about contamination of Earth (called back contamination).

The NASA 90-Day Study envisions a series of unmanned precursor missions to Mars to determine characteristics of the planet. The knowledge to be obtained is necessary for detailed mission planning, including dealing with the contamination issue. The Great Exploration concept does not include such precursor missions. The committee believes that, before humans go to Mars, there will have to be a highly capable set of precursor missions, whose precise definitions, numbers, and configurations require detailed research strategy development. Such precursor missions will allow assessment and management of some of the risks of carrying out a manned mission. The risks are not limited to concerns simply with pathogens. While the risk of pathogens is admittedly low, the potential costs are possibly very high.

Psychological Issues

As noted in the 90-Day Study, psychological effects arising during long-duration sequestering of humans have been documented, for example, in nuclear submarines and research programs in Antarctica. Although these terrestrial analogs are useful, they do not adequately simulate conditions of long-duration missions to Mars. NASA appropriately envisions continuing research in the selection process for spacefarers. Issues of spacecraft habitability, training and command structure, as well as crew mix require study, including simulation. A review of research results to date indicates that more is known about avoiding undesirable crew characteristics than is known about selecting crew for desirable traits. Clearly, the psychological profiles for individuals and for crew composition should be well understood, to reduce risks on long voyages. As is the case with most risks to humans arising from long stays in the microgravity environment, technological advances in nuclear and other propulsion systems could alleviate some adverse effects by reducing mission duration.

Physical Sciences

Because the use of local resources is likely to be an essential feature of the mission architecture, additional scientific knowledge will be required about surface materials, features, and structures, both on the Moon and Mars. Four of the five reference approaches in the 90-Day Study incorporate extraction of oxygen from lunar materials.

Present knowledge of lunar and Martian surface features is adequate for lander modules, provided that high-resolution imagery is incorporated for terminal guidance to a landing that can be directed over a sufficiently large target radius. Additional knowledge will be required for site selection, however, if the astronauts will be expected to carry out significant research while on the surface. Uncertainties also exist concerning the bearing strength of the Martian surface in areas of possible landing sites.

In the case of the Moon and a possible long-term lunar base, the flux of micrometeorites and its variability are major uncertainties that can affect the livability of a lunar station. As described in both the 90-Day Study and The Great Exploration, covering the station with lunar regolith is one possible way to reduce the hazards from micrometeorites and radiation.

A fuller examination of research emphases in this area is needed before precursor mission concepts are developed.

RESEARCH OPPORTUNITIES TO BE DERIVED FROM PROLONGED HUMAN SPACE MISSIONS

The NASA 90-Day Study describes a variety of opportunities presented by the HEI to advance scientific understanding through both the robotic and human exploration phases of the HEI. The opportunities are organized into a series of scientific themes. Several themes pose questions that challenge astronomers, and NASA notes, for example, that the Moon offers a number of advantages as a site for astronomical observatories.

The committee believes the Moon could offer potentially unique research opportunities for a number of space science disciplines, including astronomy. However, the concept of an astronomical observatory on the Moon needs to be examined more critically than was suggested in the NASA report. Specifically, lack of seismic activity does not seem to be a major feature in determining whether the Moon should be used for interferometry. Attractive features include the dark and cold sky advantages that come from being away from the Earth, and the advantages of building large structures in fractional gravity.

Before establishing a lunar base to be used for scientific research, a number of significant issues need to be understood in order to ensure the long-term utility of the base for research purposes. For example, depending upon the specific research objectives, evaluations should be made of the effects on instrumentation of such features as the micrometeorite flux, the solar wind and solar flare particles, and the electric and magnetic environments on the surface at different lunar phases. In addition, attention will have to be given to the interactions between a human presence and specific scientific instrumentation (e.g., outgassing, vibration, dust, and electromagnetic interferences).

Additional research opportunities on and from both the Moon and Mars are sketched in the 90-Day Study. There will undoubtedly be opportunities for the HEI and the space sciences to advance together. Each scientific opportunity to be derived from human space exploration should be defined and evaluated, with consideration of its relative priority in the research strategy of the appropriate discipline, and an assessment of the most effective means to achieve it.

V
Nontechnical Considerations

In addition to questions of the technical and scientific merit of specific approaches, the committee examined challenges to the HEI concerning infrastructure and management, ways in which HEI might stimulate the educational process, questions of international cooperation and collaboration, and ways to look at the costs of such an undertaking.

INFRASTRUCTURE CONSIDERATIONS

The Responsible Federal Entity

Under the Space Act of 1958, NASA was assigned the lead federal responsibility for the conduct of the nation's civil space program for research and exploration. In support of its assigned role, it also undertakes selected developmental and operational functions with Administration direction and budgetary approval.

NASA is currently well below the peak manpower and budget that it had during the Apollo era, yet it carries a number of demanding tasks. These include the operation of the Space Transportation System (STS); the conduct of a major series of Earth-orbital and planetary scientific missions, including Galileo, the Hubble Space Telescope, and Mission to Planet Earth; the operation of a major space and terrestrial communication system; the aeronautics research and development program; the development of Space Station Freedom; and a large number of smaller programs.

The major responsibilities listed above leave little room to assume responsibility for a program that could, in some variants, equal in size and complexity nearly all of the existing programs in aggregate. This raises questions of whether NASA should be expanded (via some combination of increases in civil service manpower, contractor support, or support from other federally supported entities), whether the responsibilities for HEI should be spread across several agencies, or whether all or some of the responsibilities should be transferred to a new or existing organization.

In the committee's view, NASA has the organizational expertise and demonstrated capability to conduct human space exploration. The development of that expertise and the associated laboratories and other facilities has been hard won at great national expense. To attempt to replicate such expertise elsewhere would be costly and time consuming. Yet, the long-term human exploration initiative will require that NASA and the nation develop a whole new generation of management and technological leadership.

The NASA Infrastructure

This is not to say that NASA should automatically be authorized to return to Apollo-era civil service staff levels (or even greater) to lead the HEI, although an increase may be part of some options. To proceed effectively with the HEI, the Administration should develop a plan to incorporate other federal resources that can support the HEI, as well as devise innovative uses of the private sector, universities, and federally supported research centers. It is conceivable that a new federally supported center in the mold of Bellcom, the Jet Propulsion Laboratory, the Mitre Corporation, or the Aerospace Corporation may have a role to play in various aspects of the program, although this requires further examination.

Efficient conduct of the HEI will require a number of management enhancements, some of which must counter difficulties that are government-wide.

First, NASA's procurement process should be carefully scrutinized to identify means of expediting it so it is less burdensome to both NASA and those bidding for NASA tasks. Some procurement processes, which are not unique to NASA, absorb time and increase costs. Administrative procedures must be subjected to the same cost-benefit analysis as technical approaches. Solutions to this difficulty are not within NASA's authority, although NASA can lead an analysis for joint NASA-Administration-Congressional action. NASA now has an opportunity to study and possibly implement techniques to simplify and improve procedures, and these approaches should be included in the HEI or any *de novo* program.

Second, it is too costly for the nation to rethink its objectives in space on an annual basis. Long-term objectives must be set and technical program managers given the consistent support required for the efficient pursuit of the challenging engineering and scientific objectives to meet the President's goals. Recent experience on programs such as Space Station Freedom has demonstrated the difficulties that result when a program's entire management team is consumed by phasing, rephasing, planning, replanning, rescoping, and descoping a program in ceaseless variation.

Third, proceeding with the HEI will require that the Administration and Congress give serious attention to restoring or at least retaining the basic attractiveness of NASA employment, including competitive salaries. While NASA has exciting programs that interest the nation's engineering and science communities and many young people, NASA—like other federal agencies—is losing its appeal as an employer. In addition, the skills of NASA personnel, who offer an important long-term continuity in the execution of programs, need continual enhancement.

Fourth, positive steps are needed to encourage young people to enter science and engineering careers, some of whom will enter NASA, space-related industry, or university programs. A program of the size and scope of the extended human exploration of the Moon and Mars will severely tax a US educational system that is already strained and that is producing a declining number of trained engineers and scientists. Early in the history of the US space effort, a direct stimulus expanded the participation by universities in space activities and increased the number of graduate students studying and researching space-related subjects. It again appears essential to revitalize such activities if the human resources are to be available that the exploration mission will require. Such a revitalization could have the additional benefit of attracting more young people into scientific and engineering careers.

International Considerations

The committee considered the goals and proposed implementation of the HEI from the viewpoint of US interests and national capabilities only, using the same assumptions as the NASA 90-Day Study in this regard. Thus, the findings and conclusions here are consistent with an all-US exploration program. However, it is apparent that several important benefits could accrue from international cooperation and collaboration on these programs.

The current technical and political climate is different from that which existed earlier in the space age. The European Space Agency (ESA) has developed considerable applicable expertise for human space flight through Spacelab and its development of Columbus and Hermes. Japan has similarly developed expertise in pressurized modules. Both ESA and Japan have independent launch capabilities and growing expertise and interest in space exploration. Canada's contribution in remote manipulators and robotics could prove very valuable in remote lunar and Mars exploration. Other nations less active in previous joint space ventures may also wish to participate in this long-term venture. Most importantly, the USSR has substantial relevant capability, demonstrated continued interest in Mars, and an apparent strong desire for cooperation with the US in Mars exploration. The USSR has substantial experience in long-duration (one year) human exposure to weightlessness, and the capability, with its space station *Mir*, to undertake multiyear studies and evaluations of countermeasures. The *Energia* has a considerable heavy lift capability, launched from its current facility. This capability would be reduced were Earth orbit rendezvous with Space Station Freedom desired because of the power and maneuverability required to dramatically change the spacecraft orbit.

Several potential advantages of international participation in HEI are evident. These include cost sharing, additional technical expertise, and peaceful cooperation in a multidecade program of interest to all mankind. Some potential disadvantages include possible dependence on foreign countries for critical activities, concern over transfer of US technology, and more complex management interfaces.

Considerations of the advantages and disadvantages should recognize that international collaboration requires long-term policy stability, and that the US record is not exemplary in this regard. If collaboration is contemplated, care must be taken to ensure that the enabling agreements are supported at the highest possible levels in the participating governments, with as much breadth as is feasible, and that detailed technical agreements are not made final before all parties understand and agree on requirements for the HEI or missions associated with it.

As noted earlier, the climate for international cooperation is changing and is likely to continue to change. A detailed assessment is needed of the opportunities for international cooperation that may be available and the means to overcome technical and institutional barriers. It would be prudent to remain alert to future opportunities that may arise.

Cost for the Human Exploration Initiative

By any measure, HEI will represent a major commitment of the nation's resources; it will be a multiyear program; it will involve deliberate risk, often difficult to identify and quantify; and it will use major portions of the careers of many dedicated people. For HEI to be undertaken successfully there is a clear need for a unique long-term commitment by successive Administrations and the Congress. In the committee's view, estimates of the costs likely to be incurred in carrying out the HEI are uncertain—and are likely to remain so for some time. The initiative is an ambitious undertaking that requires development and implementation of new technology. If the costs or schedule of an ambitious, daring technical advance can be estimated accurately, it is probably using obsolete technology and is neither ambitious nor daring. Accurate cost estimates are only practical in circumstances where experience with the technology exists. Currently, the technologies and even the HEI mission architectures are unknown. While the nation has experience with estimating costs of some aspects of HEI, derived from experience with the costs of past space systems, at this time mission cost estimates should only be taken as suggesting the rough order of magnitude of the eventual costs.

Analyses of past major programs have shown that there is an optimum rate of activity that results in minimum total cost. If the pace is faster, it costs more. If the program is stretched out, the total cost can also be greater. In most past experiences, space projects based on the logic of development and mission requirements usually have required high peaks in the funding profile and have resulted in demands for annual funding greater than was considered acceptable. Therefore, most programs have been stretched out and the total cost has not been optimized.

At this stage it may be useful to think about costs in terms of the level of effort that is both reasonable for making progress toward the President's goal and sustainable as a commitment of national resources over the long run. In the peak spending year of the Apollo program, which was in the nature of a race to the Moon, the NASA budget amounted to about 0.8 percent of the gross national product (GNP), or 3.85 percent of the total federal budget. The total expenditure for Apollo (which averaged about 0.2 percent of the GNP) was approximately $24.5 billion ($118.1 billion in 1991 dollars). Apollo was a ground-breaking program that incurred substantial cost to build facilities and institutions; government and industry put forth a unique effort to fulfill the vision of President Kennedy. The HEI will presumably build on this capacity and will almost certainly take longer. President's Bush's vision includes a permanent presence in space, requiring a continuing commitment of resources.

The committee believes it should be possible to return people to the Moon and establish a human presence on Mars, at a measured pace, at a relative rate of annual expenditure that is less than that of the peak Apollo commitment. NASA's current budget is between 0.2 and 0.3 percent of the GNP. The committee believes an additional national commitment of resources of a few tenths of one percent of the GNP should be sufficient to achieve and sustain the goal of the HEI, the permanent presence of humans in space. A commitment of this sort, which extends far into the future, could enable the selection of an appropriately phased mission architecture as well as research and development strategies and would enable managers to establish practical schedules. Continuing analysis of the relationship between rates of expenditure, technology development, and mission profile is obviously warranted.

HEI will involve a continuing commitment and, for such an approach to succeed and to maintain support from the American people, it should set milestones and demonstrate visible accomplishments, for example every two to three years.

A White Paper published by the National Research Council in early 1989 recommends that NASA maintain a balanced, stable base program to ensure US competence in fundamental space activities such as astronomy, planetary exploration, and Earth remote sensing. The committee believes that this base program should be assured as the nation undertakes additional large, special initiatives such as the human exploration of the Moon and Mars. The committee believes that it is important for the funding support for HEI and other major initiatives to continue to be distinct from that for the remainder of the NASA budget, to avoid eroding the base of other essential space and aeronautical capabilities.

VI
Summary Responses to Questions Posed by the Vice President

In his charge to the committee, the Vice President posed a series of specific questions. The committee's responses, taken from the body of the report, follow:

SCOPE OF THE REPORT OF THE NASA 90-DAY STUDY

1. Does the report address the widest possible range of technically credible approaches to meeting the President's exploration goals? If not, what additional areas warrant exploration?

The NASA report addresses a reasonable set of technological and strategic approaches, but not all of the technically credible approaches have been analyzed. Other approaches have been discussed in the past, and many of those have been examined by NASA. The National Commission on Space, for example, included in its recommendations cycling spaceships between Mars and Earth orbits using electric propulsion.

Regarding additional areas that warrant consideration, the committee believes it prudent to await better understanding of significant life sciences issues before deciding the detailed architecture for sending humans to Mars. The committee further believes that precursor missions, such as the Mars Observer, are essential to understanding the Martian environment and to determining appropriate landing sites, for example for exploratory landers that might be sent from a Mars orbiter.

2. [Over the next 30 years] what are the likely areas for technical breakthroughs relevant to space exploration? Has the report fully taken these into account?

Likely areas for technical advances include nuclear power, propulsion, and conversion technologies for space applications; controlled environmental life support systems; sophisticated human/machine systems; physiological and psychological countermeasures to the space environment; effective artificial gravity; and the intertwined technologies in computer science and artificial intelligence that provide for better information management. Technologies to lower the cost of access to space probably will become available, including advanced materials and a new generation of cryogenic engines. Some of the breakthroughs and evolutionary development will come principally from human exploration research and development; others will evolve whether or not humans explore space, but can benefit from the exploration initiative.

The NASA report is prudently based largely on incremental advances in technology and does not depend on breakthroughs. Aerobraking technology is scheduled for demonstration in the near future. Nuclear propulsion, although not critical to the reference approaches, would represent a breakthrough and will require demonstration prior to commitment to its use.

3. Is the range of science goals and objectives commensurate with the proposed technical capability? Does the report distinguish between critical or enabling science and complementary science?

Clearly, technical capabilities are of paramount importance to the HEI. Nevertheless, worthwhile research can be done in conjunction with the HEI if research strategies are developed by weighing (1) the scientific priority of a given research activity, and (2) whether that research might best be accomplished by another means.

Although not well distinguished from complementary science in the NASA report, the enabling research in life sciences is crucial to productive and safe human occupancy of space. Other areas of enabling science include research on the nature of the Martian atmosphere and research and technology development for the use of in-situ resources.

4. Are there implications (infrastructure-institutional/other national interest) that have not been considered?

The NASA study recognizes the need for personnel, facilities, and equipment to fulfill the HEI. As noted in the report, NASA's current facilities and civil service personnel complement may need augmentation to address the HEI. The program, led by NASA, should be designed to draw on the resources of other federal agencies. The HEI needs to be conducted with greater efficiency than are most federal programs. As the NASA report notes, the HEI ". . . presents a unique opportunity to demonstrate the viability of streamlined administrative and management processes." Procurement and budgeting obstacles are also recognized in the report.

NASA believes that international partners should be included in the early definition of HEI. While it is important to work together with other nations, the committee believes it is necessary to understand the HEI mission designs and architectures before making commitments. The report defines varying approaches to international cooperation, including "separate, but coordinated," "augmentation through cooperation," "interdependence with clear interfaces," and "joint development and operation," but NASA will need policy guidance about the right approach to employ as the HEI progresses.

CONTENT OF THE REPORT OF THE 90-DAY STUDY

1. What are the report's technical assumptions? Are they reasonable?

The report assumes continuing dependence upon the space shuttle and shuttle-derived vehicles. Some of the reference approaches assume acceleration of the availability of Space Station Freedom (SSF) and all assume that the station will become operational by the late 1990s. Operation of the station by the late 1990s appears to be a reasonable assumption. Present plans for the station, however, are not adequate to satisfy HEI life sciences needs. At this time, it is also uncertain whether the station will be the most appropriate staging base for the Moon and Mars.

The report does not assume that the Advanced Launch System will materialize, but observes that such vehicles could be used to great advantage were they available. It does not assume nuclear rockets or power, but indicates that they could be useful were they available.

2. Are there innovative uses of existing technology that the report has overlooked?

There undoubtedly will always be new ways to do things based on existing technology. That said, however, none were obvious in reviewing the NASA report and alternative scenarios. In considering this question, the committee did not regard paper studies to be existing technology, due to the uncertainties involved in experimentally proving the concepts. Inflatable space modules, on the other hand, have had several NASA prototypes; but the applications for which they can be used are uncertain. SSF modules do not yet exist, but the nation has built a space station before and knows a lot about how to do it. Use of SSF modules for bases and orbiters is a concept based on use of existing technology.

3. Are the cost estimates and schedules reasonable?

NASA has conducted exercises to estimate the order of magnitude of costs of the HEI using several cost models derived from experiences with past space systems. Accurate cost estimates, however, are only possible in circumstances where experience with the technologies exists and where objectives are clear. As a general rule, the greater the technical risk inherent in a mission approach, the larger the uncertainty.

The HEI schedule will take into consideration other national resource commitments, which should be set by the social and political process, with scientific and technical input. The schedules presented in the NASA document are therefore not highly relevant, but do serve as a backdrop against which to assess various cost scenarios and mission options.

It will not be possible to meet cost or schedule estimates without a clear, long-term commitment from the executive and legislative branches of government. In addition, a program subjected to repeated phasing and rephasing cannot meet schedule and cost targets.

- Are there alternative ways the schedule might be moved forward to provide visible, near-term accomplishments?

NASA's Reference Approach B represents one option that advances Mars exploration from 2018 to 2011, but it depends upon accelerating completion of Space Station Freedom. For technical and cost reasons, such acceleration seems unlikely.

Concepts such as the Great Exploration, using as yet unproven inflatable technologies and expedited procurement procedures, and concepts based on using space station modules for orbiters and bases could potentially enable a return to the Moon and human exploration of Mars earlier than the NASA reference missions. However, an adequate infrastructure for potential future needs would need to be built separately.

Another alternative is a scenario where initial missions to Mars would have limited capabilities. Beyond questions of technical feasibility, the question of how elaborate the initial human missions need to be should be examined. This could involve trade-offs between up-front investments for technology development (which can reduce long-term operating costs for many future missions) and low up-front investment focused on near-term objectives, an approach that will save money in the present but that may eventually lead to more expensive operating costs.

The committee believes that almost any approach to HEI can have visible, near-term milestones. Humans living and working on the Moon, construction of habitats, and scientific and mining facilities can all provide evidence of accomplishments in space.

- Similarly, are there alternate routes which could dramatically increase performance, lower costs, move the schedule forward, or reduce risks? If so, what levels of programmatic and technical risk do they have?

The alternatives that the committee examined to move forward the schedule for lunar and Mars bases entailed higher levels of programmatic, technical, and human risk than the NASA reference approaches, as well as lesser capabilities.

The levels of uncertainty in estimating costs for these alternatives are so high that it is not possible to determine which among the approaches reviewed offers the potential for lower costs. Once again, the most dramatic alternate route to increase performance would be the development of safe nuclear propulsion for interplanetary travel.

4. Are the overall approaches/architectures described in the report reasonable? For example, are the key elements of NASA's plan consistent, i.e., availability of the space station, heavy lift vehicles, etc.?

Yes, the committee believes the overall approaches described in the report are reasonable. The treatment of nuclear power and propulsion, however, appears to be somewhat ambiguous. Nuclear power on the Moon is seen as essential in the 90-Day Study, but scenarios are also provided that rely on solar dynamic power. Nuclear propulsion is listed as a critical technology for development, yet none of the reference approaches call for it. Given the developmental and societal uncertainties concerning nuclear power, however, the treatment of this matter is not unreasonable.

In general, the key elements of the NASA document are consistent. For example, a given scenario does not rely on the station or technology development without considering the time needed for it to be established or developed. A space station in LEO is considered essential for all of the scenarios; however, the requirements of the HEI may not be fully met by Space Station Freedom.

Last, the committee believes that, whatever the selected architecture for HEI, there is a need for a new emphasis on advanced technology development and that it is highly desirable to continue to cast a wide net for innovative concepts.

Biographical Sketches of Committee Members

H. GUYFORD STEVER has had a career as a scientist, engineer, educator, and administrator. He was Science Advisor to Presidents Nixon and Ford and concurrently was Director of the National Science Foundation (1972-1976). Earlier, he was President of Carnegie-Mellon University and Chief Scientist of the Air Force. Dr. Stever was Professor of Aeronautics and Astronautics at the Massachusetts Institute of Technology, as well as head of the Departments of Mechanical Engineering and Naval Architecture and Marine Engineering. More recently, he was President of the Universities Research Association and Foreign Secretary of the National Academy of Engineering. He currently serves on the Carnegie Commission on Science, Technology, and Government. He is a member of the National Academies of Sciences and Engineering. After the Challenger accident, he headed the National Research Council's Solid Rocket Booster Redesign Panel and was awarded the NASA Distinguished Public Service Medal. In 1989 he chaired the National Academy of Sciences/National Academy of Engineering study that led to the White Paper, "Toward a New Era in Space."

ROBERT H. CANNON, JR., is Charles Lee Powell Professor and Chairman of the Department of Aeronautics and Astronautics at Stanford University. His research interests include precision control of very flexible manipulators for robots and spacecraft and the space gyro experiment to test the general theory of relativity. Previously, he was Professor of Engineering and Chairman of the Division of Engineering and Applied Science at the California Institute of Technology. Between 1970 and 1974 he was US Assistant Secretary of Transportation. Prior to that he had been Chief Scientist of the Air Force, a professor at the Massachusetts Institute of Technology, and a researcher in flight control and inertial navigation systems in the aviation industry. He is a member of the National Academy of Engineering, the National Research Council's Aeronautics and Space Engineering Board, and Chairman of NASA's Flight Telerobotics Servicer Advisory Committee. He has served as Chairman of the National Research Council Assembly of Engineering and as Chairman of the President's Commission on the National Medal of Science. Dr. Cannon holds several patents and has published extensively on such subjects as the environmental impact of stratospheric flight and automatic controls for aerospace vehicles.

JOSEPH G. GAVIN is a Senior Management Consultant for Grumman Corporation. He was elected President of Grumman in 1976 and retained this position until February of 1985, when he was elected Chairman of the Executive Committee. Mr. Gavin retired from Grumman in September of 1985. He was named the Aerospace Educational Council Man of the Year in 1968. In 1971, NASA awarded him its Distinguished Public Service Medal for his contributions "as the leader and representative of the Lunar Module team at Grumman." He was chief of the Grumman missile and space engineering program and director of the Lunar Module Program throughout the Apollo years. Mr. Gavin is a Fellow of the American Institute of Aeronautics and Astronautics and the American Astronautical Society and a member of the National Academy of Engineering and the Aerospace Industries Association. He recently served as a panel member on the Department of Energy Advisory Board's International Thermonuclear Experimental Reactor Working Party, as a board member of the American Association for the Advancement of Science, and as a member of the Executive Committee of the Massachusetts Institute of Technology.

JACK L. KERREBROCK is a Fairchild Distinguished Scholar at the California Institute of Technology for 1990 and Richard Cockburn Maclaurin Professor of Aeronautics and Astronautics at the Massachusetts Institute of Technology since 1975. Before that he headed the MIT Department of Aeronautics and Astronautics and was Associate Dean of Engineering at MIT. Dr. Kerrebrock was Associate Administrator for Aeronautics and Space Technology of NASA from 1981 to 1983. He has taught and conducted research in energy conversion and propulsion since 1956, when he received his PhD degree from the California Institute of Technology. His early work was on nuclear rockets, space propulsion and power, and magnetohydrodynamic generators. More recently, he has addressed the fluid mechanics of turbomachinery for aircraft engines and gas turbines. He was Director of the MIT Gas Turbine Laboratory from 1968 to 1978. Dr. Kerrebrock is a past and present member of several governmental advisory groups, including the National Commission on Space. He was decorated by the Air Force for Exceptional Civilian Service in 1981 and received the Distinguished Service Medal from NASA in 1983. Dr. Kerrebrock is a member of the National Academy of Engineering and chaired the 1989 National Research Council study on Hypersonic Technology for Military Application.

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JOHN H. McELROY is currently Dean of Engineering at the University of Texas at Arlington. He was formerly Vice President for Technology of Hughes Communications, Inc., a subsidiary of the Hughes Aircraft Company. Dr. McElroy joined Hughes in 1985 as Director of Special Projects in the Space and Communications Group, after serving as Assistant Administrator of the National Oceanic and Atmospheric Administration, where he directed the nation's program in civil operational Earth observations from space. From 1966 to 1982, he served with NASA, where his last position was Deputy Director of Goddard Space Flight Center. He previously performed laser research at the Quantum Electronics Research Laboratory at the University of Texas at Austin and taught electronics in the US Army's air defense guided missile program. Dr. McElroy is a Fellow of the Institute of Electrical and Electronics Engineers, the American Institute of Aeronautics and Astronautics, and the Washington Academy of Sciences. He serves on many advisory committees and is Chairman of the National Research Council/Aeronautics and Space Engineering Board Committee on Advanced Space Technology.

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WILLIAM J. MERRELL, JR., is the President of Texas A&M University, Galveston, and a Rear Admiral in the U.S. Maritime Service. He holds academic appointments as Professor of Oceanography and as Professor of Marine Services at Texas A&M University. Dr. Merrell is a member of the National Research Council's Space Studies Board and has been a proponent of scientific programs designed to examine the Earth's climate changes. He is also Vice Chair of the Committee on Science and Technology of the American Association of State Colleges and Universities. Before taking up his present position at Texas A&M, he was an Assistant Director of the National Science Foundation (NSF), where he was in charge of the Geosciences Directorate and received the NSF's Distinguished Service Award in 1987. Dr. Merrell received his PhD in oceanography from Texas A&M University.

ROBERT H. MOSER is a physician and educator who has been Vice President for Medical Affairs at The NutraSweet Company since 1986. He served as flight controller of Project Mercury, consulting member of the medical evaluation team for Project Gemini, and consultant to Project Apollo. From 1984 to 1987 he was Chairman of the NASA Life Sciences Advisory Committee. Dr. Moser received his MD from Georgetown University and entered the Army, where he held many positions, including that of battalion surgeon in Korea; Chief of Medical Services for the US Army Hospital, Salzburg, Austria; Assistant Chief of Medicine, US Army Triper General Hospital; Chief of Medicine, William Beaumont General Hospital; Chief of Medicine, Brooke Army Hospital; and Chief of Medicine, Walter Reed General Hospital. Dr. Moser retired in 1969 to become Chief of Staff of the Maui (Hawaii) Memorial Hospital and Clinical Professor of Medicine at Hawaii University from 1969 to 1977, at present is Adjunct Professor of Medicine of Northwestern University Medical School and Uniformed Services University of the Health Sciences, and Executive Vice President of the American College of Physicians from 1977 to 1986. He is the author of *Diseases of Medical Progress* and has contributed over 150 articles to medical science journals and medical books. He is a member of the National Research Council's Space Studies Board.

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LAURENCE R. YOUNG is a Professor of Aeronautics and Astronautics and Director of the Man-Vehicle Laboratory at the Massachusetts Institute of Technology. His area of expertise is biomedical engineering, with a special emphasis on space medicine and biology. Dr. Young was a principal investigator on vestibular experiments aboard Spacelabs -1, -2, D-1, and SLS-1, and is the inventor of an eye movement monitor used in vestibular and other physiological research. He has been on the faculty of MIT since 1962, having received his ScD there in the same year. Dr. Young is a member of the National Academy of Engineering, the Aerospace Medicine Association, and the American Institute of Aeronautics and Astronautics. He is a charter member and Past President of the Biomedical Engineering Society and a Fellow of the Institute of Electrical and Electronics Engineers. He has served on numerous national boards and committees, including the Air Force Scientific Advisory Board and the National Research Council Committees on Human Factors, Space Station Engineering Design Issues, and Advanced Space Technology to Meet Future Needs.

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Acronyms, Abbreviations, and Technical Terms

ALS	Advanced Launch System
ESA	European Space Agency
EVA	extra vehicular activity
g;l-g	gravity; equivalent to one times the acceleration of gravity
GNP	Gross National Product
HEI	Human Exploration Initiative
LEO	low Earth orbit
NASA	National Aeronautics and Space Administration
NASP	National Aerospace Plane
NRC	National Research Council
NSC	National Space Council
SEALAR	Sea Launch and Recovery vehicle
SSF	Space Station Freedom
SSME	Space Shuttle Main Engine
STS	Space Transportation System
aerobraking	Use of a planet's upper atmosphere as a brake to slow the entry of a spaceship, rather than braking by propulsive methods.
cross range capability	The maneuvering capability of a spacecraft in orbit as well as after reentering the Earth's atmosphere. The shuttle, for example, has reasonably good cross range capability, due largely

	to having wings, while the reentry capsules employed in the early US space program had little maneuverability and were dependent on the trajectory of their orbit.
cryogenic fuels	Fuels stored at very low temperatures to maximize the energy density per unit volume of storage capacity. The fuels typically are gases at room temperature, but are stored at temperatures at which they are liquids.
specific impulse	The measure of an engine's efficiency; the ratio of pounds of thrust produced per pounds of fuel flowing through the engine each second.

Appendixes

Appendix A

THE VICE PRESIDENT
WASHINGTON

December 4, 1989

Dear Dr. Press:

As you know, President Bush charted a bold new course for the U.S. space program when he proposed on July 20, 1989, a long-range, continuing commitment to manned exploration -- first, to complete Space Station Freedom, to return permanently to the Moon, and then explore the planet Mars. At that time he also asked me, as Chairman, to lead the National Space Council in determining the necessary resources and timetables, and the feasibility of international cooperation for meeting these goals. It will take time to examine these complex issues completely, assess alternative approaches, and build the consensus necessary to proceed. The National Research Council represents a vital national resource in this process and I would like to solicit your help.

To respond to the President's tasking, the Council now has several analyses underway. The key ones are, first, an assessment of the approaches that might be taken to the program design, and how the variables of technology development, schedule, and cost can shape that design. The second is an assessment of the approaches to international cooperation -- what types of participation might be invited by the U.S. government, and what the implications of each type might be. Lastly, the Council will assess approaches to management -- what types of structures and functions will be required to manage this complex, long-term program.

A NASA team, led by Johnson Space Center Director Aaron Cohen, has submitted a report to NASA Administrator Richard Truly which was commissioned by Admiral Truly after the President's July 20 speech. Its purpose is to provide a database for the Space Council to refer to as it considers strategic planning issues.

Among other things, the NASA report describes five notional mission approaches to the Moon/Mars Initiative. The five approaches are not exhaustive, but rather a starting point for future studies and analyses. They do not represent decision options for the President, but rather reference cases. The Space Council intends to examine the approaches described in the report, as well as a range of robust technical alternatives and approaches to mission planning.

At a recent Space Council meeting, it was agreed that a review of the NASA report by the National Research Council would be most valuable.

It would be most helpful if, in its review, the National Research Council addressed the following questions. In considering these questions, we encourage your consideration of alternative approaches and other options, or range of options, for the human exploration concept. NASA will continue to seek alternative approaches to this initiative; we would appreciate National Research Council assistance in examining them as they become available.

Scope of the Report,

1. Does the report address the widest possible range of technically credible approaches to meeting the President's exploration goals? If not, what additional areas warrant exploration?
2. Over the course of the next thirty years, much technical progress will be made. What are the likely areas for technical breakthroughs relevant to space exploration? Has the report fully taken these into account?
3. Is the range of science goals and objectives commensurate with the proposed technical capability? Does the report distinguish between critical or enabling science and complementary science?
4. Are there implications (infrastructure-institutional/other national interest) that have not been considered?

Content,

1. What are the report's technical assumptions? Are they reasonable?
2. Are there innovative uses of existing technology which the report has overlooked?
3. Are the cost estimates and schedule assumptions reasonable? Are there alternate ways which the schedule might be moved forward to provide visible, near-term accomplishments? Similarly, are there alternate routes which could dramatically increase performance, lower costs, move the overall schedule forward, or reduce risk? If so, what levels of programmatic and technical risk do they have?
4. Are the overall approaches/architectures described in the report reasonable? For example, are the key elements of NASA's plan consistent? i.e. availability of the Space Station, heavy lift vehicles, etc.?

To meet our schedule of deliberations on the initiative, it would be useful to have your responses by February 28, 1990.

I expect that this review will be only the first of many interactions with the National Research Council on the various aspects of the initiative. I understand that both the Space Studies Board and the Aeronautics and Space Engineering Board have begun to examine the general question of manned space exploration. In addition, the Committee on Space Policy looked into management issues in their 1988 report. Further reviews in this area may be warranted over the next year. Clearly these will be continuing studies. Any comments you might have on the NASA concept will of course be understood to not represent a position of the National Research Council or its Boards on the value of or Administration approach to space exploration.

Sincerely,

Dan Quayle

Dr. Frank Press, Chairman
National Research Council
2101 Constitution Avenue, N.W.
Washington, DC 20418

NATIONAL RESEARCH COUNCIL

2101 CONSTITUTION AVENUE WASHINGTON, D. C. 20418

OFFICE OF THE CHAIRMAN

December 26, 1989

The Honorable Dan Quayle
Vice President of the United States
Office of the Vice President of the United States
Old Executive Office Building
Washington, DC 20501

Dear Mr. Vice President:

The National Research Council is pleased to accept your request that it undertake a review of the NASA "Report of the 90-Day Study on Human Exploration of the Moon and Mars." We are working hard to fill your need to have our report by February 28th; and have already made considerable progress in constituting the committee.

The Governing Board of the National Research Council, as well as those to be directly involved in the task, understand its importance and complexity, and the inherent limitations imposed by a very demanding schedule. In that light, while we look forward to performing this task, we concur wholeheartedly with your letter, which notes that this study is necessarily a circumscribed examination of the general question of human space exploration, that this study is only the first of what must be a larger examination of the question, and that, therefore, this initial work should not be interpreted as an endorsement by the NRC of any particular approaches to human space exploration.

Our review will comment on the technological feasibility of the options provided in the report, and will to the extent possible consider alternative approaches. The latter will again be limited by the time and information available to us, and therefore our consideration of alternative approaches cannot be inclusive.

Of course, in the final analysis, the nation's program in human exploration, including the applicable technology, will be shaped by concern about the health of the crew on long space missions and by its purposes, of which a fundamental one is scientific exploration. This latter purpose accords with the goal of the U.S. civil space program "to expand knowledge of the Earth, its environment, the solar system, and the universe." The logistics of the mission cannot be uncoupled from those scientific purposes. Therefore, we are in complete agreement with your injunction that examination of a program of human space exploration must consider whether the range of scientific goals

The Honorable Dan Quayle
Vice President of the United States
December 26, 1989
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and objectives is commensurate with the proposed technical capability. Indeed, the institution already has underway explicit examinations of the scientific issues associated with human space exploration. We will be pleased to keep you apprised of this work as it proceeds.

Again, we are pleased to accept this task and are most appreciative of your confidence in the work of this institution.

Yours sincerely,

Frank Press
Chairman

bc: Robert M. White
Joann Clayton
David Bodde
Myron Uman
Richard Hart
Dean Kastel
Louis Lanzerotti

Appendix B
List of Participants

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION REPRESENTATIVES

Admiral Richard H. Truly (Ret.), Administrator
Mr. Arnold D. Aldrich, Associate Administrator, Office of Aeronautics and Space Technology
Mr. Joseph Alexander, Assistant Associate Administrator, Office of Space Science and Applications
Mr. Darrell R. Branscome, Director, Advanced Systems Development, Office of Space Flight
Mr. Aaron W. Cohen, Director, Johnson Space Center
Ms. Lana M. Couch, Director for Space (Act.), Office of Aeronautics and Space Technology
Mr. Mark W. Craig, Director, Lunar and Mars Exploration Office, Johnson Space Center
Dr. Leonard A. Fisk, Associate Administrator, Office of Space Science and Applications
Dr. Leonard A. Harris, Chief Engineer, Office of Aeronautics and Space Technology
Mr. Richard H. Kohrs, Director, Space Station Freedom Program, Office of Space Station
Dr. William B. Lenoir, Associate Administrator, Office of Space Flight

Mr. John C. Mankins, Pathfinder Program Manager (Act.), Office of Aeronautics and Space Technology
Dr. Franklin D. Martin, Assistant Administrator for Exploration
Dr. Albert R. Miller, Assistant Associate Administrator, Office of Space Operations
Dr. Arnauld E. Nicogossian, M.D., Director, Life Sciences Division, Office of Space Science and Applications
Dr. Douglas A. O'Handley, Deputy Assistant Administrator, Office of Exploration
Mr. Lewis L. Peach, Jr., Deputy Director, Strategic Plans and Programs Division, Office of Space Station
Mr. Gregory M. Reck, Director, Mars Initiative Technology Team, Office of Aeronautics and Space Technology
Dr. John R. Rummell, Program Manager, Exobiology, Office of Space Science and Applications
Dr. Frank Sulzman, Chief, Space Medicine and Biology Branch, Life Sciences Division, Office of Space Science and Applications

OTHER BRIEFERS AND GUESTS

Dr. Mark Albrecht, Director, National Space Council (NSC)
Mr. Ivan Bekey, NSC
Dr. Timothy Coffey, Director of Research, Naval Research Laboratory
Dr. Michael J. Fry, Oak Ridge National Laboratory
Dr. Michael D. Griffin, Strategic Defense Initiative Organization
Lt. Gen. Harry Griffith (Army Ret.), Senior Vice President and Head of Washington Office, Brown & Root Co.
Lt. Gen. Richard C. Henry, Brown & Root Co.
Dr. Harry Holloway, M.D., Uniformed Services University of the Health Sciences
Mr. Maxwell W. Hunter, Consultant
Dr. Rod Hyde, Lawrence Livermore Laboratories
Dr. Yuki Ishikawa, Lawrence Livermore Laboratories
Dr. Harold Klein, Santa Clara University
Dr. Stephen J. Lanes, Department of Energy
Lt. Col. Roger Lenard, Department of Defense
Dr. Thomas O. Paine, Thomas Paine Associates
Dr. Harrison Schmitt, Consultant
Dr. Earl Wahlquist, Department of Energy
Dr. Peter Wilhelm, Naval Research Laboratory
Dr. Lowell Wood, Lawrence Livermore Laboratory, University of California
Col. Simon P. Worden, NSC

Dr. Richard Young, Vice President, Rockefeller University (Ret.)

NATIONAL RESEARCH COUNCIL

Dr. Frank Press, Chairman, National Research Council (NRC)
Dr. Robert M. White, President, National Academy of Engineering (NAE)
Mr. Philip M. Smith, Executive Officer, NRC
Mr. Edward J. Barlow, NRC Report Review Monitor
Dr. Alexander Flax, NAE Home Secretary
Dr. Richard L. Garwin, Fellow, IBM Thomas J. Watson Research Center
Dr. Richard C. Hart, Acting Associate Staff Director, Space Studies Board (SSB)
Mr. Dean P. Kastel, Director, SSB
Dr. Robert H. Korkegi, Director, Aeronautics and Space Engineering Board
Mr. Norman Metzger, Deputy Executive Officer, NRC
Dr. Myron F. Uman, Assistant Executive Officer for Special Projects, NRC

Appendix C

EXCERPTS FROM REMARKS BY THE PRESIDENT AT THE 20TH ANNIVERSARY OF THE APOLLO MOON LANDING JULY 20, 1989

. . . And space is the inescapable challenge to all the advanced nations of the Earth. And there's little question that, in the 21st century, humans will again leave their home planet for voyages of discovery and exploration. What was once improbable is now inevitable.

The time has come to look beyond brief encounters. We must commit ourselves anew to a sustained program of manned exploration of the solar system—and yes—the permanent settlement of space. We must commit ourselves to a future where Americans and citizens of all nations will live and work in space. . . . And our goal is nothing less than to establish the United States as the preeminent spacefaring nation.

. . . Today we don't have a crisis. We have an opportunity.

To seize this opportunity, I'm not proposing a 10-year plan like Apollo. I'm proposing a long-range, continuing commitment.

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

And next—for the new 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.

. . . And today I'm asking my right hand man, our able Vice President, Dan Quayle, to lead the National Space Council in determining specifically what's needed for the next round of exploration—the necessary money, manpower, and material—the feasibility of international cooperation—and develop realistic timetables, milestones along the way. The Space Council will report back to me as soon as possible with concrete recommendations to chart a new and continuing course to the Moon and Mars and beyond.

EXCERPTS FROM THE NATIONAL SPACE POLICY (EMPHASES ADDED) NOVEMBER 2, 1989

. . . The overall goals of the United States space activities are: (1) to strengthen the security of the United States; (2) to obtain scientific, technological and economic benefits for the general population and to improve the quality of life on Earth through space-related activities; (3) to encourage continuing United States private-sector investment in space and related activities; (4) to promote international cooperative activities taking into account United States national security, foreign policy, scientific, and economic interests; (5) to cooperate with other nations in maintaining the freedom of space for all activities that enhance the security and welfare of mankind; and *as a long-range goal, (6) to expand human presence and activity beyond Earth orbit into the solar system*.

. . . The objectives of the United States civil space activities shall be (1) to expand knowledge of the Earth, its environment, the solar system, and the universe; (2) to create new opportunities for use of the space environment through the conduct of appropriate research and experimentation in advanced technology and systems; (3) to develop space technology for civil applications and, wherever appropriate, make such technology available to the commercial sector; (4) to preserve the United States preeminence in critical aspects of space science, applications, technology, and manned space flight; *(5) to establish a permanently manned presence in space*; and (6) to engage in international cooperative efforts that further United States overall space goals.

CIVIL SPACE SECTOR GUIDELINES—Space Exploration

Human Exploration. To implement the long-range goal of expanding human presence and activity beyond Earth orbit into the solar system, NASA will continue the systematic development of technologies necessary to enable and support a range of future manned missions. This technology program (Pathfinder) will be oriented toward a Presidential decision on a focused program of manned exploration of the solar system.

Unmanned Exploration. NASA will continue to pursue a program of unmanned exploration where such exploration can most efficiently and effectively satisfy national space objectives by, among other things: achieving scientific objectives where human presence is undesirable or unnecessary; exploring realms where the risks or costs of life support are unacceptable; and providing data vital to support future manned missions.

Permanent Manned Presence. NASA will develop the Space Station to achieve permanently manned operational capability by the mid-1990s. Space Station Freedom will: (1) Contribute to United States preeminence in critical aspects of manned spaceflight; (2) provide support and stability to scientific and technological investigations; (3) provide early benefits, particularly in the materials and life sciences; (4) promote private sector experimentation preparatory to independent commercial activity; (5) allow evolution in keeping with the needs of Station users and the long-term goals of the United States; (6) provide opportunities for commercial sector participation; and (7) contribute to the longer term goal of expanding human presence and activity beyond Earth orbit into the solar system.