International Cooperation for Mars Exploration and Sample Return

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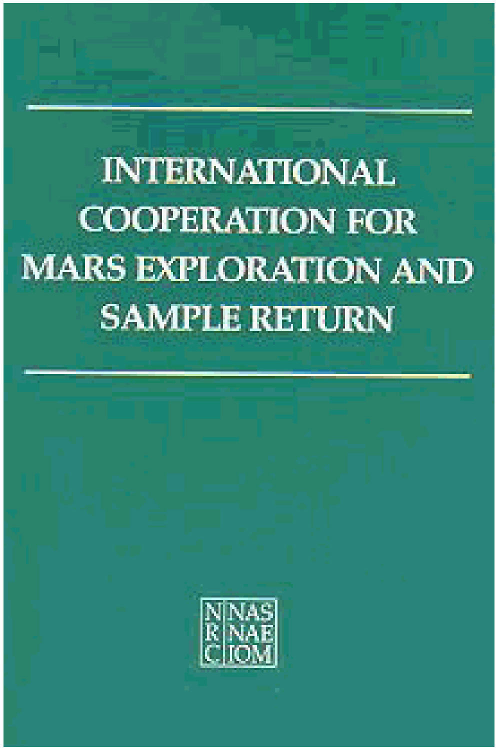

Committee on Cooperative Mars Exploration and Sample Return
Space Studies Board
Commission on Physical Sciences,
Mathematics, and Resources

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International Cooperation for Mars Exploration and Sample Return

Executive Summary

The goal of intensive Mars exploration by robotic systems coupled with the return to Earth of martian materials is one of historic proportions and is widely recognized as a premier objective of solar system investigation. The discoveries and understanding generated in such an endeavor will be of fundamental scientific importance in their own right and will be a focus of worldwide interest. The scientific results will be basic to further exploratory activity and technological developments.

The National Research Council's Space Studies Board has previously recommended that the next major phase of Mars exploration for the United States involve detailed in situ investigations of the surface of Mars and the return to Earth for laboratory analysis of selected martian surface samples. [1] In addition, Mars exploration is of wide scientific and technical interest to several other nations. More recently, the European space science community has expressed general interest in the concept of cooperative Mars exploration and sample return. The USSR has now announced plans for a program of Mars exploration incorporating international cooperation. If the opportunity becomes available to participate in Mars exploration, interest is likely to emerge on the part of a number of other countries, including Japan and Canada, among others.

The Space Studies Board's Committee on Cooperative Mars Exploration and Sample Return was asked by the National Aeronautics and Space Administration (NASA) to examine and report on *the question of how Mars sample return missions might best be structured for effective implementation by NASA* along with international partners.

The committee examined alternatives ranging from scientific missions in which the United States would take a substantial lead, with international participation playing only an ancillary role, to missions in which international cooperation would be a basic part of the approach, with the international partners taking on comparably large mission responsibilities. On the basis of scientific strategies developed earlier

by the Space Studies Board, the committee considered the scientific and technical basis of such collaboration and the most mutually beneficial arrangements for constructing successful cooperative missions.

GENERAL PREMISES

The committee's charge was to examine the opportunities and benefits of various approaches to international cooperation in Mars exploration as these derive from the scientific objectives. That examination requires certain assumptions about the quality and character of future U.S. and world space science. A large number of the developed nations have evinced interest in Mars exploration. However, as will be developed in this report, the committee noted that the United States and the USSR currently occupy special positions with respect to experience, capability, and commitment to intensive space exploration in general, and to Mars exploration in particular. For this reason, the committee concluded that the character of intensive Mars exploration will be determined by program commitments made in the United States and the USSR and that the participation of other nations will be shaped largely by opportunities deriving from those programs. Thus the level and the nature of U.S.-Soviet cooperation are critical elements that will determine the character of Mars exploration as well as its international aspects. Consequently, this report takes the potential and the problems of U.S.-Soviet cooperation as its primary, though not exclusive, focus.

The response of this committee to its charge rests on premises of overall policy upon which the recommendations depend. The committee has summarized and briefly discussed these premises as follows:

1. There is a need for the United States to reestablish its leadership in some aspects of space science, including planetary exploration. At present, the architectural goals of the U.S. space science program require both definition and a firm plan for implementation. The committee assumes, for the purpose of this report, that the United States will carry forward a vigorous national space science program of high quality. This program is assumed to include international participation and cooperation as enunciated in the National Aeronautics and Space Act of 1958 and in the 1988 "Presidential Directive on National Space poliey." [2,3]

2. Mars is an appropriate focus of a program that supports intensive scientific investigation of our solar system, with the goal of developing our understanding of the evolution of the terrestrial planets. The Space Studies Board has defined Mars as the key immediate objective of this effort because the evolutionary track that Mars has followed, while clearly divergent from the Earth's, has still produced some remarkable similarities in the two planets. Moreover, by virtue of its proximity and environment, Mars is unusually accessible to the intensive scientific investigations that are required to address these questions of terrestrial planet science.

3. The nation or group of nations that makes the necessary commitment to

intensive Mars exploration with sample return will create a focus of intense international attention and interest, both scientifically and in the public at large. The principal nations involved will thus play a leading role in space science activities and technological development for at least a decade.

SCIENTIFIC AND TECHNICAL PREMISES

In formulating recommendations, the committee took careful note of the breadth and intensity of the investigations that will be needed to accomplish the Mars scientific objectives. The motivation for intensive scientific exploration of Mars is to understand that planet at a level that will allow important questions to be answered about the planet's history and evolution and about the character and stability of its environment. In some respects, the character of the questions that we seek to answer in exploring Mars is similar to the character of questions that we address in studies of Earth. To achieve these scientific goals, it will be necessary to conduct a sequence of missions to Mars that involve both in situ investigations and sample return. The committee envisions that a first phase of such detailed Mars investigations should entail several missions, conducted over a number of years, to a set of selected, diverse sites. Such a program would provide a major increment of knowledge about the planet Mars and about the states and evolutions of terrestrial planets in general. It would also provide the basis of fact that is needed to inform future decisions about further levels of Mars investigation, including the potential for human exploration of that planet.

This breadth and character of Mars exploration, as they are dictated by the scientific objectives, provide the framework of anticipated exploratory and scientific endeavors on Mars that should be the focus of cooperative international activity.

Certain technical issues also enter into determining the most effective approach to international cooperation in the exploration of Mars. Cooperation between two or more independent technical organizations involves costs as well as benefits. The magnitude of the costs is especially dependent on the character of the technical and management interfaces involved. The costs of a major joint undertaking are also highly susceptible to variations on the existence of stable long-term working relationships, an established means of communication, and mutual understanding about the partner's institutions. The committee's recommendations attempt to balance the benefits and the costs of cooperation, within the specific framework of the required scientific and technical activities, and to provide a path along which relationships can be built that can lead to closer cooperation in the future. However, it is also recognized that decisions to undertake Cooperative programs may be based on other national policy considerations and social motivations. Such an approach could dictate more intimate cooperation from the beginning to achieve objectives connected with demonstrating the ability of the United States and the USSR to cooperate. Thus the need to establish cooperative relationships and understanding might be seen as a net benefit rather than a net cost. Such an expansion of the initial cooperation would not be inconsistent with the committee's recommendations, but rather would constitute an acceleration of the recommended, longer-term evolution of the cooperative relationship. This issue lies in the realm of U.S. national policies that are outside the purview of this report.

GENERAL BACKGROUND

The accomplishments of the 1976 U.S. Viking mission generated a major advance in the study of Mars. The further commitment of the United States to the 1992 Mars Observer mission represents a logical next step in a Mars exploration program. Beyond Mars Observer, the United States has announced no specific plans for defining and implementing a strategy for continuing intensive exploration of Mars. There exists a clear need for the United States to reestablish vigorous leadership in crucial aspects of space science, including planetary exploration. A commitment to leading participation in a multinational program of Mars investigation would meet this need and would be in full consonance with the 1988 "Presidential Directive." [3]

Intensive Mars exploration is an appropriate focus of international scientific cooperation. The breadth and significance of the scientific problems to be investigated on Mars—as well as the expected expansion of knowledge about terrestrial planets in general, including Earth—make Mars investigations of deep and persistent interest to a broad, international community of scientists. The scope of investigations and operations needed to explore Mars provides a rich opportunity for a variety of missions that can fruitfully involve all of the interested nations and space agencies. The number of missions required to survey and sample an appropriate diversity of sites on Mars means that substantial economies can be realized by combining the resources of several nations in a joint program of the highest quality and productivity. The intrinsic significance of Mars exploration and sample return has evoked a major announced activity within the Soviet Union to aggressively pursue the scientific exploration of Mars; the first mission in this long-term Soviet endeavor was the 1988 Phobos mission, which, however, did not achieve all of its scientific objectives.

Establishment of a multinational Mars exploration program will demand effective international cooperation and commitment to the longevity of that cooperation. There is a tradition of cooperation between the United States and European scientific and industrial communities. This relationship has been highly synergistic. Continuing such relationships in the context of international investigation of Mars, with full appreciation and respect for the scientific and technological maturity of European space science and for the potential importance of European contributions to such a program, would represent a natural and mutually beneficial evolution of past and present associations. It is important in this context to recognize that the European scientific community has become increasingly involved in Soviet space programs as U.S. launch opportunities and space science programs have diminished and as USSR programs have increasingly encouraged participation by Western nations. This trend is likely to continue; the European nations and scientific communities have important interests of their own and should be expected to pursue these interests by the most effective means available to them.

At least three space agencies—those of the United States, the USSR, and the European community—are capable of planning and executing ambitious planetary exploration programs. A larger number of nations and space agencies are eager to participate in the scientific and technical opportunities offered by these three agencies. High interest has been shown by several European nations, and by the European Space Agency, in participating in Mars exploration; there is the possibility, in the context of an exciting international opportunity for Mars exploration, that many other nations will wish to participate, including Japan and Canada, among others.

Although many nations have a broad interest in Mars exploration, the United States and the USSR will play unique roles in any comprehensive international Mars initiative because of their historic commitments to space exploration and because of their launch capabilities and their established scientific and technical infrastructures for planetary exploration. The United States and the USSR are the only nations currently in a position to take on the lead role in a major Mars program that includes surface exploration of the planet and sample return. Therefore, the committee has assumed that the gross structure of any intensive Mars exploration program will be determined by policy and programmatic decisions made in the United States and the USSR and that, for at least the next decade, the opportunities for other nations to participate in intensive Mars exploration will depend on the programs undertaken by the United States and the USSR. It is for that reason that the present report focuses primarily on the possibility of U.S.-USSR cooperation and on the question of how best to achieve the potential of such cooperation. This focus is not intended to underestimate the importance of participation by other nations and space agencies. The highly developed scientific and technical talents and capacities that exist in these nations would render their participation extremely valuable and important.

There is little precedent for long-term or close cooperation between the United States and the USSR in major space endeavors. However, one cooperative mission (Apollo-Soyuz) has been carried out, and mechanisms of scientific exchange have been increasing regularly to the point that longer-term plans and mission possibilities are now exchanged. The exchange of scientific and technical data during and, after missions has become increasingly common. In addition, there have been instances of limited cooperation and technical interchange in space projects. There is no compelling constraint, at the scientific level of consideration, on the expansion of existing relationships between the two nations, or on the creation and formalization of those new modes of interaction that would be needed to implement a cooperative program of Mars exploration. However, a prudent approach would be to begin cooperating in activities that are especially resilient to unforeseen technical and nontechnical problems, and to anticipate building closer kinds of future cooperation on the basis of accumulated success and experience. Considering the complexity of such an enterprise, a time scale of perhaps a decade may be required to achieve this goal.

The committee assessed a range of possible approaches to U.S.-USSR cooperation in the exploration of Mars. The approaches considered have been divided into three general categories:

- *Independently conducted programs.* In this approach, there would be essentially no significant level of cooperation. Each side would plan and conduct its own program. Opportunities that might fortuitously arise would be candidates for possible low-level cooperative activities. But the planning for such opportunities would not play a major role in the shaping of either nation's program. This approach would continue the status quo.
- *Split responsibilities and joint technical operations.* This is the most ambitious approach insofar as international cooperation is concerned. The two sides would divide specific technical responsibilities in the context of missions that would be conducted jointly. The dependence of each side on the other and the intimacy of the technical interfaces would be maximized in this approach. The success of each mission would hinge on the success of the interaction.
- A *highly coordinated exploration program.* In this approach, the two sides would define, plan, and carry out a joint program of Mars exploration and sample return. The program—extending over a period of years—would consist of a sequence of highly coordinated missions, carried out in pairs, one mission by each side. Each mission could largely succeed without depending on its counterpart„ but the success of the overall program would depend on the overall success of the cooperation and the contributions of the two sides.

The committee considers that the best approach to carrying out cooperative exploration of the planet Mars would strike a balance between very close cooperation that involved division of responsibility and joint technical operations, and independent, nearly noninteracting programs. *Insofar as the major participants would be the United States and the USSR, the committee recommends an approach in which the two nations initially would agree to carry out a highly coordinated program of intensive Mars exploration and sample return, consisting of independently conducted missions.* The two sides would work together at all levels, from the initial planning of scientific objectives, experimental approaches, principles of sample collection, and site selection. However, in the early stages, the two sides would conduct their own self-contained and independently designed missions, with specific interaction at Mars limited to the coordination of networked investigations, where that is beneficial, and to mutual support and backup of communications and data telemetry. The exchange of instruments and scientific investigators would be encouraged in cases where it would be beneficial. An important element in the planning of this program would be to provide opportunities for participation by other interested nations.

RECOMMENDATIONS

In analyzing the possibilities for international cooperation in Mars exploration and sample return, the committee identified both substantial benefits and potential costs. Mars presents a large and complex system and poses planetary-scale scientific questions, obtaining the answers to which will require an ambitious program of in situ investigations and sample return. The scale of needed Mars investigation is such as to make it desirable to combine the resources of the world's major spacefaring nations in this scientific, exploratory, and technical endeavor of historic proportions.

1. It is recognized that the United States must be selective in its objectives in space exploration. Because of the importance of a Mars program in terms of the quality and significance of the scientific objectives, the prestige and scientific importance associated with the return of the martian materials, and the substantial implications for new technologies such as robotics and artificial intelligence*, this committee concurs with previous recommendations of the Space Studies Board and recommends that the vigorous scientific exploration of Mars with the return of martian materials be a prominent part of the U.S. national space science program and part of a continuing balanced exploration of the solar system.*

2. 7b answer fundamental questions related to the origin and evolution of the terrestrial planets requires a coherent program of excursions to the surface of Mars. *The committee recommends robotic study of the martian surface and the return of martian materials from several diverse sites, ranging from equatorial to polar, in order to understand the rich diversity of martian processes These excursions will require extended and advanced robotic mobility, robotic manipulative capability, and on-board artificial intelligence in order to adequately study, sample, and return selected materials from the various sites and to conduct scientific measurements and experiments on the surface.*

3. *The committee recommends that intensive Mars exploration be undertaken initially in an international program coordinated with the Soviet Union.* Longer-term evolution of joint activities with the USSR, based on accumulated experience and success along with lines of communication and working relationships that would be created, may lead to a more intensively cooperative and mutually dependent program in the future.

4. The United States should develop the capability to undertake several of these excursions independent of the performance of the USSR. *Within the context of the recommended cooperative international program, the committee recommends that the actual design of spacecraft hardware and conduct of early missions be carried out independently and in parallel by the two nations. The committee further recommends that the United States and the USSR cooperate to identify the scientific objectives of their programs and to coordinate mission planning in detail to optimize the scientific return of the missions.* The commitment to cooperation in such a program should be announced jointly by the United States and the USSR to make it clear that the two parties are major collaborators. *The committee recommends that nonmission-critical hardware, such as individual scientific experiments, be considered for inclusion on the spacecraft of the other nation when there is a distinct scientific or performance advantage.* The evolution of these working relationships may grow to a point that more complex interdependent

missions can be considered.

5. The returned martian samples will be of utmost scientific importance and will have immense prestige associated with them. *The control, care, and distribution of these materials will be under the jurisdiction of the nation returning the samples, but the committee recommends that there be a commitment to a joint scientific research program with the USSR that will provide these materials to quakfied scientists throughout the world. The interchange of scientific information and close collaboration on all aspects of the science derived from these missions should be intrinsic and continuing components of the program, from its inception through the advanced stages of scientific analysis.*

6. *The committee recommends that the United States encourage close cooperation with its more traditional scientific collaborators following the mechanisms that are already established.* The U.S. program will make use of the knowledge of these collaborators in determining scientific mission objectives and in contributing to mission design. *The committee recommends that this cooperation also allow the traditional collaborators to provide mission-critical subsystems as well as scientific packages when there is a distinct benefit to the program.* Such a substantial commitment among nations may require an improved mechanism for ensuring the needed long-term commitments to approved missions or programs.

CONSEQUENCES

If the committee's recommendations are carried out, several prominent consequences will ensue.

- The United States will have reestablished a role of international leadership in space science in the context of a new and constructive cooperation with the world's major spacefaring nations.
- A very-high-priority scientific goal will have been accomplished through international effort, thus advancing the state of knowledge about Earth-like planets.

Altogether, the recommended approach

- would allow a rapid start on international cooperation for Mars exploration and sample return;
- would yield substantial economies in the context of a program that realized the recommended science objectives for Mars investigations;
- would aid in defining launch capabilities required for deep-space exploration;
- would allow a graceful path to increasingly close levels of cooperation with the Soviet Union as experience is gained and as the international situation might permit and make desirable; and
- could be implemented now without undue concern for technology transfer or extraordinary burdens associated with interfacing and

integration across unfamiliar international boundaries.

International Cooperation for Mars Exploration and Sample Return

1

Introduction

The goals of planetary exploration are to understand the origin and evolution of the solar system, how the planets formed, and how the planets evolved to their present states and environments. The history and evolution of Earth indicate that life can have profound effects on the development of a planet's surface and atmospheric environment. Parallel goals are to understand the chemical precursors of life and the conditions that led to the origin of life on Earth and to ascertain the prevalence of analogous prebiotic or biotic environments elsewhere. Altogether, planetary exploration seeks to answer questions that are fundamental to our understanding of our existence on Earth, as well as to the present state of our planetary environment and its evolution.

These planetary questions have stimulated human thought and scientific investigation throughout history. They continue to be among the most basic and pressing of scientific questions today. Thus planetary exploration has been recognized as a fundamental element of the U.S. space program and as a source of great international prestige. Investigation of the terrestrial planets has been put forward by the Space Studies Board (SSB) as a principal focus of planetary exploration1; the importance of terrestrial planet studies has subsequently been reiterated in program implementation plans put forward by the National Aeronautics and Space Administration (NASA) [4,5] and by the SSB. [6] In the context of this focus, it is recognized that Mars occupies a special position as a target for intensive investigation.

The triad of terrestrial planets—Earth, Mars, and Venus—has been a major target of investigation by both the United States and the USSR because these three terrestrial planets pose a particularly sharp set of scientific questions and because their proximity makes them attractive targets for investigation. Earth, Mars, and Venus are similar in their sizes, masses, compositions, and locations with respect to the Sun. Yet these planets have evolved to have widely (different surface conditions in ways that are of special interest to human beings, whose existence and survival depend on the special surface conditions of Earth. Studies of these three planets have already revealed that terrestrial planet environments may change their states in highly unstable ways. It is possible that, at times past, the conditions on both Mars and Venus may have been more similar to present-day terrestrial conditions. It is important to understand the possible varieties and causes of changes in terrestrial planet environments, especially today, when human perturbations of Earth's environment are no longer negligible and are growing larger.

In these three planets we observe three natural experiments in planetary evolution. One experiment produced the Earth, where abundant free water on its surface and in its atmosphere has enabled the origin and persistence of life. Another experiment produced Venus, where most of the outgassed volatiles remained in a carbon-dioxide-rich atmosphere but where the water apparently escaped. And the third experiment produced Mars, which either has lost part of its atmosphere or never had one of large substance, but which has undergone extraordinary environmental change.

For these reasons, investigation of the triad of terrestrial planets with persistent atmospheres has very high scientific priority, The primary scientific objective of studying this group of terrestrial planets is to understand the reasons for their diverse evolutions and their very different present environments. An additional motivation for giving a high priority to the investigation of terrestrial planets is that such investigations will illuminate our understanding of the planet Earth.

Early investigations of Mars, undertaken in the U.S. space program during the past 20 years, have revealled that that planet poses numerous profound questions about the behavior of terrestrial planets and their environments. Evidence of broad climatological changes, apparently encompassing ancient temperate episodes with flowing water as well as the cold dry conditions that we observe today, challenges our understanding of the behavior of planetary environments and raises questions about the stability of planetary environments, including that of Earth. Moreover, from a practical point of view, after Earth, Mars is the terrestrial planet most accessible to investigation, because of both its proximity and its relatively benign surface conditions. Altogether, the intensive investigation of Mars offers a broad spectrum of important scientific reward, technical challenge, and opportunity.

The National Research Council's Space Studies Board has recommended that the next major phase of Mars exploration involve detailed in situ investigations of the surface of Mars and the return to Earth for laboratory analysis of selected martian surface and subsurface samples. [1] Mars sample return and intensive Mars surface investigation have been accepted by NASA as essential to accomplishing very-high-priority terrestrial planet scientific objectives within a balanced program of planetary and space science and have been included in NASA planning by NASA and its internal advisory panels. [4,5] In addition, Mars exploration is of wide scientific and technical interest in several other nations. [7] A Mars surface rover project, recognized as a necessary element of a Mars sample return program, has been identified as a desirable candidate for joint NASA-European Space Agency (ESA) collaboration by the U.S. National Academy of Sciences-European Science Foundation Joint Working Group on Cooperation in Planetary Exploration.a The ESA has also expressed general interest in a broader program of cooperative Mars exploration and sample return. The USSR has announced national plans for an extensive program of Mars investigation that incorporates substantial international cooperation.

The present Committee on Cooperative Mars Exploration and Sample Return was established at the request of NASA. The charge to the committee was to examine and report on the question of how Mars sample return missions might best be structured for effective implementation by NASA along with international partners. The committee considered alternatives ranging from scientific missions in which the United States would take a substantial lead, with international cooperation playing only an ancillary role, to missions in which international cooperation would be a basic part of the approach, with the international partners taking on comparably large mission responsibilities. The committee considered the scientific basis of such collaboration and the most mutually beneficial arrangements for constructing missions of separate supporting elements. Although the committee considered the possibility that the United States would play only a minor role while intensive Mars exploration was carried on by other nations, this alternative is not treated in detail in this report. The committee agreed with previous recommendations of the Space Studies Board as to the importance and priority of intensive Mars exploration and sample return and took as a premise the desirability of a high level of U.S. participation.

The Joint Working Group on International Cooperation in Planetary Exploration also reported specific details of recommended candidate joint projects and made specific recommendations as to the types of cooperation that could serve as a basis of U.S.-European joint projects in several aspects of planetary exploration, including the investigation of Mars.8 The recommendations for U.S.-European cooperation in planetary exploration were based on the relatively long record of experience with various levels of cooperation between U.S. and European scientists and between NASA and the several European space agencies. Those recommendations also took into account the long tradition of open communication, travel, cooperation, and technical exchange that has existed between Western Europe and the United States.

For reasons given in Chapter 2, the United States and the USSR occupy unique positions with respect to the intensive levels of exploration associated with the next steps of Mars exploration and Mars sample return. Because of this, the present study has focused on developing policy recommendations for possible cooperation between the United States and the USSR, specifically in the context of strongly stated interests by both nations in conducting intensive scientific explorations of Mars that include in situ investigations at Mars and the return of samples to Earth for laboratory analysis. The high scientific importance that is attached to such intensive studies of the planet Mars, the ambitious nature of the needed Mars investigations, and the fact that the two leading spacefaring nations have both expressed strong interest in and have announced plans for Mars investigations create a strong motivation to explore possible means of cooperation in this historic and consequential endeavor.

The scope of the present study and the recommendations in this report have purposefully been constrained to deal with those issues that are especially pertinent to the specific question of U.S.-USSR cooperation in a program of Mars investigations with sample return. A great many other issues and questions arise that are not dealt with in detail in this report. Many of these issues—including the pertinent scientific objectives and the detailed strategy of investigating Mars and collecting surface samples—have been addressed in previous scientific policy reports of the National Research Council [1,8] and in implementation plans of NASA and are not taken up further here. This report relies on those earlier recommendations to define the scientific context within which U.S.-USSR cooperation would take place.

International Cooperation for Mars Exploration and Sample Return

2

General Considerations

NATIONAL POLICY

The National Aeronautics and Space Act of 1958 and subsequent statements of U.S. national policy charge NASA to conduct, for the United States, a vigorous program of space activities and to establish a position of international leadership in the exploration and understanding of the solar system and the broader universe. It is recognized that space science and exploration are an important international enterprise in which many of the world's nations wish to participate. For two decades, during the 1960s and 1970s, the United States led the world in planetary exploration. Investigations by U.S. scientists, with the participation of many international colleagues, yielded discoveries and conceptual insights that have profoundly advanced our understanding of the solar system as a cosmic phenomenon. Information returned from space flight missions in the U.S. program has expanded human perception about the varieties and behaviors of planetary bodies. During the two decades of vigorous U.S. activity in planetary exploration, the space program played an important role in projecting an international image of U.S. leadership in cooperative and peaceful scientific enterprises.

For more than two decades the advancement of science has been one of the most important aspects of the U.S. space program. In its unmanned exploration program, the United States has carried out brilliant reconnaissance missions to Mars, Mercury, Venus, Jupiter, Saturn, Uranus, and Neptune that have established U.S. preeminence in planetary exploration. The success of the Apollo missions has served both as a symbol of national achievement to the world and as a source of pride to all parties from the many nations that have had the opportunity to participate in the study of lunar samples. Although the scientific component of the U.S. lunar exploration program was only a small segment of the total enterprise, it is evident that the scientific advances that grew out of that work have been most impressive.

In February 1988, the president approved a new directive on national space policy, the "Presidential Directive on National Space Policy," 3 which restates the U.S. commitment to vigor, leadership, and cooperation in the conduct of the nation's space program. The directive states that the goals of U.S. space activities include the promotion of "international cooperative activities taking into account United States national security, foreign policy, scientific, and economic interests," and the expansion of "human presence and activity beyond Earth orbit into the solar system." In addition, the directive states that the "United States will conduct international cooperative space-related activities that are expected to achieve sufficient scientific, political, economic, or national security benefits for the nation. The United States will seek mutually beneficial international participation in its space and space-related programs."

Among the guidelines given for implementing the directive, several stand out as especially pertinent to the subject of the present report:

- *Space science.* NASA, with the collaboration of other appropriate agencies, will conduct a balanced program to support scientific research, exploration, and experimentation to expand understanding of (1) astrophysical phenomena and the origin and evolution of the universe; (2) Earth, its environment, and its dynamic relationship with the Sun; (3) the origin and evolution of the solar system; (4) fundamental physical, chemical, and biological processes; (5) the effects of the space environment on human beings; and (6) the factors governing the origin and spread of life in the universe.
- *Space exploration.* NASA should conduct a balanced program of manned and unmanned exploration in order to investigate phenomena and objects both within and beyond the solar system.
- *Manned exploration.* To implement the long-range goal of expanding human presence and activity beyond Earth orbit into the solar system, NASA should begin 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 should continue to pursue a program of unmanned exploration, where such exploration can most efficiently and effectively satisfy national space objectives when the presence of humans is undesirable or unnecessary or where the risks or the costs of life support are unacceptable for the purpose of exploration, and for providing data vital to support future manned missions.
- *International cooperation.* The United States should foster increased international cooperation in civil space activities by seeking mutually beneficial international participation in its civil space and space-related programs.

The intensive investigation of Mars and the establishment of international cooperation for that purpose would constitute major strides in the direction of implementing central elements of the space policy outlined in the 1988 "Presidential Directive." Such an investigation, carried out with the use of robotic instruments and artificial intelligence, would provoke technological developments important in their own right and would serve as essential precursors of any program leading to the manned exploration of Mars. Mars exploration offers a range of exciting scientific and technological challenges and opportunities that could serve as a focus for mutually beneficial cooperation among the world's nations.

THE STATUS OF THE U.S. PROGRAM AND PROGRAMS OF OTHER NATIONS

The United States pioneered the scientific exploration of the planet Mars. Between the Mariner 4 flyby in 1964 and the Viking landings in 1976, the United States obtained global images of the martian surface, made the first determinations of the chemistry of martian soil and the martian atmosphere, established strict upper limits on the presence of biogenic material and biological activity, and conducted initial meteorological and seismological measurements. At the time of this writing, however, the United States has launched no further missions to Mars since Viking; indeed, only two planetary missions (Magellan to Venus in May 1989 and Galileo to Jupiter in October 1989) have been undertaken since 1978. Due to the Challenger accident in 1986 the United States had no operational civilian launch capability for 18 months. As a result of this loss and related fiscal constraints, a long and growing queue of planetary missions awaited reestablishment of an adequate launch capability, either with the Space Shuttle or with expendable vehicles, thereby creating a mission backlog that still persists. The launch date for the only approved future U.S. mission to Mars, the Mars Observer, was recently moved back by 25 months to 1992. As this report is written, progress toward recovery of the U.S. civil space program remains slow and unsure. The operational status and ultimate capacity of the Space Shuttle remain to be established, and the restoration of a reliable, routine launch capability is still to be accomplished.

During this long hiatus in U.S. space exploration, other nations have mounted scientifically sophisticated and highly successful planetary missions. During the 1970s and 1980s, the USSR sent to Venus a series of spacecraft that made important measurements of atmospheric and soil composition and obtained radar images of one-quarter of the planet's surface. The year 1986 saw encounters with Comet Halley by five spacecraft from Japan, the USSR, and the ESA; these spacecraft made pioneering measurements of the properties of the nucleus, coma, and solar wind interaction of an active comet. The USSR VEGA probes incorporated instruments from several European nations, and the program was managed with a large degree of international participation. U.S. scientists also participated in the Soviet VEGA project as team members and by building a small number of scientific instruments and components that were included in the payload. The USSR has announced specific plans to mount an intensive study of Mars and its satellites, starting with the 1988 Phobos mission (which, as this report is going to press, has failed) and extending into the 1990s with Mars orbiters, landers, roving surface vehicles and, ultimately, sample return.

The emergence of capable and ambitious space programs in a number of other nations presents both opportunities and challenges. The opportunity to undertake solar system exploration with major components of international cooperation will allow advantage to be gained by combining complementary and overlapping capabilities for science and technology. To capitalize on this opportunity, however, and to sustain a position of scientific leadership, it will be necessary for the United States to reestablish a robust capability for solar system exploration. At the time of this writing, the United States occupies an ambiguous position with respect to continued major participation and leadership in planetary exploration. Decisions are needed at the highest levels to determine the future of U.S. participation and leadership in planetary exploration.

The resumption of vigorous participation and leadership in space science and solar system exploration by the United States is not assured. However, in formulating the present recommendations, the committee made necessary assumptions about the U.S. commitment to reestablishing a vigorous space program*. Specifically, for the purpose of this report, the committee makes the assumption that the United States will resume and cany forward a vigorous national space science and solar system exploration program of high quality. The committee also makes the assumption, for the purpose of this report that the program will include international participation and cooperation as enunciated in the Space Act of 1958 and the 1988 "Presidential Directive."* [2,3]

THE ENVIRONMENT FOR INTERNATIONAL COOPERATION

The United States has traditionally conducted an open civil program of space science and exploration, inviting participation by a broad cross-section of participants from the international community. In recent years a broad internationalization of space science has developed. The USSR has begun to announce major planetary exploration initiatives in advance and to invite broad-scale international participation. The Soviet VEGA mission to Venus and Comet Halley apparently marked the beginning of a major internationalization of the USSR space science program. The internationalization of the Soviet program is expanding in the context of announced Soviet plans for Mars studies and appears to represent a recent move by the USSR toward the use of peaceful space science and exploration as an instrument of national and foreign policy. The ESA marked its entry into deep-space planetary exploration activities with its Giotto mission to Comet Halley. Current ESA planning includes commitment to further planetary mission. [8] Japan also entered independently into deep-space planetary investigations during the recent appearance of Comet Halley and has discussed plans for future planetary investigations.

In these circumstances, the appropriate role and structure of international cooperation should be considered for any major space projects. Exploration of the planetary system is an especially appropriate arena in which to foster and develop increasing levels of international cooperation. It is in part through the results of space exploration that a sharp understanding of the uniqueness, finitude, and fragility of our own terrestrial environment has been fixed into the minds of all Earth's people. This has caused a better appreciation of the need for cooperative, unified steps to ensure Earth's future. Moreover, at this early stage of planetary exploration, the enterprise is not entangled with complicated problems of immediately nationalistic and territorial concerns. Thus exploration of the planets offers, at this time, an arena for international cooperation that can be free from many directly competitive and complicating factors and that potentially can help lead to more constructive international relationships in the future.

At least three space agencies—those of the United States, the Soviet Union, and the European community—are capable of planning and executing ambitious planetary exploration programs. Only the United States and the USSR are now capable of executing programs of the scale involved in intensive Mars investigations. A larger number of nations and space agencies are eager to participate in the scientific and technical opportunities offered by these three agencies. Ambitious space projects require a long-term, stable commitment, even if executed by individual nations. International cooperation on such projects amplifies the need for a stable commitment among the participating nations that can best be assured by a clear national policy aimed toward international cooperation in space exploration. According to a 1987 NASA report examining options for future U.S. space exploration, "The broad spectrum of space activities and the increasing number of space-faring nations make it virtually impossible for any nation to dominate." 9 Leadership, however, requires that a nation not only enunciate its objectives but also have the perceived and real ability to carry out programs and achieve the objectives. Because Mars exploration necessitates a multimission program, the commitment among nations to cooperate in this endeavor offers a long-term, multifaceted opportunity to develop and evolve cooperative experience and to benefit substantially from the economies that a cooperative approach can offer.

If it is to be undertaken, international cooperation in the intensive exploration of Mars should be implemented so as to effectively accomplish the pertinent scientific goals. The opportunities for cooperation, and the benefits, depend on the nature of the specific scientific activities involved. The study that is reported here (1) examined the elements that will be required in order to address the scientific objectives that have been defined for Mars and (2) analyzed the opportunities for international cooperation in that context.

This report focuses on the question of how best to approach the potential of U.S.-USSR cooperation. This focus is not intended to underestimate the importance of participation by other nations and space agencies. High interest has been shown by several European nations, and by ESA, in participating in Mars exploration; there is the possibility, in the context of an exciting international opportunity for Mars exploration, that many other nations will wish to participate, including Japan and Canada, among others. The highly developed scientific and technical talents and capacities that are found in these nations would render their participation extremely valuable and important. However, the United States and the USSR are unique in that they are the only nations presently in a position to take on the lead role in a major Mars program that includes surface exploration and sample return. Therefore, the committee has assumed that the gross structure of any intensive Mars exploration program will be determined by policy and programmatic decisions made in the United States and in the USSR, and that, for at least the next decade, the opportunities for other nations to participate in intensive Mars exploration will depend on the programs undertaken by the United States and the USSR; it is for that reason that this report focuses on the possibility of U.S.-USSR cooperation. It should also be recognized, however, that because of the announced commitment by the USSR, international cooperation in Mars exploration is likely to be implemented whatever the U.S. decision is with respect to participating or adopting a position of leadership. There is a high probability that many nations in Europe and elsewhere will be very enthusiastic about participating in the Soviet program, even if the United States decides to remain on the sidelines.

This report finds that the nature and scope of Mars investigations provide a rich opportunity for international cooperation. Cooperation can both enhance the science and provide substantial economies to the nations involved. Moreover, there is a variety of possible and beneficial cooperative modes. Full-scale cooperation could be initiated at this time and in such a way as to realize the major benefits of cooperation without major susceptibility to either the concerns about undesirable technology transfer or the possibility of large unexpected burdens that might arise in administering technical and management interfaces between unfamiliar partners.

Both the United States and the USSR have made major advances in understanding the origin and evolution of the solar system and the evolution of planets and their environments. These advances have resulted from vigorous spacecraft investigations of various solar system bodies, from intensive laboratory studies of extraterrestrial materials, from theoretical research and modeling calculations, and from astronomical observations. The vigorous planetary science and exploration programs of the United States and the USSR over the past quarter century have precipitated the growth, in both nations, of impressive scientific communities with parallel interests and research activities. The committee believes that these communities could work together in a cooperative fashion with some facility and with positive results.

International cooperation may entail special costs and burdens that should be weighed against the benefits. The administration of technical and management interfaces is a major task even for projects conducted within a single agency. Such problems are exacerbated by the need for long-distance communications, by language barriers, and by different ways of conducting business in a major international project. The costs and burdens imposed by these problems vary with the degree of previously existing cooperative experience. The record of actual intensive and close cooperation between U.S. and USSR scientific communities, and between the governments and their respective space agencies, is not a long one, although there exist important specific examples of very fruitful and valuable collaborations on several levels and in a variety of areas. Therefore, the establishment of cooperative programs involving intensive technical interaction between the United States and the USSR presents special problems that arise as a result of the lack of experience with intensive cooperation, especially for a program as ambitious and complex as that envisioned for intensive Mars exploration. International cooperation requires an infrastructure in which mutual exchange can occur freely. In the context of U.S.-USSR cooperation, there is limited experience in cooperative ventures and the added burden of sensitivity about such matters as the exposure or transfer of technologies related to national security.

Significant cooperative space projects are inherently of long duration. Even a project run by one nation alone entails a commitment of more than a decade for planning, design, construction, flight, operations, and data analysis. The typical time between the formal new start of a space project in the United States and the launch is approximately 5 years. The planning leading up to a new start normally entails at least 2 to 3 years, generally more. Added to that are the flight time of about 1 year to Mars, 1 or 2 years of spacecraft and instrument operation time on Mars, and several years of analysis following the flight mission, so that the duration of the project begins to approach 15 years. A program involving several flights over several years will further increase the overall duration of the project. Finally, the added complications entailed in very close technical integration of major project parts across national boundaries would inevitably add more time to the schedule. The inherent duration of a project such as the exploration of Mars is longer than the previously demonstrated stability of the U.S.-USSR relationship.

International cooperation may be undertaken to accomplish a variety of goals beyond those of a purely scientific nature. Although the present report is oriented toward analyzing cooperation in exploring Mars on the basis of the science that might be accomplished, it is also recognized that any major cooperative endeavor is likely to be shaped so as to be responsive to other national goals. Indeed, some aspects of cooperation that might be seen as negative in the context of accomplishing the science alone—such as the management of difficult technical interfaces across poorly established channels of communication—might be seen as positive and advantageous in the context of international relationships. For instance, scientific cooperation could be seen as a benign arena in which to begin improving international communication and technical cooperation. In that case, meeting the challenges posed by managing new and difficult interfaces might be seen as major motivation from the outset. The pace with which such objectives are to be addressed involves policies and political questions that are outside the scope of the present study. However, the results of this study indicate that substantial scientific benefits may be derived from various forms of cooperation.

International Cooperation for Mars Exploration and Sample Return

3

Intensive Investigations of Mars

GENERAL CHARACTERIZATION OF THE PLANET

The martian surface has clearly evolved under the influence of a variety of processes of internal, surficial, and external origin. The major processes that shaped the surface of Mars include eruption and emplacement of volcanic deposits, water erosion and sedimentation, impacts, and faulting and other tectonic processes, as well as glacial phenomena. Valles Marineris, a canyon system more than 4000 kilometers long, seems to have been the result of rifting and other tectonic processes as well as major erosion. Extensive layered deposits are visible in the sides of the canyons and in the associated mesas. Some of these deposits may have arisen as sediments in vast lakes that once filled parts of the canyon system. However, other speculations are that some layered deposits resulted from lava flows, explosive volcanic deposits, or wind-laid sediments. Regardless of the origin, these layered deposits and the canyon walls may reveal critical clues about a large part of martian history, in much the same way that the deposits and walls in Arizona's Grand Canyon reveal much about Earth's history.

Some regions of Mars are dissected by large and small channels apparently cut through young rock, indicating that liquid water existed on the surface of Mars relatively late in the planet's history. Other, more degraded, channels dissect ancient terrain and appear to have formed earlier in the history of the planet. Altogether, the present indirect clues suggest the likelihood of profound climatic change on Mars, including the possibility that flowing water occurred at least several times throughout the history of the planet.

Mars has distinct seasons, with carbon dioxide cycling between the polar caps driving a major component: of the atmospheric circulation. Layered sedimentary deposits near the martian poles provide additional evidence of long-term climatic changes whose origins are poorly understood and that pose some of the most fundamental scientific questions motivating intensive Mars investigation. On Earth, such climatic change has given rise to the occasional ice age, a phenomenon also still poorly understood.

The Viking mission indicated the absence of even relatively small amounts of organic molecules on Mars. Viking also confirmed the existence of intensely oxidizing conditions at the martian surface. These factors strongly suggest that living organisms are not now present. Whether Mars was less hostile to the development of life during earlier times, when it may have had a denser atmosphere, higher surface temperatures, and liquid water, is still an open question. So far as is known, Earth is the only planet with surface conditions, an atmosphere, and a hydrosphere that have allowed the formation of life as well as its sustenance and evolution over a long period of time. Terrestrial life forms have substantially altered the chemistry of the atmosphere, oceans, and major sedimentary rocks on Earth's surface.

Fundamental questions to be addressed through investigations of Mars also include questions about the role' that life plays in the evolution of a planetary surface and environment; these questions are most effectively addressed through detailed investigation of another planet on which life seems to have played a much smaller role than it has on Earth, or no role at all. Other basic questions about Mars include the state and evolution of the planet's interior, the physical processes that have shaped the surface, the fate of the apparently missing water, and the nature of current and past hydrological cycles that link the polar caps, ground water, and atmosphere.

THE SCIENTIFIC AND TECHNICAL CHARACTER OF MARS EXPLORATION

The scientific objectives of intensive Mars investigation are to understand the planet's gross planetological characteristics, the principal processes that govern its present state, the history of variation in the martian environment, and phenomena that have been responsible for such environmental change. It is also a principal objective to ascertain whether any stages of chemical and biological evolution might have occurred on Mars and to determine whether evidence can be found for the existence of life at any time during the history of the planet. Strategies and approaches for achieving these scientific goals have been analyzed in previous Space Studies Board and NASA reports. [1,5,6,10] In this report the committee briefly summarizes those conclusions in order to define the context of scientific objectives in which its recommendations about cooperation are made.

Investigation of the structure and dynamics of the martian interior will require the use of a globally distributed network of sensitive seismometers—at least three—on the surface of the planet, with a substantial period of simultaneous operation extending over the order of 1 year or more. Investigation of the atmospheric circulation and climate will require at least a similar number of widely spaced monitoring stations distributed over the martian globe in latitude and longitude and operating for an overlapping interval lasting at least 1 martian year.

To obtain the variety of samples needed to answer the principal scientific questions, it will be necessary to obtain planetary material of a variety of ages, including material from the most ancient sites on the heavily cratered terrains, material more recently brought to the planet's surface on the intermediate-aged, resurfaced plains areas, and materials from the youngest identifiable volcanic deposits. Material spanning this range of planetary age will be necessary for tracing the planet's interior and crust. Material capturing stratigraphic records will be recoverable from crater ejecta as well as from material on channel walls. Sedimentary deposit material—including such material from beneath the surface—will be important for exploring questions pertaining to the history and nature of flowing water on Mars, and to possible biochemical and biological aspects of the planet's history. The margins of the polar ice caps, seasonal ice-related deposits, and the ice sheets themselves hold important information about the planet's volatile inventory and about climatic variation on Mars; the polar margins are also essential targets of study for questions about the past and present biological potential of the planet. Identifiable regions of contemporaneous volcanism would be important targets of investigation for studying geochemical and geophysical questions, as well as questions pertaining to the planet's biological potential.

Altogether, Mars exhibits a variety of geological terrains and environments that are widely separated and distributed over the planet. The scientific objectives dictate that a variety of sites be investigated for several reasons: investigation of the global questions requires an absolute minimum of three widely separated sites; and the varieties of materials required for scientific analysis are distributed widely over the planet's surface; and the varieties of environments and manifestations of evolutionary history are distributed in many different locations on the planet. The.exact number of missions needed in the next phase of Mars intensive investigation will depend on technical details not yet resolved, including such questions as rover range and maneuverability, accuracy of lander targeting, and feasible modes of deploying scientific instruments. To obtain answers to the major scientific questions and to build an understanding, of Mars at the level needed to address comparative planetological questions will require the exploration of, and sample return from, several diverse sites—in the range of four to six. A program of this nature would also provide the base of information needed to determine the value of possible human exploration of Mars and to assess the technical questions involved in planning for possible future human exploration.

Investigations of Mars will play a critical role in achieving a general understanding of the terrestrial planets and their environments. Because of the importance of a Mars program in terms of the quality and significance of the scientific objectives, the prestige and scientific importance associated with the return of the martian materials, and the substantial implications for new technologies such as robotics and artificial intelligence, *this committee concurs with previous recommendations of the Space Studies Board and recommends the vigorous scientific exploration of Mars, with investigations on the martian surface and the return of marcian materials from several diverse sites, ranging from equatorial to polar, in order to* *understand the rich diversity of martian processes.*

To fulfill the scientific objectives, investigations on the surface of Mars that include a variety of in situ measurements and analyses, as well as the collection of a set of selected and documented martian samples for return to terrestrial laboratories, are needed. Investigations on the surface will require substantial mobility to allow the selection of measurement sites and manipulative capability to enable the emplacement of instruments. Sample collection will require the mobility to reach the most promising sample sites; the manipulative capability to use sample collection tools, including drills, for sample collection; the ability to divide samples and analyze them at a level needed for selection; and the ability to package and store samples in such a way as to maintain their scientific integrity during the return to Earth. Thus *the committee recommends that operational capabilities at Mars include extended robotic mobility, manipulative capacity, and artificial intelligence in order to adequately study, sample, and return materials from the various sites on Mars.*

International Cooperation for Mars Exploration and Sample Return

4

Possible Cooperative Mission Modes and Their Implications

Various approaches to establishing cooperative investigation of Mars are possible. For the purposes of this report, the essential aspects of the major approaches, and their implications, can be captured by several general considerations.

The USSR has announced intentions for a Mars exploration program, which appears to include in situ surface investigations with robotic rovers, orbiting spacecraft, and sample return. In view of the USSR's announced intentions, the major variables in the set of alternative program modes that the committee has examined are the level of U.S. participation in Mars science and the character of U.S.-USSR cooperation, if any. Three levels of U.S.-USSR cooperation in intensive Mars exploration have been considered by the committee:

- Independently conducted programs,
- Split responsibilities and joint technical operations, and
- A highly coordinated exploration program.

Each of the possibilities also assumes that other nations and space agencies would play substantial roles in the planning and execution of Mars exploration within a framework largely defined by the U.S. and USSR programs. The final recommendations are based on an analysis of the implications, for the United States, of each of these possibilities.

THE PRESENT STATE OF U.S. MARS INVESTIGATIONS AND PLANNING

At the time of this writing, the U.S. program for further, exploration of Mars consists of the Mars Observer mission, scheduled for launch in 1992, as the only specifically planned initiative. The broad survey measurements to be carried out by Mars Observer address a number of important global- and regional-scale questions. The overall understanding of Mars as a planet will be greatly advanced by the Mars Observer's mapping of the planet's surface structure and chemistry, investigations of the atmosphere, and measurement of Mars's magnetic field, all of which will set the stage for intensive investigations to follow. The very-high-resolution images that will be obtained of selected small areas will also prove important to the planning of future Mars surface explorations. NASA has undertaken studies of possible future Mars exploration initiatives that might be carried out either by the United States with the participation of international partners or as, part of a truly joint international endeavor with comparable contributions from one or more major partners. As yet, the United States has not announced national plans to undertake any intensive investigations of the martian surface.

Experience with the Soviet VEGA project, with the Phobos mission, and with planning for follow-on Mars missions indicates that. the USSR will continue to invite and welcome participation from scientists in Western nations, including the United States. Should the United States fail to assume a major role in the exploration of Mars, there is likely to be some opportunity for U.S. scientists to participate in continuing Mars science through direct affiliations with the Soviet program or, indirectly, through affiliation with scientific teams from the other nations that will participate in a Soviet-led program.

However, if the United States forgoes a primary role in Mars exploration, then any cooperation is likely to be restricted to a low level, and U.S. scientists are likely to be involved only in minor or supportive roles as international leadership in this historic scientific endeavor is assumed by the USSR. Primary consideration by the USSR in planning its own projects would likely be directed toward cooperation with European nations and space agencies, and the result would be a highly intensified relationship between those partners.

VARIETIES OF U.S.-USSR COOPERATION

In this section, the committee summarizes an analysis of the major possible approaches to U.S.-USSR cooperation and, for the purpose of this analysis, notes that (1) the USSR has announced its intentions for Mars exploration in sufficient detail to suggest the scope of that nation's plans and ambitions; (2) USSR leaders have publicly stated a desire for cooperation with the United States in the exploration of Mars; and (3) the USSR is conducting detailed discussions with numerous other nations about the possibilities of participation in Mars exploration. Therefore, the committee assumes that during the next two decades the USSR will conduct a Mars exploration at a level approximating the announced plans. Moreover, on the basis of the public pronouncements, the committee takes as given that the USSR is open to international cooperation in a variety of modes, depending on the desires of potential partners.

As has already been noted, the future vigor of U.S. programs and a U.S. posture of international leadership in this area are not assured. However, the remainder of this analysis assumes that the United States will engage in intensive Mars investigation beyond the Mars Observer. This analysis also assumes that any cooperation will involve a program extending over a decade, entailing several missions to several diverse sites on Mars, and including both in situ investigations and sample return, as described earlier.

The committee considered many possible program scenarios, ranging from strongly linked missions in which mission success would depend on the success of mutual interactions, to more weakly coupled versions, with cooperation implemented in a different way. The analysis of possible cooperative modes includes consideration of several discriminating factors, including (1) impact on the overall science return; (2) the possibility of reduced cost to the United States, within a fixed anticipated overall science return; (3) impact on mission risk; (4) impact on technology development; (5) susceptibility to concerns about technology transfer; (6) contribution to enhancing scientific relationships with the traditional U.S. partner nations; and (7) possible contribution to improving the U.S.-USSR relationship. In addition, several other factors were considered, such as the contribution to building U.S. national prestige.

Independently Conducted Programs

The lowest level of U.S.-USSR cooperation considered in this report involves a situation in which each nation conducts an independent program of Mars investigation with minimal levels of cooperation or coordination. At this level, it is still assumed that the usual scientific interactions generally characteristic of basic scientific research will continue to occur, including the exchange of data obtained by the missions.

This level of cooperation does not preclude the possibility of some operational coordination and interaction to take advantage of circumstances that might arise in the conduct of the separate programs; however, it is assumed that, at this low level of cooperation, such fortuitous possibilities do not play a major role in shaping the plans of either nation. This is the level of cooperation that exists today between the United States and the USSR. Examples include the use of one nation's spacecraft as a communications relay for the other nation. Although `even this relatively low level of interaction requires advanced planning during the spacecraft design stages and for operations, the interfaces that are involved are generally simple and straightforward.

With respect to the discriminating factors:

- *Science return.* Assuming that a commitment to achieve the scientific objectives is actually carried out, conducting independent programs may have little fundamental effect on accomplishing the scientific objectives; the United States is fully capable of accomplishing all Mars scientific objectives. However, the ability to maximize scientific return within the constraints of the present technical capabilities of the two sides would be lost if programs were conducted separately.

- *Cost.* The cost of conducting an independent Mars exploration program is significant. Assuming fixed scientific objectives, the United States will be forced to provide full resources for carrying out an independent program and for accomplishing the objectives, regardless of the plans and programs of the USSR
- *Risk.* The committee identified no inherent impact on mission risk from conducting an independent program, inasmuch as this is the normal mode of carrying out space science missions.
- *Technology development.* The independent approach has the potential to greatly benefit U.S. technology development. Planning and carrying out an intensive program of Mars exploration and sample return will focus development efforts and implementation in a variety of important technological areas, including scientific instrumentation, propulsion and launch systems, and robotics and artificial intelligence. Many of these developments will have application to other activities on the ground and in space.
- *Technology transfer.* An independent program eliminates any additional risk of technology exposure or transfer that might result specifically from cooperation with the USSR.
- *Relationships with traditional partners.* Inasmuch as the United States is assumed, in this approach, to be conducting a Mars exploration program of its own, then the usual opportunities will be available for cooperation with traditional U.S. partners and allies. This would serve to reinforce a significant area of existing cooperation and would provide many nations with a path to Mars exploration as an alternative to, or in parallel with, participation in a Soviet program.

U.S.-USSR relationships. An independently conducted program makes no contribution to developing U.S.-USSR experience in cooperative technical and social endeavors. It could also ignite a space competition similar to the race to the Moon.

Split Responsibilities and Joint Technical Operations

In this approach the United States and the USSR would undertake a significant level of joint technical operations within the context of one or more missions. The planning and execution of such missions would be conducted collaboratively, and the achievement of major mission objectives would depend on sustaining successful cooperative efforts from the time of initial mission design through to the completion of data analysis. This level of cooperation generally would involve substantial hardware, software, and management interfaces at the level of major spacecraft systems and at institutional and governmental levels.

There are potential advantages to this high level of U.S.-USSR cooperation. A commitment by both nations to a fully cooperative venture of the magnitude and duration of a Mars sample return program would have a greater, presumably positive impact on U.S.-Soviet relations than would options involving lesser degrees of interaction and reliance. A high level of cooperation would permit the undertaking of ambitious and scientifically outstanding missions, such as the return of Mars samples from a diversity of terrains at less cost to each nation than if the same set of missions were executed unilaterally, although this advantage also accrues to some cooperative options that involve less entanglement at the systems level. Finally, this high degree of cooperation would enable missions that take full advantage of the complementary and mutually supportive capabilities of the two space programs (e.g., the present advantage in .heavy lift capability of Soviet launch vehicles and the advantage of high analytical precision, sophistication, and computational capacity enjoyed by U.S. flight instruments and systems).

Against these potential advantages must be balanced several disadvantages. A mission with a high degree of dependence on the cooperative efforts of both the U.S. and Soviet space programs would sit as a potential hostage to political events that might disrupt communication and interaction between the two nations. Missions can be envisioned in which the science could be successfully accomplished by either side even if the bilateral cooperation were truncated for political reasons during the mission planning or operation stages. However, such mission configurations either involve a considerable redundancy of effort, substantially offsetting the cost advantage mentioned above, or admit the possibility of a substantially degraded scientific return if full cooperation is not sustained through the project. A project with a high level of U.S.-USSR cooperation, if it is to yield a savings in cost over unilateral missions of similar scope and if it is to take maximum advantage of the complementary capabilities of the two space programs, involves the assignment of responsibility for major engineering modules to one or the other nation. Whether either nation will agree to relinquish to the other the development of major components of enabling technology is not apparent. There is, in addition, a substantial burden on resources and personnel involved in coordinating and managing the interfaces involved in such intimate cooperation; this would be exacerbated by lack of experience in this kind of activity. This burden would offset the potential savings to an unknown degree and must be weighed carefully in assessing the financial implications of the high degree of cooperation and mutual dependence involved in this approach.

In one frequently discussed example of a mission conducted at this level of cooperation, one nation would build a lander and a sample-return vehicle while the other nation would build a roving vehicle for collecting samples and conducting in situ science. The roving vehicle could be carried on the same lander as the sample-return spacecraft or on a separate lander, and one or both nations could launch Mars orbiters to serve as communication links and to conduct global remote-sensing measurements. Obviously, design and logistical considerations would differ depending on the configuration of the one or more landed packages.

This type of mission seems attractive, from a cost standpoint, as an individual mission: it would share the cost of an otherwise unilaterally executed rover and sample return mission. Because the rover and the sample-return vehicle—with the latter also assumed to have some limited sample-acquisition capability—each would accomplish important independent scientific objectives, significant science would accrue even if one of the two vehicles were to fail. As long as the rover and the sample-return vehicle were launched separately from Earth, the two parts of the mission could also proceed independently of one another should political considerations force a termination of cooperative efforts. However, the science return would be severely diminished if the separate components were not able to complete their combined, fully interactive mission. The lift capabilities of the launch vehicles of the two nations-with the present Soviet capabilities far exceeding those of the United States-and the present U.S. lead in technologies associated with the rover, suggest that the most natural division of responsibilities would be for the United States to develop the rover and for the USSR to construct the sample-return vehicle.

Such an assumed configuration would, of course, leave the United States without an independent sample return capability and would relinquish the actual return of martian samples to the USSR (although in such a scenario the returned samples would be jointly controlled by the two nations): This configuration also does not acknowledge the Soviet interest in developing and deploying robotic roving vehicles for use on Mars. If the USSR were to go ahead, in any case, with its plans to develop rovers, the benefit to the USSR of cooperation with the United States might be largely political and scientific, but the financial advantage to the USSR would not be so clear. The longer-term scientific and political benefits of cooperation for the United States would be partly offset by ceding the development of Mars sample-return vehicle technology to the Soviet Union. Altogether, to the extent that technology development is likely to be a major motivation on both sides and to the extent that both launch capability and artificially intelligent robotic technology are seen as desirable by both sides, it is likely that both parties will be reluctant to abdicate the development of either technology.

The committee considered the possibility that this approach, taking advantage of the existing complementary strengths of each side, might speed progress toward a launch and result in the earliest initiation of Mars exploration and sample return. The needed technological developments could proceed in parallel. However, the technical, social; and political obstacles associated with inaugurating such a complex cooperative effort in the absence of prior experience could be expected to introduce delays that would be difficult to estimate a priori. Therefore, the committee is not convinced that mission modes involving such very intimate technical interdependence and joint activities at Mars would indeed lead to the most rapid initiation of Mars exploration.

With respect to the discriminating factors:

- *Science return.* This approach potentially allows the greatest optimization of overall science return within the constraints of the present technical capabilities of the two sides. With nontechnical restrictions removed, the project could be planned to take advantage of the best capabilities, wherever those might reside.
- *Cost.* The cost of conducting missions involving split responsibilities and joint technical operations on Mars is significant. Assuming fixed scientific

objectives, then each side would have responsibility for only a part of the overall system, thus opening the possibility for considerable cost savings. However, there are significant costs associated with establishing cooperation of this kind between two nations on opposite sides of the globe, with little prior cooperative experience, and with, poorly established communications. These costs would offset an unknown fraction of the savings that might otherwise be realized.

- *Risk.* This approach must be considered to be inherently very risky. The United States and USSR have no prior experience with the degree of cooperation necessary to carry out a technical project of this complexity or magnitude. There are no previously established modalities of cooperation and relatively few existing lines of communication. Each side has little preexisting working knowledge of the other's technical and management practices or institutions. The demonstrated stability of the relationship is such as to at least raise concerns, at: this time, about relying on the consistency of the relationship over a period of a decade or more into the future. The failure of all or part of the system as a consequence of these risks would, at best, result in a severely degraded scientific return.
- *Technology development.* This approach minimizes the effort to develop the necessary technology by taking advantage of the best capabilities available on each side and by dividing the responsibility so that neither side is responsible for all aspects of a mission. However, it is not clear that either side will wish to yield to the other the most challenging and beneficial of the technology developments.
- *Technology transfer.* This mode of cooperation inherently involves the exposure and transfer of large amounts of technology and technical knowledge.
- *Relationships with traditional partners.* In this approach, the opportunities for participation by traditional U.S. partners and allies would occur within a multilateral framework shaped by agreements between the United States and the Soviet Union. This modality would foster international, multilateral approaches to technical cooperation.
- *US-USSR relationships.* This approach has the potential to make a large and positive contribution to developing cooperative relationships between the United States and the USSR.

A Highly Coordinated Exploration Program

In this approach, the United States and the USSR would agree to conduct a highly coordinated program of intensive Mars exploration and sample return missions at roughly equal levels of scientific and technical commitment. The two sides would work together at all stages, including the initial planning of scientific objectives, experimental approaches, principles of sample collection, and site selection. However, the two sides would conduct their own self-contained and independently designed missions, with specific interaction at Mars limited to the coordination of networked investigations, when that is beneficial, and to mutual support and backup of communications and data telemetry. The post-mission scientific analyses and sample distribution would be conducted with a high degree of cooperation and collaboration. This approach would also permit the United States and the USSR to carry forward, in their individual fashions, other aspects of international cooperation. European scientists and agencies would undoubtedly act to .enhance their scientific participation in the context of opportunities arising in the U.S. and Soviet programs.

The approach of conducting a highly coordinated program of separately implemented missions captures elements of each of the other two approaches discussed above. On the one hand, the scientific objectives would be fully met. On the other hand, within fixed scientific objectives, a large cost advantage is apparent. Recognizing that the scientific objectives dictate a sequence of several missions, each side would need to commit to roughly one-half of the needed missions, assuming cooperation in the selection of sites and investigations.

The committee considered a number of variations on this approach, which have the effect of increasing the level of joint technical operations while still remaining within the framework of coordinated missions conducted separately. One variant at this level of cooperation could be constructed so as to take advantage of the simultaneous presence of two groups on the martian surface. For example, in the case that both nations mount a complete surface-rover and sample return mission, it would be able to choose complementary landing sites and rover traverse paths so as to optimize the return of a diversity of samples, visit a wide variety of geological features and units, and deploy network instruments over a geographical region that enhances the scientific return from those instruments. While scientific, political, and social benefits of full cooperation would accrue from such a mission configuration, there would be little if any cost penalty, above the cost of conducting separate missions entirely. The failure of one of the missions would result in a decrease of the overall scientific yield but would not precipitate a failure in the coordinated program.

The committee also considered mission scenarios in which landing sites would be coordinated and closely spaced so that each rover could conduct a traverse to the sample-return vehicle of the other nation and deliver its collection to that vehicle. Modest scientific gains might include a richer diversity of samples and an enhanced opportunity for some in situ investigations (e.g., rover-to-rover electromagnetic or seismic sounding) and network science (meteorology, seismology, and magnetometry) experiments. A dual surface-rover and sample return mission to landing sites situated within rover traverse range could provide additional robustness if one of the roving or sample return vehicles were to fail mechanically, although providing for this contingency would require substantial advanced planning and hardware coordination. Based on the present state of knowledge of the martian surface, the present limitations on achieving highly accurate targeted landings, the uncertainties associated with operating rover vehicles past unexpected barriers in the martian terrain, and the limited level of enhancement in the scientific return that would occur from such complex operations, the committee concluded that such complex mission scenarios were not warranted for early stages of Mars exploration, but might be considered for later missions.

The primary distinction between this approach and the approach based on split responsibilities and joint technical operations is that each side would be fully responsible for the overall systems involved in its own missions; there would be no need for intimate technical and management interfaces at the system level that could affect the likelihood of mission success. The committee believes that this would relieve the large extraneous burdens and costs that otherwise could be associated with a cooperative program. However, there would remain the highly desirable possibility of exchanging scientific instrument packages built by one side and included on a vehicle of the other side. The interfaces—both technical and management—associated with such instrument exchanges are relatively simpler than the overall system interfaces and could be designed so as to minimize the likelihood of a major mission failure in the event of problems. Also, in this approach, it is expected that there would be substantial collaboration and exchange of personnel at the science-team level.

With respect to the discriminating factors:

- *Science return.* This approach allows all of the scientific objectives to be realized.
- *Cost.* The cost-benefit impact of conducting a program of highly coordinated but separately implemented missions is large. Neither side would be responsible for mounting missions to the entire suite of required sites on Mars. Assuming fixed science objectives, each side would have responsibility for only a part of the overall program. Moreover, because each side would be planning and carrying out its own missions, the overhead costs associated with implementing close technical and management interfaces would be eliminated.
- *Risk.* Risk is minimized in a program that has a high level of cooperation. Because each side would be implementing missions on its own, the interfaces would be minimized. There would be no risk of mission failure due to technical, management, or political failures.
- *Technology development.* This approach provides each nation with the advantages of undertaking full technical development—in the areas of spacecraft launch systems, automation, and scientific instrumentation—needed for Mars exploration and sample return.
- *Technology transfer.* This mode of cooperation minimizes the transfer of technology and technical knowledge. The committee believes that incorporation of modular scientific packages from one nation on a vehicle of the other nation could be accomplished with little concern that unwanted technology transfer would occur.
- *Relationships with traditional parmers.* Opportunities for participation by traditional U.S partners and allies would occur within a context of two separate programs carried out in parallel. It is likely that other nations would seek the best opportunities, among those offered in the U.S. and the USSR programs; for participating in Mars exploration.

- *U.S.-USSR relationships*. This approach has the potential to make a large and positive contribution to developing cooperative relationships between the United States and the USSR.

International Cooperation for Mars Exploration and Sample Return

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Summary and Concluding Recommendations

Although this report addresses the question of U.S.-USSR cooperation, a more basic issue underlies the formulation of U.S. policy in this area. A policy leading to international cooperation cannot usefully be enunciated in the absence of clearly stated US objectives and intentions toward Mars exploration in particular and toward space science more generally. The United States needs to reestablish its leadership in some aspects of space science, including planetary exploration. At present, the architectural goals of the US space science program require both definition and a firm plan of implementation. This report takes as a premise that the United States will undertake a significant program of Mars exploration, and it focuses on the implementation of U.S.-USSR cooperation in that context. From a scientific perspective, international cooperation can be utilized to accomplish scientific objectives in a most effective manner. There may be many other benefits of a political and social nature to be gained from international cooperation in space science. However, the committee considers that the greatest total benefit will be derived if international cooperation is directed toward realizing objectives that are, of themselves, of the highest scientific importance and toward programs that are already regarded by all participants to be of high priority. Therefore, the committee considers it essential that a U.S. policy be enunciated that recognizes the high priority that has been given to intensive Mars investigations and sample return and that clearly states U.S. intentions with respect to such activities.

To accomplish the Mars scientific objectives that have been formulated by the Space Studies Board, it will be necessary to conduct a sequence of missions to Mars, involving both in situ investigations and sample return. 1,5,6,10 lie committee considers that detailed Mars investigations should be initiated in the context of a program aimed at visits to a set of selected sites (four to six) and entailing several missions conducted over a number of years. Such a program would provide a major increment of knowledge about the planet Mars and about the states and evolution of terrestrial planets in general. It would also provide the basis of fact that is needed to inform future decisions about further levels of Mars investigation, including the possibility of manned exploration of that planet.

The scale of needed Mars investigation is such as to make it desirable to combine the resources of the world's major spacefaring nations in this scientific, exploratory, and technical endeavor of historic proportions. Inasmuch as the United States and the USSR are the only two nations presently carrying out space activities of the scale and scope needed to effect major Mars exploration, the committee considers that the plans and programs of the United States and the USSR will determine the overall conditions of Mars exploration, and that, for at least the next decade, other nations will engage in major Mars exploration to the extent that they participate in either the U.S. or Soviet programs, or both. The committee sought to recommend an approach, in which (1) each participant would make a substantial contribution, (2) the cooperation would enhance the total scientific benefit and would achieve economies, and (3) the cooperation would be robust against unforeseen difficulties and would provide the greatest likelihood of success.

A U.S.-USSR joint program would double the number of martian sites accessible with a fixed, level of expenditure on each side. Exploration and sampling by robotic rovers among the several individual landing sites would greatly increase the surface area of Mars that could be explored and the quality of global network studies that could be undertaken. While the same objectives could also be achieved in the context of a single national program, such a unilateral approach would require a much larger commitment of resources. In a cooperative joint program of the kind recommended here, U.S. scientists would play a leading role in defining the scientific objectives, and U.S. scientists and engineers would be critical in the formulation and evaluation of scientific objectives, and in determining the nature of systems and instrumentation, as well their development and deployment. In the alternative event that they merely participate in missions conducted by another nation, U.S. scientists could not expect to have a substantial role, either in the scientific return or in the formulation and development of associated exploration systems.

All of these considerations have led the committee to the conclusion that a program of cooperative Mars exploration with joint leadership by the United States and the USSR, and with significant contributions, yet to be defined, from the world scientific community, including the European nations and possibly Japan and Canada, is by far the preferred approach. *The committee considers that the best approach to initiating cooperative Mars exploration with the USSR would be a highly coordinated exploration program of independently conducted missions that strikes a balance between the two extremes of very close cooperation involving split responsibilities and joint technical operations, and independently conducted, nearly noninteracting, parallel programs.* Concurrent but independent missions will not yield, in comparable measure, the above benefits. The committee considers that the other extreme of fully joint missions, involving major systems hardware, software, and management interfaces, is too risky an undertaking, at this time, to be justified on the basis of scientific and technical considerations alone. An evolutionary program of several missions is recommended, one that starts with an easily implemented but serious level of joint planning, coordination, and scientific cooperation, followed in the future by subsequent missions with substantially greater levels of coordination and possibly leading, ultimately, to missions that involve mission coordination with substantial hardware and software system interfaces and divided responsibilities.

Such a program could effectively be carried out jointly with the Soviet Union. Coordination should be implemented at the inception and at all levels of program and mission planning. This should include discussions and agreement about science objectives, sites for sample collection, approaches to and coordination of in situ investigations, sample collection strategies and techniques, and mission schedules.

The recommended framework for cooperation calls for exchange of scientific investigators on the various teams, specific coordination of investigations (in real time and otherwise) where useful and appropriate, exchange of data and samples, and jointly conducted data analysis. Ail of these elements of cooperation could be implemented now without undue concern about technology transfer or the burdens associated with interfacing and systems integration across international boundaries. Moreover, this framework provides considerable latitude for increasing the intimacy of cooperation in staged degrees; from the beginning, it allows modular scientific instrument packages from one nation to be flown on the spacecraft or Mars surface vehicles built and operated by the other nation.

In summary*, the committee recommends that intensive Mars exploration be begun in an international program coordinated with the Soviet Union.* Longer-term evolution of joint activities with the USSR, based on accumulated experience and success along with the lines of communication and working relationships that would be created, may lead to a more intensively cooperative and mutually dependent program with joint operations.

To implement Mars exploration and sample return, the United States should develop the capability to undertake several of these excursions independent of the performance of the USSR. *Within the context of the recommended cooperative intemational program, the committee recommends that the actual design of spacecraft hardware and conduct of early missions be carried out independently and in parallel by the two nations.* The committee further recommends that the United States and the USSR cooperate to identify the scientific objectives of their programs and to coordinate mission planning in detail to optimize the scientific return of the missions. The commitment to cooperation in such a program should be announced jointly by the United States and the USSR to make it clear that the two nations are major collaborators. *The committee recommends that nonmission-critical hardware, such as individual scientific experiments, be considered for inclusion on the spacecraft of the other nation when there is a distinct scientific or performance advantage.* The evolution of these working relationships may grow to a point that more complex interdependent missions can be considered in the future.

The committee recognizes the danger, inherent in this recommended approach, that the intended cooperation could deteriorate into a race for Mars. However, the recommendation specifically calls for a program in which the schedule is planned and paced in a manner agreed to by both sides. In such a context, the deleterious aspects of a "race," which might otherwise arise, should be well controlled. At the same time, the committee recognizes that some elements of competition are beneficial in science and in technology development and are inevitable in any such programs, cooperative or not. With a coordinated schedule and targets of exploration agreed upon in advance and by mutual consent, the competitive elements of Mars exploration could be confined to those areas in which they would indeed be beneficial the enhancement of the science as well as the related and required technologies.

Altogether, the recommended approach would allow a rapid start on international cooperation for Mars sample return, would yield substantial economies if the program were to achieve the recommended scientific objectives for Mars investigations, could be implemented now without undue concern for technology transfer or burdens associated with interfacing and systems integration across unfamiliar international boundaries, and would allow a graceful path to increasingly close levels of cooperation as experience was gained and as the international situation might permit and make desirable. This approach would be resistant to failure resulting from unforeseen changes in the political relationship.

PARTICIPATION OF OTHER NATIONS

The United States has a long record of scientific and technical cooperation, as well as social ties and economic interchanges, with many Western nations. As a result, there exist well-established and effective lines of communication, as well as mutual familiarity with programs, practices, and institutions. With varying levels of participation, European scientists, engineers, industries, and space agencies lave played important roles in numerous joint projects with the United States. Because of this tradition, it is often desirable to engage in high levels of lscientific and technical cooperation that enrich programs of the United States and the USSR. The present committee considers the general modalities of close technical cooperation between the United States and European nations that were recommended in the U.S. NAS-ESF joint working group report8 to be equally applicable in the context of a U.S.-USSR cooperative program as recommended in this report and in the context of an independent U.S. program.

The committee recommends that the United States encourage close cooperation with its more traditional scientific collaborators following the mechanisms that are already established. The U.S. program should make use of the knowledge of these collaborators in determining scientific mission objectives and in contributing to mission design. *The committee recommends that this cooperation also allow the traditional collaborators to provide mission-critical subsystems as well as scientific packages when there is a distinct benefit to the program.* Such a substantial commitment among nations may require an improved mechanism for ensuring the needed long-term commitments to approved missions or programs.

SAMPLE RETURN AND SUBSEQUENT SCIENTIFIC ANALYSIS

A principal objective of the next phase of Mars exploration is to select, gather, and return to Earth for analysis a scientifically representative sample of martian material. Because of the nature of the scientific questions, steps will be required to protect the integrity of the material so that important evidence is preserved. Inasmuch as the surface of Mars is relatively cold, questions about volatile constituents of the material, as well as about chemical states that would be altered by exposure to high temperatures, will be of high scientific importance. Similarly, answering questions pertaining to the past and present biological potential of martian material will require that stringent steps be taken to protect martian samples from alteration during collection, during the return flight (including such steps as cryogenic storage), and during their examination on Earth. Avoiding such alteration means that samples cannot be subjected to heat or chemical sterilization. Protocols governing the introduction of extraplanetary materials, as a result of purposeful space missions, are the subjects of international agreements. In preparation for eventual Mars sample return, it will be necessary to review the relevant protocols and practices in order to ensure the preservation of the scientific value of returned samples.

A major component of the scientific program associated with any space exploration project involves the continuing analysis, experimentation, and development of theory that continues after the missions. The returned martian samples will be of utmost scientific importance and will have immense prestige associated with them. *The control, care, and distribution of these materials will be under the jurisdiction of the nation returning the samples, but the committee recommends that there be a commitment to a joint scientific research program with the USSR that will provide these materials to qualified scientists throughout the world. The interchange of scientific information and close collaboration on all aspects of the science derived from these missions should be intrinsic and continuing components of the program, from its inception through the advanced stages of scientific analysis.*

International Cooperation for Mars Exploration and Sample Return

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