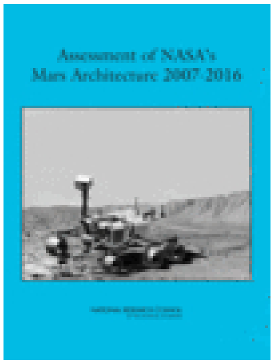
Assessment of NASA's Mars Architecture 2007-2016



Committee to Review the Next Decade Mars Architecture, National Research Council

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Assessment of NASA's Mars Architecture 2007-2016

Committee to Review the Next Decade Mars Architecture
Space Studies Board
Division on Engineering and Physical Sciences

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Cover: An artist's impression of NASA's next-generation rover, the Mars Science Laboratory. Illustration courtesy of NASA/Jet Propulsion Laboratory.

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Preface

In a letter sent to Space Studies Board (SSB) Chair Lennard Fisk on December 29, 2005, Mary Cleave, NASA's Associate Administrator for the Science Mission Directorate (SMD), explained that new scientific results from ongoing Mars missions, together with changes in funding levels for the Mars Exploration Program, have compelled the SMD to revisit the program's architecture and the sequence of missions planned for launch to Mars after 2010. As a result, NASA requested that the SSB review and evaluate the new architecture in a time frame to support NASA approval of the Mars Exploration Program's revised architecture in mid-summer of 2006. In response to this request, the ad hoc Committee to Review the Next Decade Mars Architecture was established and met at the National Academies' Keck Center in Washington, D.C., on March 29-31, 2006. The committee's deliberations and discussions relating to the conclusions and recommendations contained in this report were initiated at the Washington meeting and continued in a conference call held on April 6. During the course of the Washington meeting the members of the committee consulted related reports issued by the SSB and other National Research Council (NRC) committees[1] and heard relevant presentations. A draft report was completed during the first week in May and sent to external reviewers for commentary. A new draft responding to the reviewers' comments was completed in early June, and the report was approved for release on June 16. Edited copies of the report, formatted as a letter, were sent to NASA on June 30. This, the final version of the report, supersedes all previous versions.

The work of the committee was made easier thanks to the important help, advice, and comments provided by numerous individuals from a variety of public and private organizations. These include the following: J. Douglas McCuistion (NASA, Science Mission Directorate), Daniel McCleese (NASA, Jet Propulsion Laboratory), Noel Hinners (Lockheed Martin Astronautics, retired), W. Bruce Banerdt (NASA, Jet Propulsion Laboratory), Michael Meyer (NASA, Science Mission Directorate), and Raymond Arvidson (Washington University).

[1]National Research Council reports consulted included *Preventing the Forward Contamination of Mars* (2005), *Science in NASA's Vision for Space Exploration* (2005), *Assessment of Mars Science and Mission Priorities* (2003), *New Frontiers in the Solar System* (2003), *Signs of Life* (2002), *The Quarantine and Certification of Martian Samples* (2002), "Assessment of NASA's Mars Exploration Architecture" (1998), *Mars Sample Return: Issues and Recommendations* (1997), *Review of NASA's Planned Mars Program* (1996), "On NASA Mars Sample-Return Mission Options" (1996), and *An Integrated Strategy for the Planetary Sciences: 1995-2010* (1994). These reports were published by the National Academy Press (as of mid-2002, The National Academies Press), Washington, D.C.

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

The committee wishes to thank the following individuals for their participation in the review of this report: Martha S. Gilmore, Wesleyan University; Donald M. Hunten, University of Arizona; Harry Y. McSween, University of Tennessee; Dawn Y. Sumner, University of California, Davis; G.J. Wasserburg, California Institute of Technology; A. Thomas Young, Lockheed Martin Corporation (retired); and Maria T. Zuber, Massachusetts Institute of Technology.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Richard M. Goody, Harvard University (professor emeritus). Appointed by the NRC, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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Executive Summary

This assessment by the ad hoc Committee to Review the Next Decade Mars Architecture was conducted at the request of Dr. Mary Cleave, NASA's Associate Administrator for the Science Mission Directorate, who asked the National Research Council (NRC) to address the following three questions:

1. Is the Mars architecture reflective of the strategies, priorities, and guidelines put forward by the National Research Council's solar system exploration decadal survey and related science strategies and NASA plans?
2. Does the revised Mars architecture address the goals of NASA's Mars Exploration Program and optimize the science return, given the current fiscal posture of the program?
3. Does the Mars architecture represent a reasonably balanced mission portfolio?

It is important to note that the original order of the questions posed by Dr. Cleave was 2, 3, and 1. That is, the one that now appears first was originally listed as last. The committee has taken the liberty of reordering the questions because it is strongly of the opinion that logic dictates that it start its assessment of the Mars architecture by first addressing the architecture's scientific foundations.

Following presentations, discussions, and deliberations, the committee developed the following findings and offers specific recommendations relating to each:

1. *Is the Mars architecture reflective of the strategies, priorities, and guidelines put forward by the NRC's solar system exploration decadal survey and related science strategies and NASA plans?* **The committee finds that the proposed Mars architecture addresses some of the strategies, priorities, and guidelines promoted by the solar system exploration (SSE) decadal survey and the Mars Exploration Program Analysis Group (MEPAG) and is basically consistent with NASA's plans as exemplified by the agency's 2006 strategic plan[1] and the Vision for Space Exploration.[2] However, the absence of a sample return mission and a geophysical/meteorological network mission runs counter to the recommendations of the SSE decadal survey and significantly reduces the architecture's scientific impact. Other topics of concern include the lack of well-defined mission parameters and scientific objectives for the Mars Science and Telecommunications Orbiter, Astrobiology Field Laboratory, and Mid Rover missions; issues relating to the phasing and responsiveness**

of these missions to the results obtained from past missions; and the incompletely articulated links between these missions and the priorities enunciated by the SSE decadal survey and MEPAG.

The committee offers the following recommendations to NASA:

- ***Recommendation:*** **Include the Mars Long-Lived Lander Network in the mix of options for the 2016 launch opportunity.**
- ***Recommendation:*** **Consider delaying the launch of the Astrobiology Field Laboratory until 2018 to permit an informed decision of its merits and the selection of an appropriate instrument complement in the context of a mature consideration of the results from the Mars Science Laboratory and other prior missions.**
- ***Recommendation:*** **Establish science and technology definition teams for the Astrobiology Field Laboratory, the Mars Science and Telecommunications Orbiter, the Mid Rovers, and the Mars Long-Lived Lander Network as soon as possible to optimize science and mission design in concert with each other. (This model has been employed successfully by the heliospheric community.)**
- ***Recommendation:*** **Devise a strategy to implement the Mars Sample Return mission, and ensure that a program is started at the earliest possible opportunity to develop the technology necessary to enable this mission.**

2. *Does the revised Mars architecture address the goals of NASA's Mars Exploration Program and optimize the science return, given the current fiscal posture of the program?* **The committee finds that it cannot definitively say whether or not the revised Mars architecture addresses the goals of NASA's Mars Exploration Program because the architecture lacks sufficient detail with respect to the science and the cost to allow a complete evaluation. The various mission options are, as stated above, incompletely defined, and the strategic approach to, and the selection criteria to distinguish among, various mission options are lacking. The presence of Mars Scout missions in the architecture is welcomed because they help to optimize the science return and provide balance. Nevertheless, the Mars architecture as a whole is not optimized, because the importance of foundational strategic elements—for example, research and analysis programs and technology development—is not articulated.**

In response to this finding, the committee offers the following recommendations to NASA:

- ***Recommendation:*** **Develop and articulate criteria for distinguishing between the three options for missions to launch in 2016. Similarly, define a strategy that addresses the short lead time between science results obtained from the Mars Science Laboratory and selection of the mission to fly in 2016.**
- ***Recommendation:*** **Clarify how trade-offs involving mission costs versus science were made for the various launch opportunities to justify the rationale behind the proposed sequence of specific missions and the exclusion of others.**
- ***Recommendation:*** **Maintain the Mars Scouts as entities distinct from the core missions of the Mars Exploration Program. Scout missions should not be restricted by the planning for core missions, and the core missions should not depend on selecting particular types of Scout missions.**
- ***Recommendation:*** **Immediately initiate appropriate technology development activities to support all of the missions considered for the period 2013-2016 and to support the Mars Sample Return mission as soon as possible thereafter.**
- ***Recommendation:*** **Ensure a vigorous research and analysis (R&A) program to maintain the scientific and technical infrastructure and expertise necessary to implement the Mars architecture, and encourage collaboration on international missions.**

3. *Does the Mars architecture represent a reasonably balanced mission portfolio?* **The committee finds that in the context of the basic types of missions, the Mars architecture is a reasonably well balanced one: both landed and orbital missions are included in an appropriate mix, given the current state of Mars exploration.**

To the extent that the specific science objectives of the proposed missions are defined, one of the three crosscutting themes for the exploration of Mars identified in the SSE decadal survey is largely neglected, as are very high priority topics related to understanding near-surface and boundary-layer atmospheric sciences, and so, in this respect, balance is sorely lacking.

To optimize efforts to implement a balanced portfolio of missions, the committee offers the following recommendations to NASA:

- ***Recommendation:*** **Include the Mars Long-Lived Lander Network in the mix of options for the 2016 launch opportunity.**
- ***Recommendation:*** **If the Mars Long-Lived Lander Network cannot be implemented in the period under consideration, provide for an effort to make some of the highest-priority measurements on the landed missions that are included in the proposed Mars architecture.**
- ***Recommendation:*** **Ensure that the primary role of the Mars Science and Telecommunications Orbiter is to address science questions, and not simply to serve as a telecommunications relay. This distinction is particularly important with respect to the required orbital parameters that are adopted.**

NOTES

1. National Aeronautics and Space Administration (NASA), *2006 Strategic Plan*, NP-2006-02-423-HQ, NASA, Washington, D.C., 2004. Available at <www.nasa.gov/pdf/142302main_2006_NASA_Strategic_Plan.pdf>.
2. National Aeronautics and Space Administration (NASA), *The Vision for Space Exploration*, NP-2004-01-334-HQ, NASA, Washington, D.C., 2004. Available at <www.nasa.gov/pdf/55583main_vision_space_exploration.pdf>.

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Introduction

SCIENTIFIC AND PROGRAMMATIC BACKGROUND

The United States and the former Soviet Union have been sending spacecraft to Mars since the beginning of the space age.[1] Indeed, as early as 1966, the exploration of Mars was highlighted as a priority target for NASA spacecraft.[2] After several unsuccessful prior attempts, the Soviet Union achieved partial success when its Mars 1 spacecraft made a distant flyby of the Red Planet in 1963. A NASA spacecraft, Mariner 4, made the first successful close flyby of Mars in 1965 and returned images of the planet's cratered surface. Numerous additional spacecraft were dispatched from both sides of the Cold War divide during the remainder of the 1960s and early 1970s. Although there were many failures on both sides, there were some notable firsts, included the first attempted landing (unsuccessful) by Mars 2 in 1971 and the first successful Mars orbiter, NASA's Mariner 9, also in 1971. The culmination of this first era of Mars exploration was the successful landing of NASA's Viking 1 and 2 on the martian surface in 1976. The twin landers, supported by twin orbiters, operated successfully for many years. Although the primary experiments on the landers were designed to search for evidence of life—a task that was unsuccessful—additional, non-biological experiments did return a treasure trove of scientific data. Nevertheless, Viking was widely regarded as a programmatic failure because the life detection experiments did not return evidence of life on Mars. The lack of clear positive results from the life detection experiments undercut political support for additional Mars missions in the United States until the launch of NASA's Mars Observer in 1992. Perhaps the key lesson learned from the Viking experience was that the search for life on Mars should be undertaken only in the context of a comprehensive understanding of the origin and evolution of the martian environment. In the absence of a clear understanding of key parameters of the martian environment—e.g., the chemistry of the martian regolith—the design of biological experiments and the interpretation of the results from such experiments will be fraught with difficulties.

The failure of Mars Observer shortly before entering orbit about the Red Planet in 1993 led to a fundamental revision of NASA's Mars exploration strategy. Rather than relying on large spacecraft with comprehensive, multidisciplinary payloads as was the case with Mars Observer, future missions would embody the faster-cheaper-better design philosophy. That is, missions would be smaller, would be more focused on a narrow set of scientific goals, and would be launched at every possible Mars launch opportunity. Mars Global Surveyor and Mars Pathfinder, both launched in 1996, were the first missions to embody this new approach.[3] The programmatic and scientific success of both missions—combined with the political impetus fueled by claims of evidence of past life in the martian meteorite, ALH 84001—prompted the federal government to devote greater resources to NASA's Mars Exploration Program.[4]

The failure in 1999 of both of NASA's next two Mars missions—Mars Polar Lander and Mars Climate Orbiter—led to major revisions in the Mars Exploration Program and to the abandonment of many aspects of the faster-cheaper-better philosophy.[5] Despite the two failures, scientific interest in Mars did not wane; nor did political and financial support for a robust program of Mars Exploration. The lander mission planned for launch in 2001 was canceled, but the 2001 orbiter mission, Mars Odyssey, proceeded on schedule and has, subsequently, provided much valuable scientific data concerning Mars's global geochemistry.

Interest in Mars exploration is not confined to NASA. In 1998, Japan's Institute for Space and Astronautical Science launched Nozomi, a small orbiter designed to focus on studies of Mars's upper atmosphere and interactions with the solar wind. Unfortunately, this spacecraft suffered multiple failures and was unable to enter orbit around Mars. In 2003, the European Space Agency launched Mars Express and NASA launched the twin Mars Exploration Rovers. Finally, in August 2005 NASA launched the Mars Reconnaissance Orbiter, and this spacecraft successfully entered orbit around Mars in March 2006. As a result of this unprecedented level of activity, there are currently six operating spacecraft on or in orbit about Mars.

The resilience of the Mars Exploration Rovers, Spirit and Opportunity, and the wealth of data that they and their companion spacecraft have gathered on Mars, are opening a new chapter in understanding of the Red Planet. Discoveries of stratigraphic layers, evaporite deposits, and mineral forms show clearly that Mars experienced a somewhat Earth-like warmer and wetter era.[6,7] Questions remain as to how this era came to be and how Mars changed to its current cold and dry climate. Another significant set of results from Mars concerns the putative spectroscopic detection of methane in the planet's atmosphere by ground-based telescopes[8,9] and the Mars Express spacecraft.[10] Although the result obtained from Mars Express is still somewhat controversial, all three sets of observations indicate methane at concentrations of about 10 parts per billion. This is significant in that methane is unstable in the martian atmosphere and would disappear in ~300 years if not replenished. Although the origin of the methane has not yet been determined, possible sources include volcanic activity, chemical reactions between water and iron-bearing minerals in a hydrothermal system, and biological activity.[11]

These and other recent advances are not the only factors influencing NASA's Mars Exploration Program. Other factors include the following:

- The development of a highly effective, community-based group, the Mars Exploration Program Analysis Group (MEPAG), which devised a comprehensive series of Mars exploration goals and priorities and has drafted topical reports on specific Mars exploration opportunities;[12]
- The publication in 2003 of the NRC's first solar system exploration (SSE) decadal survey report, *New Frontiers in the Solar System: An Integrated Exploration Strategy*,[13] which places the exploration of Mars in the context of other SSE activities and also provides specific recommendations and priorities for a variety of Mars exploration activities;
- The enunciation on January 14, 2004, of the Vision for Space Exploration, President Bush's overarching plan for "a sustained and affordable human and robotic program to explore the solar system and beyond";[14] and
- Changes in the Mars Exploration Program's budgetary expectations for fiscal years 2006 and 2007, which resulted in various programmatic adjustments, including the cancellation of the planned 2009 launch of the Mars Telecommunications Orbiter, the loss of several Mars Scout missions in the post-2011 period, the termination of a series of robotic human-precursor missions, and the deletion of a variety of technology-development activities.[15]

These factors and, in particular, the last, compelled NASA's Science Mission Directorate to revisit the sequence of missions the agency plans to launch to Mars in the period 2007-2016. After several months of study, consideration and incorporation of the guidance from NRC studies and the Vision for Space Exploration, and community consultations via individual inputs and a MEPAG-sponsored working group, the Jet Propulsion Laboratory's Mars Advanced Planning Group developed a revised program architecture for the coming decade of Mars robotic exploration. This architecture is embodied in the report *Mars Exploration Strategy 2007-2016*.[16]

THE MARS EXPLORATION ARCHITECTURE 2007-2016

NASA's Mars Exploration Program seeks to understand whether Mars was, is, or can be an abode of life. The key to understanding the past, present, or future potential for life on Mars can be found in the overarching goals for Mars exploration: determine if life ever arose on Mars, characterize the climate and geology of Mars, and prepare for human exploration of Mars.[17]

The Mars exploration architecture proposed by NASA envisages the launch of a mission to Mars at every possible launch opportunity, i.e., every 26 months. The missions considered for the period 2007-2016 are as follows:

- 2007, Phoenix (the first competitively selected Mars Scout);
- 2009, Mars Science Laboratory;
- 2011, Mars Scout (the second competitive selection for flight);
- 2013, Mars Science and Telecommunications Orbiter; and
- 2016, Astrobiology Field Laboratory or two Mid Rovers.

Phoenix

The Phoenix mission, scheduled for launch in August 2007, is the first of NASA's principal-investigator (PI)-led, competitively selected Mars Scout missions. When Phoenix lands on Mars in May 2008, it will begin a program of investigations specifically designed to measure volatiles (especially water) and complex organic molecules in the arctic plains of Mars, where the Mars Odyssey orbiter has discovered evidence suggesting ice-rich soil very near the surface. Its science objectives are to study the history of water in all its phases, to search for evidence of a habitable zone in the near-surface regolith, and to assess the biological potential of the ice-soil boundary.

Mars Science Laboratory

The Mars Science Laboratory (MSL) is an advanced rover mission designed to follow the highly successful Mars Exploration Rovers, Spirit and Opportunity. The primary goal of the mission is to assess Mars's potential as a past or present abode of life, i.e., to determine whether Mars ever was, or is still today, an environment able to support microbial life. The mission's specific scientific objectives are as follows:

- Determine the nature and inventory of organic carbon compounds;
- Inventory the chemical building blocks of life (i.e., carbon, hydrogen, nitrogen, oxygen, phosphorus, and sulfur);
- Identify features that may represent the effects of biological processes;
- Investigate the chemical, isotopic, and mineralogical composition of the martian surface and near-surface geological materials;
- Interpret the processes that have formed and modified rocks and regolith;
- Assess long-timescale (i.e., 4-billion-year) atmospheric evolution processes;
- Determine the present state, distribution, and cycling of water and carbon dioxide; and
- Characterize the broad spectrum of surface radiation, including galactic cosmic radiation, solar proton events, and secondary neutrons.

The Mars Science Laboratory mission was not well defined at the time the SSE decadal survey was drafted. Nevertheless, its importance to addressing key Mars science goals was recognized, and this mission was determined to be the highest-priority medium-cost Mars mission for the decade 2003-2013.[18] Since then the scope and cost of the mission have grown significantly.

The combination of MSL's highly capable science payload, its long expected lifetime, and its use of as-yet untested entry, descent, and landing systems has led some observers to suggest that it would be prudent to send two. Indeed, NASA's 2005 *Roadmap for the Robotic and Human Exploration of Mars* recommends that two MSL spacecraft should be launched "to ensure mission success and maximize the science return."[19] Such an approach might be an appropriate risk-reduction strategy. However, its implementation at such a late stage in the development of a large and complex mission seems ill advised, irrespective of its financial implications for the rest of the Mars program. The committee notes that a recent Space Studies Board review—focusing "on the scientific balance implications for the overall program and the capacity of the program to maximize scientific return"—found no scientific justification in the 2005 Mars Roadmap for two MSLs.[20]

Mars Scout 2011

NASA proposes to launch the second of the PI-led, competitively selected Mars Scout missions no later than January 2012. Given the programmatic scope of the Scout missions, the nature, goals, and capabilities of this mission are currently unknown. NASA released an announcement of opportunity for this mission in early May 2006. The importance of Mars Scout missions rests in their ability to address high-priority science goals related to unexpected discoveries and in the opportunity they provide for maintaining program balance. These factors led the SSE decadal survey to rank the Mars Scout program as the highest-priority activity in the small Mars mission category.

Mars Science and Telecommunications Orbiter

The Mars Science and Telecommunications Orbiter (MSTO) is envisaged as being comparable in size, scope, and cost with the Mars Reconnaissance Orbiter and capable of addressing a broad range of scientific objectives associated with the study of Mars's atmosphere and space-plasma environment. Its scientific goals and instrument complement are only partially defined at the moment. Science goals endorsed in the recently completed study by MEPAG's Mars Science and Telecommunications Orbiter Science Analysis Group include the following:[21]

- Determine the interaction of the solar wind with Mars;
- Determine diurnal and seasonal variations of Mars's upper atmosphere and ionosphere;
- Determine the influence of the crustal magnetic field on ionospheric processes;
- Measure thermal and non-thermal escape rates of atmospheric constituents and estimate the evolution of the martian atmosphere;
- Measure composition and winds in the middle atmosphere; and
- Address in detail the issue of methane in the atmosphere.

As currently conceived, this mission will also have a secondary role of serving as a telecommunications relay to enhance the data return from surface missions such as MSL (if it is still operating) and/or the Astrobiology Field Laboratory (AFL) or the Mid Rovers. The dual science and mission-support role of MSTO presents issues concerning the selection of appropriate orbits. Those mission goals related to studies of the martian thermosphere, ionosphere, and solar wind interactions suggest an orbit that dips into the atmosphere to altitudes as low as 130 km. On the other hand, the mission goals that seek to delineate the dynamics of the neutral atmosphere would benefit from a 400-km to 500-km circular orbit. The mission's role as a telecommunications orbiter also suggests a circular orbit. The just-completed MEPAG study of MSTO presents a plan for orbit changes during the course of the mission, which does represent a reasonable compromise among the different requirements. A likely scenario would include an initial 130-km-by-4000-km orbit followed by a circular orbit near 400 km.

Although this mission concept postdates the publication of the SSE decadal survey, its aeronomy goals are similar to the survey's second-highest-priority small Mars mission, the Mars Upper Atmosphere Orbiter.

Astrobiology Field Laboratory

The Astrobiology Field Laboratory mission is conceived as being a highly capable rover derived from the Mars Science Laboratory. Its principal goals are to assess the biological potential of sites, interpret the paleoclimate record, and search for biosignatures of ancient and modern life. It is generally recognized that the viability of the mission depends on results obtained by MSL in its search for organics. This mission concept postdates the publication of the SSE decadal survey.

Mid Rovers

The Mid Rovers are conceived as being more capable than the Mars Exploration Rovers but less complex, costly, and heavy than the Mars Science Laboratory. Their principal purpose is to serve as geological explorers, i.e., to evaluate the geological context of specific sites and search for organic compounds at targets identified by prior missions. As currently envisaged, NASA's goal is to fly two rovers for a cost approximately equal to that of the Mars Science Laboratory. The Mid Rovers would be equipped with a modest yet capable payload and be capable of landing in an error ellipse ≤ 50 km long. This mission concept postdates the publication of the SSE decadal survey. NASA's plan for flying two such missions at the same launch opportunity appears to be an appropriate strategy.

TOPICS CONSIDERED BY THE COMMITTEE

Given the short duration of this study, it was not possible for the committee to develop its conclusions and recommendations ab initio. Nor, given its composition and expertise, was it possible for the committee to speak definitively on topics other than those concerning scientific goals, priorities, and investigations. Given these caveats, the committee adopted an approach to addressing the three questions posed by NASA that relies heavily on the interpretation and reiteration of advice contained in past NRC reports and, in particular, *New Frontiers in the Solar System*, the SSE decadal survey. The committee's reliance on past advice is limited to the extent that this advice is still valid in the light of new discoveries. The SSE decadal survey was completed 4 years ago, and since then there have been significant advances in our understanding of Mars. Thus, the committee's first step was to determine whether or not the decadal survey's advice and recommendations concerning the exploration of Mars are still valid.

In summary, the committee's approach to answering the three questions posed by Dr. Cleave was to break them down, and to consider the subtopics listed under each question as follows:

- Question 1: Is the Mars architecture reflective of the strategies, priorities, and guidelines put forward by the NRC's SSE decadal survey and related science strategies and NASA plans?
  — The exploration of Mars in a solar system context
  — Major new discoveries since the SSE decadal survey report was issued
  — The Mars architecture and the SSE decadal survey's Mars exploration goals
  — The Mars architecture and related science strategies
  — The Mars architecture and other NASA plans
- Question 2: Does the revised Mars architecture address the goals of NASA's Mars Exploration Program and optimize the science return, given the current fiscal posture of the program?
  — The Mars architecture and the goals of NASA's Mars Exploration Program
  — Optimizing the science return
- Question 3: Does the Mars architecture represent a reasonably balanced mission portfolio?

Subsequent chapters address each of these topics in turn. Where appropriate, conclusions are drawn and recommendations are made.

NOTES

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14. See, for example, National Aeronautics and Space Administration (NASA), *The Vision for Space Exploration*, NP-2004-01-334-HQ, NASA, Washington, D.C., 2004.
15. J. Douglas McCuistion, Mars Exploration Program, NASA Headquarters, presentation to the committee, March 29, 2006.
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2

NRC Strategies, Priorities, and Guidelines for the Exploration of Mars

Is the Mars architecture reflective of the strategies, priorities, and guidelines put forward by the NRC's solar system exploration decadal survey and related science strategies and NASA plans?

THE EXPLORATION OF MARS IN A SOLAR SYSTEM CONTEXT

How does the Mars Exploration Program fit into the overall goals for solar system exploration as defined in the SSE decadal survey? The decadal survey envisions a very active and balanced Mars Exploration Program that would substantially contribute to an integrated understanding of the formation and evolution of the solar system. This is demonstrated by the fact that, although down-sized from what was considered just a year ago, the proposed architecture addresses key questions associated with all four of the crosscutting themes of the survey.

The crosscutting themes and key questions associated with them that are addressed by the Mars Exploration Program as outlined in the proposed architecture are described in the next four subsections.

The First Billion Years of Solar System History

This theme is concerned with the formative period that features the initial accretion and development of Earth and its sibling planets, including the emergence of life on our globe. This pivotal epoch in the solar system's history is only dimly glimpsed at present. Key SSE decadal survey questions associated with this theme that are addressed by exploring Mars include the following:

- What processes marked the initial stages of planet and satellite formation?
- How did the impactor flux decay during the solar system's youth, and in what way(s) did this decline influence the timing of life's emergence on Earth?

Volatiles and Organics: The Stuff of Life

This crosscutting theme addresses the reality that life as we understand it requires organic materials and volatiles, notably, liquid water. Key SSE decadal survey questions associated with this theme that are addressed by exploring Mars include the following:

- What is the history of volatile compounds across the solar system?
- What is the nature of organic material in the solar system, and how has this matter evolved?
- What global mechanisms affect the evolution of volatiles on planetary bodies?

The Origin and Evolution of Habitable Worlds

This crosscutting theme recognizes that our concept of the "habitable zone" has been overturned, and greatly broadened, by recent findings on Earth and elsewhere throughout our galaxy. Key SSE decadal survey questions associated with this theme that are addressed by exploring Mars include the following:

- What are the habitable zones for life in the solar system, and what planetary processes are responsible for generating and sustaining habitable worlds?
- Does (or did) life exist beyond Earth?
- Why did the terrestrial planets differ so dramatically in their evolutions?

Processes: How Planetary Systems Work

This crosscutting theme concerns the search for a deeper understanding of the fundamental mechanisms operating in the solar system today. A key SSE decadal survey question associated with this theme that is addressed by exploring Mars is the following:

- How do the processes that shape the contemporary character of planetary bodies operate and interact?

In response to the question, How does the Mars Exploration Program fit into the overall goals for the solar system as defined by the SSE decadal survey?, the committee is in agreement that because the exploration of Mars addresses all of the crosscutting themes and many of the key questions identified in the SSE decadal survey, it continues to be a significant priority in a balanced program for exploring the solar system.

MAJOR NEW DISCOVERIES SINCE THE SSE DECADAL SURVEY REPORT WAS ISSUED

What major new discoveries have occurred since the SSE decadal survey report was issued that might call into question the recommendations of that report? The solar system exploration decadal survey, *New Frontiers in the Solar System*, captured the state of Mars exploration in early 2002, and the recommendations of that study were based on that state of knowledge. A range of seminal observations have been made since that time, and these properly influence the view of this committee. These observations address two equally fundamental issues about the history and evolution of Mars.

- Evidence for the past presence of water; and
- Evidence of a diverse igneous history, possibly extending to the present.

Past Presence of Water

Key recent discoveries relating to the presence of water in the martian past include the following:

- Observations from Mars Odyssey for the presence of abundant near-surface hydrogen (possibly indicative of water ice) at mid- to high latitudes;[1]
- The inference, from Mars Global Surveyor observations of layered sedimentary rocks in craters, that large areas of the martian surface have periodically been buried and exhumed;[2]
- The positive identification of clay minerals in ancient terrains by Mars Express;[3]

- Observations of sedimentary rocks, including hydrated minerals, and fluvial structures at the Opportunity landing site on Meridiani Planum;[4-6] and
- Observations for aqueous alteration of igneous rocks at the Spirit landing site at Gusev Crater.[7,8]

These observations reinforce the strength of an integrated program of robotic exploration. Orbital reconnaissance observations of hematite by the Thermal Emission Spectrometer on Mars Global Surveyor, and of near-surface hydrogen by the Gamma-Ray Spectrometer on Mars Odyssey, led to the in situ examination of Meridiani Planum by the Mars Exploration Rover, Opportunity, which revealed evidence for hydrated minerals and fluvial structures. The combination of the in situ results and orbital data allows much broader inferences to be made regarding the extent of a regional-scale hydrologic system.

These discoveries also help address one of the pivotal questions asked by the SSE decadal survey—How hospitable was Mars to life? The past presence of liquid water on Mars has now been demonstrated, triggering NASA to follow a pathway of searching for evidence of past life. The next step in the incremental investigation of Mars's potential as a past or present abode of life might be to ask: Where, when, and for how long did water exist? The answer to these questions may require new approaches, instruments, and types of missions.

Igneous Diversity

Mars exhibits evidence of a diverse igneous history, possibly extending to the present. Key recent findings include the following:

- Detection (putative) of significant and spatially variable amounts of methane that may indicate igneous or biological activity;[9,10]
- Observations of lava flow fields with low crater densities that could potentially indicate that volcanism has occurred within the past few million years;[11] and
- Evidence for localized evolved igneous compositions ranging from alkalic basalts at the Spirit landing site to quartz-bearing and dacitic compositions on regional scales observed from orbit.[12-15]

As is discussed in a subsequent section, the SSE decadal survey highlighted the observation of magnetic anomalies in the southern hemisphere of Mars. The survey also explicitly noted the importance of internal heat in determining the stability field of liquid water and the magnetic field in shielding the surface from harmful radiation as keys to the evolution of life. Coupled with these more recent observations, exploration of the interior structure of Mars seems of paramount importance to understanding its role in both the evolution of the planet and martian surface composition, and as a key to understanding the sources of energy for, and possible origin and evolution of, life.

In response to the question, What major new discoveries have occurred since the SSE decadal survey report was issued that might call into question the recommendations of that report?, the committee is in agreement that there have been no new developments that change the recommendations of the SSE decadal survey report; if anything, recent scientific discoveries reinforce the report's recommendations.

THE MARS ARCHITECTURE AND THE SSE DECADAL SURVEY'S MARS EXPLORATION GOALS

Is the Mars architecture reflective of the strategies, priorities, and guidelines put forward by the NRC's solar system exploration decadal survey? The SSE decadal survey recommended a Mars exploration program (Appendix A) addressing the following broad thematic goals:

- Mars as a potential abode of life;
- Water, atmosphere, and climate on Mars; and
- Structure and evolution of Mars.

Mars as a Potential Abode of Life

Key scientific issues identified in the SSE decadal survey relevant to the overarching theme of Mars as a potential abode of life include the following:

- *How hospitable was, and is, Mars to life?* Even though biological processes produce a range of biosignatures, most geological processes progressively destroy them. Thus, the recognition that organisms and their environment constitute a system, each producing an effect on the other, is key to the search for life on Mars. Therefore, all of the missions in the proposed architecture have the potential to provide insight regarding the question of whether Mars did or does host hospitable environments. Appropriately instrumented AFL or Mid Rover missions could, potentially, perform a comprehensive characterization of the geochemistry and mineralogy of the materials they analyze and provide significant insights regarding the biological potential of the environments they examine. The rover missions might also provide information relevant to assessing the possibility of locating biosignatures in the environments examined.
- *Did life ever exist there?* An appropriately instrumented AFL mission—i.e., one equipped with instruments capable of simultaneously providing information about past or present environments suitable for life and, also, microbial biosignatures—should make significant advances toward achieving this goal. To initiate the process of life detection requires the comprehensive geochemical characterization of samples analyzed over a range of spatial scales within the context of a geological setting. The strategy of following the MSL mission, which will provide an environmental model based on geological and some geochemical information, with an AFL that carries instruments designed to detect and characterize with high precision potential biosignatures should continue to be emphasized in the Mars mission architecture. MSTO could also provide clues to the evolution of the martian atmosphere, which will have affected the potential for Mars as an abode for past and present life.
- *Does life currently exist on Mars?* A confirmation of the existence of potential biogenic gases by MSTO or other means would be a significant advance in the search for extant life on Mars. Microbial environments on Earth's surface, in the shallow subsurface, and in the deep rock fracture habitat zone (to many kilometers) are known to produce distinguishable trace gases as by-products of their activities. Knowledge of the trace gas inventory of Mars, and of the location and residence time of anomalous concentrations of trace gases, could be invaluable in leading researchers to sites with high astrobiological potential.

The SSE decadal survey identified the following future steps as being of the greatest importance for advancing understanding of Mars as a potential abode of life:

1. *Sample return missions will ultimately be required to permit definitive tests in terrestrial laboratories for present and past life on Mars; robotic missions preceding the sample return missions will assist in locating the most fruitful sites to be sampled.* A Mars sample return mission is not included in the architecture. The precision and sophistication of in situ instruments are anticipated to improve, provided that the necessary research and technology-development funding is sustained. Nevertheless, the amount of information that can be extracted in terrestrial laboratories from samples returned from Mars will dwarf the science forthcoming from an in situ analysis on the planet. All the missions in the Mars architecture can contribute in one way or another to the selection of sites from which samples will ultimately be returned to Earth. However, none of the planned missions, either alone or in combination with others, will achieve the type of sustained analysis possible with a Mars sample return mission. The recent application of new technologies and techniques to samples of rocks returned from the Apollo missions underscores this point.
2. *A broad program of study of the Mars environment, present and past, is needed to understand the context in which life did or did not arise on that planet.* The full spectrum of Mars missions outlined in the architecture is responsive to the need to understand the past and present martian environment. Astrobiological investigations are best conducted in a systems framework. Thus, other, non-biological investigations will have a significant impact on astrobiological goals for the exploration of Mars. Overarching issues that, if addressed, could have a significant impact on astrobiological search strategies for Mars include the absolute chronology of the planet, the chemistry of

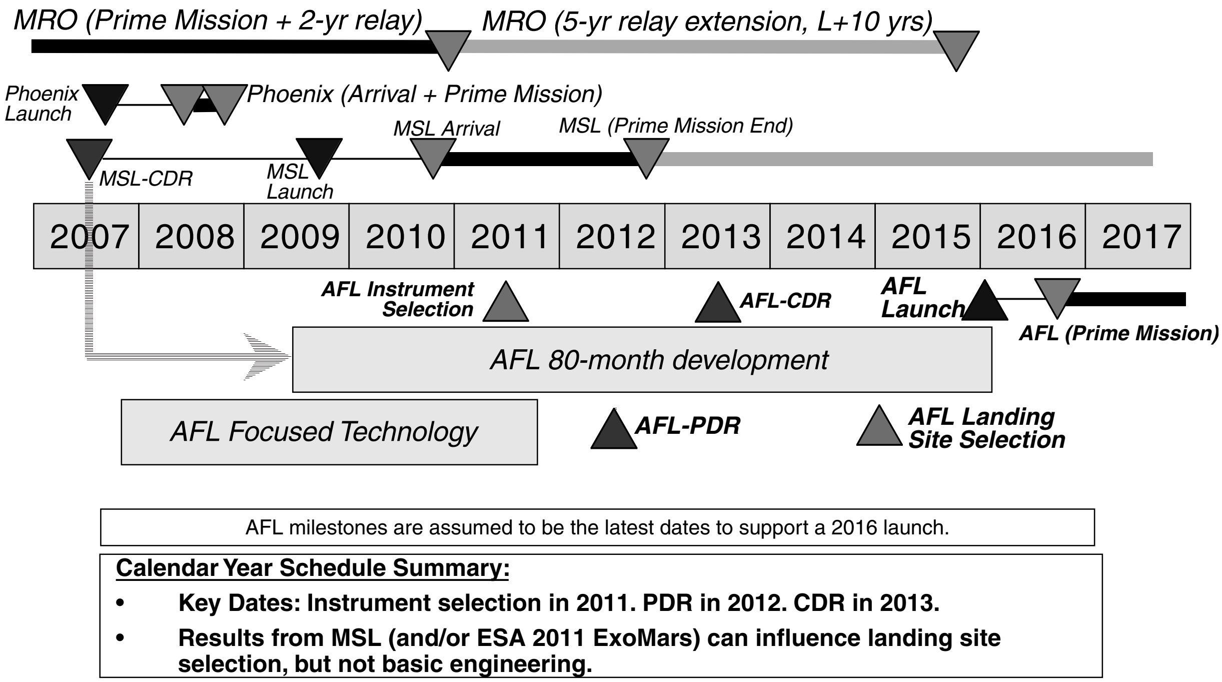

FIGURE 2.1 A notional timeline indicating the critical steps in the development of the Astrobiology Field Laboratory mission. The timeline indicates that if AFL is to be launched in 2016, a normal development schedule would imply that the instruments for this mission would have to be selected in 2011, just months after the landing of the Mars Science Laboratory. Thus, it is highly likely that those individuals proposing instruments will not be able to respond to any of the results from MSL. Courtesy of Luther Beegle, James F. Jordan, Gregory Wilson, and Michael Wilson, Jet Propulsion Laboratory. NOTE: AFL, Astrobiology Field Laboratory; CDR, critical design review; ESA, European Space Agency; L, launch; MRO, Mars Reconnaissance Orbiter; MSL, Mars Science Laboratory; and PDR, preliminary design review.

trace martian gases (potentially addressed by MSTO), and the geochemical or mineral traces of past environments that can guide the selection of landing sites (addressed by MSL, AFL, and Mid Rovers).

The proposed architecture will make important contributions to addressing the SSE decadal survey's theme, Mars as a potential abode of life. The architecture embodies a discovery-based strategy to search for potential environments on Mars suitable for life. That is, the results from ongoing missions—e.g., Mars Reconnaissance Orbiter (MRO)—and future missions such as Phoenix and Mars Science Laboratory will determine whether AFL or the Mid Rovers will be selected to fly in 2016. The relative timing of MSL and AFL is potentially problematic. The 6 years separating the launch of the two missions is barely sufficient for the findings from MSL to influence the scope of AFL. Indeed, consideration of the notional development timeline (Figure 2.1) suggests that AFL instruments would have to be selected just a few months after MSL arrives at Mars. In other words, those individuals involved in the selection of the instruments would have the benefit of the early results from MSL, but the instrument proposers would have to draft their proposals while MSL is en route to Mars.

Another issue of potential concern with AFL is that the likelihood of finding definitive biosignatures in situ with a single mission is low. Thus, the absence of any discoveries of potential biosignatures could severely impact future programmatic support of Mars missions in much the same way as did the negative results from the life detection experiments on the Viking landers in 1976.

Two high-priority missions identified by the SSE decadal survey, Mars Sample Return and Mars Long-Lived Lander Network, are not in the architecture. These missions are, however, relevant to issues relating to the search for life on Mars. A sample return mission would optimize researchers' ability to determine whether or not life exists or ever existed on Mars. A network mission would provide estimates of geothermal heat flow potential and fracturing, which could be significant in providing habitat assessment and locating sites of potential biogenic gas escape. Similarly, if the network stations include a trace-gas-analysis capability, then they can potentially contribute to understanding of whether or not there might be extant life on Mars.

Water, Atmosphere, and Climate on Mars

A second unifying theme for Mars exploration identified by the SSE decadal survey concerns Mars's water, atmosphere, and climate. Clearly, this theme is coupled to the life theme, in the context of both past and present conditions that could be suitable for life and the preservation of evidence of life.

The most important scientific investigations in this area as identified by the SSE decadal survey are as follows:

- *What are the sources, sinks, and reservoirs of volatiles on Mars?* Phoenix should contribute substantially to addressing this question, by directly searching for near-subsurface water ice (the presence of which has been inferred from orbital observations) at high northern latitudes. Dust is generally understood as being included in the category of volatiles for Mars, and Phoenix will also make valuable observations of the atmospheric dust using a lidar. The proposed MSTO mission will directly address the permanent sink of volatiles which loss to space represents, if it carries the full aeronomy instrument payload that is baselined. The mission is planned to have the capability of studying trace atmospheric gases, and thus it will be able to investigate the sources, sinks, and reservoirs of any volatiles that it is able to measure in the atmosphere. These could include methane, which would be of particularly great importance in relation to the life theme. The rover missions (MSL, AFL, and Mid Rovers) all have at least the potential to address the question above; the MSL meteorology experiment will definitely address it.
- *How does the atmosphere evolve over long time periods?* Phoenix will make a contribution to addressing this question, particularly via its search for subsurface ice. MSL could provide additional information on the presence of water in the past and will make meteorological measurements that will improve understanding of the current atmosphere and thus the ability to model the evolution of the atmosphere. The aeronomy component of MSTO would make a very strong contribution to answering this question, by greatly advancing understanding of current atmospheric escape processes. The AFL and Mid Rover missions could provide additional observations relating to the presence of water, as well as to the current atmosphere and climate.

Of somewhat lesser importance are questions relating to the following topics:

- *Is there an active water cycle on Mars?* This question is strongly tied to investigating the exchanges of water between surface and subsurface reservoirs and the atmosphere. Phoenix will make extremely important measurements, both above and below the surface, of relevance to this question. If the trace-gas component of the proposed MSTO mission provides measurements of atmospheric water, then this mission will also contribute to understanding this question. This mission should also be able to determine the rate of net loss of water from the current atmosphere. The meteorology package on the MSL mission will make measurements of atmospheric humidity at one site. The other proposed rover missions (AFL and Mid Rovers) could carry instruments to measure atmospheric and subsurface water, but these capabilities are not explicitly included in the discussion of the science objectives of these missions.
- *What are the dynamics of the middle and upper atmosphere of the planet?* The MSTO mission could provide a great amount of information relating to this question, if the right instruments are included. A direct wind-sensing instrument is crucial to investigating the dynamics of this region of the atmosphere.

- *What are the rates of atmospheric escape?* The MSTO mission would allow the current atmospheric escape rates to be determined, if it has the necessary instruments to make the key measurements in the exospheric region. None of the other currently proposed missions will address this question.

A final question, relating to building the foundation of knowledge of the solar system, is the following:

- *What is the three-dimensional distribution of water in the martian crust?* Phoenix should contribute very significantly to this study, by directly investigating the presence of near-subsurface ice in the north polar region. All planned landed missions could address this question, given the right instruments; MSL does not have any instruments that can address this question directly.

Important topics for future studies relating to Mars's water, atmosphere, and climate as identified by the SSE decadal survey are the following:

1. *The ground-level chemical and isotopic composition of the atmosphere, including humidity, should be tracked for at least a martian year at a network of lander stations.* A surface network mission is not, however, included in the Mars architecture.
2. *The distribution of water (in both solid and liquid form) in the crust, globally or at a wide variety of sites, should be established (e.g., by sounding radar).* A surface network mission is not included in the Mars architecture. Water sounding instruments could potentially be included on any landed mission, but they are not included in the selected payload for MSL and are not part of the science discussed for the AFL or Mid Rover missions (although the science for these is not currently well defined).
3. *The composition and dynamics of the middle and upper atmosphere and the rate of escape of molecules from the atmosphere should be measured.* Given a full complement of appropriate aeronomy instruments, the proposed MSTO mission could go a long way toward meeting this objective.

The proposed Mars architecture does a reasonably good job of addressing the key questions relating to the theme of water, atmosphere, and climate on Mars but not, necessarily, in the manner envisaged by the authors of the SSE decadal survey. The recommended decadal survey missions most relevant to this theme are the Mars Long-Lived Lander Network and the Mars Upper Atmosphere Orbiter. The former is not included in the architecture, and the latter may possibly be identified with the proposed MSTO mission (see MEPAG's recently released report on MSTO[16]). What is clear, however, is that an appropriately instrumented MSTO mission can, potentially, address many if not all of the highest-priority science questions relating to Mars's atmosphere, climate, and volatiles. The current Scout mission—Phoenix—will likely make important contributions, as will the rover missions.

Structure and Evolution of Mars

The SSE decadal survey concluded that the single most compelling question for Mars is the extent to which it was (or is) an abode of life. However, the decadal survey also recognized that Mars is a system and that questions concerning past or present martian life are strongly coupled to the evolution of the planet's atmosphere and interior. For instance, the existence of an early dynamo may have had profound implications both for the evolution of volatiles and for biological potential. Thus, one of the three key themes identified by the decadal survey was the structure and evolution of Mars.

The most important scientific questions related to the structure and evolution of Mars are as follows:

- *What rock types constitute the crust of Mars?* The rovers (MSL, AFL, and Mid Rovers) all have the potential to address this question. To expand knowledge of the rock types on Mars, careful site selection to visit the full diversity of terrains identified by global mapping will be needed.
- *What are the nature and origin of Mars's crustal magnetism?* High-resolution maps of the martian magnetic field can, potentially, be obtained by low-altitude measurements from MSTO. Such sampling is also needed, along

with simultaneous upper-atmosphere measurements, to establish and understand the link between crustal fields and solar wind/ionosphere interactions that affect escape rates. Instruments on rovers may be capable of identifying specific magnetized minerals.

Additional questions of importance are the following:

- *What is the degree of internal activity in Mars?* None of the missions in the current architecture addresses this issue. A network mission including seismometers would do so.
- *What is the size of the martian core, and is it partly or wholly liquid?* Again, a definitive answer to these questions requires a network of seismometers.
- *What was the origin and fate of the Mars dynamo?* It is unclear how this question might be answered in the absence of a comprehensive Mars sample return program, although both absolute chronology measurements and seismology (e.g., absence of a liquid core) could provide some important insights.
- *What is the absolute chronology of the planet?* Although the capacity to gauge in situ chronology, even with uncertainties on the order of ±500 million years, would be highly significant, the technical challenges of performing the necessary measurements remain formidable. A precise understanding of the timing of key events in martian history, including the duration of water at any single location, will require Mars sample return, likely with roving and, perhaps, caching capabilities.
- *How does the oxidation state of the Mars crust vary with depth?* The oxidation state of the upper meter or so of the crust of Mars is potentially accessible to rover technology; however, for depths of geological interest (kilometers), this question is unlikely to be answered in the near to mid term.

The SSE decadal survey also identified the following future steps as being of the greatest importance for advancing understanding of the structure and evolution of Mars:

1. *A long-lived network of seismic stations is needed on Mars for determining the structure, properties, and activity of its interior.* The current architecture does not satisfy this recommendation.
2. *Heat flow from Mars ultimately should be measured at a series of surface stations.* The current architecture does not satisfy this recommendation.
3. *The compositions and ages of crystalline rocks from a distribution of martian sites should be measured. This will best be done by studying returned samples, but the database can be expanded with in situ measurements made by landers.* The rover missions (MSL, AFL, Mid Rovers) can begin to meet this recommendation but, ultimately, a sample return mission is needed.
4. *A high-resolution magnetic map of Mars's southern highlands should be made.* None of the missions in the proposed architecture, which the possible exception of MSTO, is likely to address this recommendation.

The proposed Mars architecture does not, in general, do a good job of addressing the key questions regarding the structure and evolution of Mars. Information on crustal composition (and potentially magnetization) may be provided by the proposed rovers. However, the nature of the deep interior, its degree of activity, the state and evolution of the core, and the chronology of the crust are not addressed by any of the proposed missions. The architecture's ability to address these key scientific topics is hindered by the absence of two high-priority Mars missions identified by the SSE decadal survey, Mars Sample Return and the Mars Long-Lived Lander Network.

Summary

In response to the question, Is the Mars architecture reflective of the strategies, priorities, and guidelines put forward by the NRC's solar system exploration decadal survey?, the committee is in agreement that the proposed Mars architecture does a good job of addressing two of the SSE decadal survey themes relating to Mars—i.e., (1) Mars as an abode of life and (2) water, atmosphere, and climate on Mars—and a poor job of addressing the third theme, the structure and evolution of Mars. Of the five high-priority Mars missions mentioned in the decadal survey, two are explicitly included in the proposed architecture—i.e., Mars Science Laboratory and Mars Scout (goals defined as part of the competitive selection process)—and two are explicitly excluded from the proposed architecture—i.e., Mars Sample Return and the Mars Long-Lived Lander Network. The committee notes, in passing, that a Mars sample return mission has been a fundamental element of the Mars exploration strategy enunciated by the Space Studies Board for the last three decades.[17-22] It is likely that an appropriately instrumented MSTO will be able to address the goals of the fifth of the SSE decadal survey's missions, the Mars Upper Atmosphere Orbiter. The committee cannot be more specific at this time because much depends on the exact scope and instrument complement of missions such as MSTO, AFL, and the Mid Rovers. The committee recognizes that this lack of definition allows the Mars Exploration Program some flexibility to respond to future discoveries. Indeed, responsiveness to new scientific results and community input are major strengths of NASA's Mars Exploration Program. Nevertheless, flexibility must be tempered with programmatic realities. While some aspects of mission design can be left undecided until a particular spacecraft is on the launch pad—most notably, the selection of landing sites—others cannot. Given that it can take a decade for an instrument concept to be developed to the point at which it is ready for flight, basic mission parameters—power, mass, volume, data rate, orbital parameters, and instrument accommodation issues—need to be defined well in advance. For these reasons, the committee sees the lack of definition of what these missions are, what they will do, and how they will do it as a major deficiency in the Mars architecture. Deficiencies of this type have traditionally been resolved by the convening of science and technology definition teams. Such an action would provide sufficient detail concerning the relevant missions that further assessment and refining of the architecture could be contemplated and needed technology development could be identified. Finally, the absence of sample return and a geophysical/meteorological network mission significantly reduces the potential for achieving many of the SSE decadal survey's goals for the exploration of Mars.

THE MARS ARCHITECTURE AND RELATED SCIENCE STRATEGIES

Is the Mars architecture reflective of the strategies, priorities, and guidelines put forward by related science strategies, in particular, those issued by MEPAG? At periodic intervals over the last 5 years MEPAG has issued a comprehensive assessment of goals, investigations, objectives, and priorities for the exploration of Mars.[23] MEPAG's goals for the exploration of Mars are as follows:

- Determine if life ever arose on Mars;
- Understand the processes and history of climate on Mars;
- Determine the evolution of the surface and interior of Mars; and
- Prepare for human exploration.

Although the goals are not ranked, each is, however, broken down into a prioritized, hierarchical listing of objectives, investigations, and measurement (Appendix B). Consideration of how the Mars architecture addresses each of the first three MEPAG goals is found below. Discussion of how the architecture addresses issues relating to human exploration is postponed until the section below titled "The Mars Architecture and Other NASA Plans."

Life

Although MEPAG's four goals are coequal, the goal of determining whether life ever arose on Mars is often considered "first among equals." The proposed Mars architecture addresses the life goal by an ordered sequence of missions. This sequence begins with a search for organic materials using the Mars Science Laboratory, continues with measurement of trace gases (e.g., methane) by the Mars Science and Telecommunications Orbiter, and leads up to a decision as to what science payload the Astrobiology Field Laboratory should carry and whether or not it should fly in 2016. This general sequence of missions has the potential to make significant progress toward the life goal's highest-priority objective—i.e., assessing the possibility of extinct or extant life on Mars. However, the decision to fly AFL versus another mission in 2016 must be made early during MSL's prime mission. Therefore, as noted in the discussion of the SSE decadal survey's Mars priorities, the committee is worried that the necessary data and results may not be in hand to distinguish the relative merits of AFL versus other options for launch in 2016. It might prove better to delay AFL until the 2018 opportunity so that decisions on its merit relative to other possible missions and on the choice of appropriate instrumentation (e.g., for remote and direct access to the subsurface) can be informed by a mature consideration of the results from prior missions, particularly MSL.

Climate

The MSTO mission in 2013 is presumably focused on the highest-priority MEPAG objective with respect to the climate goal—i.e., characterization of Mars's atmosphere, present climate, and climate processes. Definition of the science to be accomplished with MSTO is currently incomplete, and so assessing how many MEPAG climate investigations this mission will address is difficult. A clear science justification for MSTO should be made and linked to investigations outlined in the MEPAG document. The committee notes that MEPAG's MSTO Science Analysis Group just issued a draft report discussing these linkages.[24] Finally, the committee points out that the inclusion of a network of meteorological stations, as a third alternative for the 2016 launch opportunity, would also provide a means of addressing MEPAG's climate goal.

Surface and Interior

Recent Mars missions (e.g., Odyssey, Mars Exploration Rovers, and, now, Mars Reconnaissance Orbiter) have focused strongly on the objective of determining the nature and evolution of the geological processes that have created and modified the martian crust and surface. As a result, considerable progress is being made toward investigations related to determining the nature and evolution of geological processes on Mars. Missions now in development (e.g., MSL and, possibly, AFL) will undoubtedly further understanding of these areas. Unfortunately, few missions or instruments geared toward gaining a better understanding of the interior of the planet have been flown, despite numerous studies by alternate groups stating the importance of so doing. The committee believes strongly that the possibility of making progress toward this MEPAG goal and its objective of characterizing the structure, composition, dynamics, and evolution of Mars's interior should be included in the proposed Mars architecture. An approach to achieving this is to include a geophysical network mission as an option for the 2016 launch opportunity.

Summary

In general, much of the proposed Mars architecture can be viewed as somewhat consistent with existing priorities and guidelines of the Mars science community as represented by MEPAG. However, although the stated focus of the architecture's proposed missions can be traced to MEPAG's current goals relating to the study of life, climate, and geology,[25] important details are lacking. This lack of detail introduces uncertainties as to whether or not MEPAG's prioritized objectives will be addressed in an integrated and comprehensive fashion. Hence the committee had difficulty in assessing this question.

Mars Scout missions are the wild card in the architecture, and it is difficult to predict how they might address one or multiple MEPAG goals and objectives. The committee agrees that Scout missions are extremely valuable and should continue, but there is a potential for overlap between proposed Scout missions and strategic (e.g., MSTO) missions during later launch opportunities. However, it is not possible to predict how a Scout proposal might be evaluated in this instance or how it might impact other missions in the Mars Exploration Program. Nevertheless, the committee supports the addition of funds to the Scout program that may enable a broader range of mission scenarios to be proposed that could better satisfy one or multiple MEPAG goals, objectives, and investigations.

Finally, a Mars sample return mission has the potential to yield samples uniquely capable of addressing all four MEPAG goals and multiple objectives. The committee agrees that issues of cost[26] and technical readiness imply that a sample return mission will fall beyond the horizon of the coming decade. Nevertheless, the committee reaffirms the importance of a mission to return samples of Mars to Earth for study and strongly argues that there is an immediate need for developing relevant technologies and infrastructure to enable the implementation of this mission as soon as possible after 2016.

In response to the question, Is the Mars architecture reflective of the strategies, priorities, and guidelines put forward by related science strategies, in particular, those issued by MEPAG?, the committee is in agreement that the Mars architecture does address certain of the broad goals and objectives defined by MEPAG, but the strategy for achieving those goals and related science objectives is incompletely articulated and/or justified. High-priority MEPAG objectives (e.g., those relating to meteorological and geophysical studies) are absent, and longer-term goals (e.g., preparation for sample return) are neglected. In this respect, NASA's proposed Mars exploration architecture is an inadequate implementation of MEPAG goals.

THE MARS ARCHITECTURE AND OTHER NASA PLANS

Is the Mars architecture reflective of the strategies, priorities, and guidelines put forward in other NASA documents such as NASA's 2006 strategic plan and, in particular, the Vision for Space Exploration? The Vision for Space Exploration (VSE) is an explicitly articulated statement of the human drive to explore and learn. In a memorial service for the crew of the Space Shuttle Colombia, President G.W. Bush said, "This cause of exploration and discovery is not an option we choose; it is a desire written in the human heart."[27] As Administrator Michael Griffin remarked in the 2006 edition of NASA's strategic plan, "This . . . plan embraces the goals articulated in the Vision for Space Exploration and addresses our strategy for reaching them."[28] The VSE has become the major focus of NASA activities.

Although often discussed as if they were entirely unrelated and even competing enterprises, robotic planetary science missions and eventual human exploration are one in spirit, although typically requiring a focus on different technologies and involving very different budgetary scales. Those who labor over robotic missions are some of the great explorers of our times, even though their feet never tread the soil of another world. As their minds touch alien destinations, they truly have a passion for exploration written in their hearts. When a robotic mission heads beyond its planet of origin, it is not stripped of its essential humanity. Similarly, as humans move out into the solar system, they will do so with the intimate assistance of their robotic devices. Thus, the robotic-human continuum informs all future activities—be that classified as purely scientific, purely exploration, or something in between. The VSE specifically recognizes this close connection, and researchers must consider it even as they plan the near-term decade of robotic Mars missions.

The space science enterprise is one of significant risk and uncertainty; thus, it is essential to be mindful of potential drawbacks in maintaining a close intellectual connection to the VSE. The Mars Exploration Program and mission architecture must be driven by fundamental scientific questions to be successful. Connections between scientific exploration of Mars and the VSE are highly beneficial to both robotic and human exploration, particularly when the scientific investigations drive the intellectual framework and instrumentation of missions. At the same time, soundly grounded, fundamental Mars mission science can provide significant synergistic benefits if it also addresses potential future human impacts. Such impacts come from virtually every conceivable area of science, from magnetic field studies to aeronomy to geochemistry and beyond. The search for ancient and modern habitats spelled out in the *Mars Exploration Strategy 2007-2016* document can be slightly amended to read "ancient, modern, and future habitats" to encompass the notion of the human exploration phase of our future and thus couple the Mars Exploration Program to the VSE.

Given the desire to create a seamless relationship between the robotic science missions and human exploration without adversely affecting either program element, how can researchers connect to the VSE given the pre-VSE Mars architecture considered here? There are numerous significant measurements planned for robotic missions that will have a major impact on characterization of the martian environment from the point of view of human habitation. Table 2.1 illustrates several examples of this interconnectedness.

In response to the question, Is the Mars architecture reflective of the strategies, priorities, and guidelines put forward in other NASA documents such as NASA's 2006 strategic plan and, in particular, the Vision for Space Exploration?, the committee is in agreement that the Mars architecture is basically consistent with NASA's

TABLE 2.1 Mars Mission Science Important for the Vision for Space Exploration

Mars Mission Science	Value Added for VSE	Relevant Missions
Soil chemistry and physical parameters	Characterization of corrosive effects on humans and equipment, potential for plant growth medium, abrasion and electrostatic properties of materials and equipment	Phoenix, MSL, AFL, Mid Rovers, and MSR are essential
Surface and subsurface geochemistry, geology, etc.	Mapping of availability of water, determining presence of VSE-utilizable features, e.g., materials suitable for radiation shielding	Phoenix, MSL, AFL, Mid Rovers, and MSR are essential
Trace gas chemistry	Potential to provide in situ resources for manufacture of propellants, breathing mixes for life support systems, toxicity potential, etc.	Phoenix, MSL, AFL, Mid Rovers, and MSR are essential. MSTO?
Weather network	Understanding of weather, solar power generation impact (dust transport), heat rejection from nuclear power sources	ML^3N, MSTO
Aeronomy	Characterization of atmospheric variability in support of entry, descent, and landing; aerocapture and aerobraking operations, landing and ascent hazards, radiation attenuation	MSTO
Magnetic field studies	Understanding of weather, radiation implications	ML^3N, MSTO?
Seismological studies	Data on landscape stability, potential geohazards, access to subsurface resources, e.g., water or geothermal energy	ML^3N
Astrobiology	Attention to planetary protection issues (forward and backward contamination)	Phoenix, MSL, AFL, Mid Rovers, and MSR are essential
Infrastructure development	Experience in development and operation of an increasingly complex, cohesive support structure	All missions

NOTE: AFL, Astrobiology Field Laboratory; ML^3N, Mars Long-Lived Lander Network; MSL, Mars Science Laboratory; MSR, Mars Sample Return; and MSTO, Mars Science and Telecommunications Orbiter.

strategic plan and the Vision for Space Exploration. A strong, independent architecture will stand alone on its scientific merit and will also contribute significantly to the VSE. Both the utility of the Mars mission architecture and its value within the VSE and NASA's strategic plan would be strengthened by the addition of a network of meteorological/seismic stations and a sample return mission.

RESPONSE TO QUESTION 1

In response to the question, Is the Mars architecture reflective of the strategies, priorities, and guidelines put forward by the NRC's solar system exploration decadal survey and related science strategies and NASA plans?, **the committee finds that the proposed Mars architecture addresses some of the strategies, priorities, and guidelines promoted by the solar system exploration decadal survey and the Mars Exploration Program Analysis Group and is basically consistent with NASA's plans as exemplified by the agency's 2006 strategic plan and the Vision for Space Exploration. However, the absence of a sample return mission and a geophysical/meteorological network mission runs counter to the recommendations of the SSE decadal survey and significantly reduces the architecture's scientific impact. Other topics of concern include the lack of well-defined mission parameters and scientific objectives for the MSTO, AFL, and Mid Rover missions; issues**

relating to the phasing and responsiveness of these missions to the results obtained from preceding missions; and the incompletely articulated links between these missions and the priorities enunciated by the SSE decadal survey and MEPAG.

The committee offers the following recommendations:

Recommendation: **Include the Mars Long-Lived Lander Network in the mix of options for the 2016 launch opportunity.**

Recommendation: **Consider delaying the launch of the Astrobiology Field Laboratory until 2018 to permit an informed decision of its merits and the selection of an appropriate instrument complement in the context of a mature consideration of the results from the Mars Science Laboratory and other prior missions.**

Recommendation: **Establish science and technology definition teams for the Astrobiology Field Laboratory, the Mars Science and Telecommunications Orbiter, the Mid Rovers, and the Mars Long-Lived Lander Network as soon as possible to optimize science and mission design in concert with each other. (This model has been employed successfully by the heliospheric community.)**

Recommendation: **Devise a strategy to implement the Mars Sample Return mission, and ensure that a program is started at the earliest possible opportunity to develop the technology necessary to enable this mission.**

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26. Estimates provided to the committee by NASA representatives suggest that a Mars sample return mission would likely cost $3 billion to $5 billion. Given the Mars Exploration Program's current budget, a Mars sample return mission would likely require that NASA bank the resources of three to five Mars launch opportunities. Implementing such a strategy would have numerous scientific, technical, programmatic, political, and budgetary pitfalls. Some have argued that a sample return mission will cost far more than NASA's current estimates, whereas others have argued that a simple "grab sample" can be acquired at far less cost. Commenting on the realism of these competing claims and the scientific usefulness of grab samples versus carefully selected samples is beyond the scope of this current study.

27. See, for example, NASA, *The Vision for Space Exploration*, National Aeronautics and Space Administration, Washington, D.C., 2004, inside front cover.

28. NASA, *2006 Strategic Plan*, National Aeronautics and Space Administration, Washington, D.C., 2006.

3

The Goals of NASA's Mars Program

Does the revised Mars architecture address the goals of NASA's Mars Exploration Program and optimize the science return, given the current fiscal posture of the program?

THE MARS ARCHITECTURE AND THE GOALS OF NASA'S MARS EXPLORATION PROGRAM

Does the revised Mars architecture address the goals of NASA's Mars Exploration Program? The agency's overall goals for the exploration of Mars can be summarized under the headings life, climate, geology, and preparation for human exploration. A common thread linking these four topics is water,[1] specifically its origin, nature, amount, and distribution as a function of time.

Table 3.1 summarizes information relating to these four goals as extracted and summarized from the report *Mars Exploration Strategy 2007-2016.*[2] The bottom two rows contain the committee's assessment of the degree to which the proposed architecture will address the four stated goals. For identifying shortfalls, the committee has also suggested potential mitigating options, although this potential still needs to be addressed in studies of appropriate trade-offs, technology readiness, and cost analysis.

The committee explicitly notes that all stated implementations, with current shortfalls, still require adequate technology, instrument development, research and analysis, and, especially, astrobiology programs in order to be successful.

Two issues arise in consideration of the proposed architecture's ability to address NASA's Mars exploration goals—the role of the Mars Scouts and the decision rules governing the selection of the mission to be launched in 2016.

Mars Scout

An important component of the Mars architecture is the Mars Scout program. But, as mentioned above, the Scouts are wild cards. These competitively selected missions have the potential to fill in needs. However, it must be kept in mind that Scouts must be proposed as "complete missions" and not as architectural elements. Hence, the more demanding implementations required for addressing the Mars exploration goals may require multiple missions. Thus, by definition, individual missions that are required for implementing the architecture cannot be fulfilled by Scouts. The SSE decadal survey was highly supportive of the initiation and continuation of the Mars Scout line, and so NASA is to be commended for the inclusion of two Scout missions in the period under consideration—i.e., Phoenix in 2007 and an as-yet unselected mission in 2011. Indeed, the inclusion of two missions is in accord with the decadal survey's recommendation that a Scout be included at every other Mars launch opportunity.

2016 Mission Selection

Choosing between the alternatives for the 2016 opportunity will depend on the results of the Mars Reconnaissance Orbiter and the initial results from the Mars Science Laboratory. As stated above, the committee is concerned that there may not be sufficient time for analysis of MSL data before a decision must be made on the 2016 opportunity. Indeed, the document *Mars Exploration Strategy 2007-2016* comments that the "response time for missions to investigate findings from prior missions [is] typically 6 to 7 years."[3] Thus, by the architecture's own admission, it is far from clear how a mission launching in 2016[4] can be influenced by the results from MSL, which will not reach Mars until the middle months of 2010.[5] NASA needs to articulate explicitly a strategy to address the short lead time between science results obtained from MSL and selection of the mission to fly in 2016. Of equal or greater concern is the absence from the architectures of any criteria for distinguishing between the various options for launch in 2016. NASA needs to clarify how trade-offs between mission costs versus science will be made for the various launch opportunities to justify the rationale behind the proposed sequence of specific missions and the exclusion of others.

Summary

The committee cannot definitively say whether or not the revised Mars architecture addresses the goals of NASA's Mars Exploration Program because the architecture lacks sufficient detail with respect to science and cost to allow a complete evaluation. The various mission options are, as already stated above, not fully defined, and the strategic approach to, and selection criteria to distinguish between, various mission options is lacking.

OPTIMIZING THE SCIENCE RETURN

Does the Mars architecture optimize the science return, given the current fiscal posture of the program? The anticipated budget for NASA's Mars Exploration Program over the next 5 years is about $3 billion less than expected as recently as 1 year ago. This reduction is not unique to the Mars program. The combined effect of recent delays, descopings, deferments, and deletions of other NASA science programs led a Space Studies Board committee to conclude that the "program proposed for space and Earth sciences is not robust; it is not properly balanced to support a healthy mix of small, medium, and large missions and an underlying foundation of scientific research and advanced technology projects; and it is neither sustainable nor capable of making adequate progress toward the goals that were recommended in the National Research Council's decadal surveys."[6] Nevertheless, the Mars Exploration Program's current budget still amounts to some $600 million per year, and so a mission costing as much as $1 billion could, in principle, be flown at every Mars launch opportunity. On the other hand, the near- to mid-term expectation is for flat budgets, and so inflation will eat away at the program's buying power over time. Yet, in the near term at least, the resources available for Mars exploration are still remarkably healthy. If the architecture is regarded purely as a sequence of near-term missions, then NASA is to be congratulated for designing missions that will almost certainly provide a science return at least commensurate with what the Mars program has achieved over the last 5 years.

The Mars Exploration Program's prospects over the longer term are far from clear. The program's resilience in the face of major upsets is an issue of concern to some observers. The cost of MSL has grown significantly in the past few years. What if its costs continue to grow? What happens if its new landing system fails and MSL is lost? The key to a robust program is a mix of orbiters and landers, a mix of large and small missions, and a mix of strategic and PI-led missions. Problems are likely to arise when the coupling between missions at adjacent launch

TABLE 3.1 The Mars Architecture and Its Responsiveness to the Goals of NASA's Mars Exploration Program

Mars Exploration Architecture	Goals of NASA's Mars Exploration Program			
	Life	Climate	Geology	Human Exploration
Accomplishments to date and next steps	Highest priority: establishing that life is or was present on Mars, or, if life never was present, understanding why not; distribution and history of water; sources of biologically usable energy; composition, states, and reservoirs of C, N, S, O, H, and P	Climate change as a central theme; history and process; emphasis on process	None identified in report[a]	None identified in report[a]
Improved knowledge to date	Liquid water has been present and weathered the crust; crust complex and diverse with early sustained hydrological cycle, episodic volcanic eruptions, and climate cycles driven by obliquity; putative observation of methane	Primary progress has been from the Thermal Emission Spectrometer, the Mars Orbiter Camera, and the radio science from Mars Global Surveyor; seasonal cycles of dust, temperature, and water discerned; boundary layer observations are not complete; upper atmosphere only sparsely sampled; vertical mixing and trace gas loss rates not yet examined	Geological evolution of planet from previous missions and current MER rovers; geological diversity and complex evolution; dynamo early in planet's history and volcanic emissions may have helped provide active hydrothermal systems; previous beds under salty groundwater identified; chemistry bounds deduced on hydrological cycle on surface; possible relation to long-term orbital obliquity changes	Risks to humans can be mitigated through precursor scientific investigations (~20 identified), with four having high priority: water accessibility near landing site, wind shear and turbulence effects on landing, martian life effects on Earth's biosphere, and adverse effects of dust on mission hardware; also level of radiation exposure, but technical development and flight systems on hold due to fiscal constraints
Potential outcomes of near-term investigations	May find water and/or ice reservoirs; may discover more biologically significant landing sites	Most promise from MRO observations, lower atmosphere in greater detail; landed spacecraft will likely not constrain boundary-layer processes; surface-atmosphere aerosol fluxes will remain beyond observation; high latitudes of unique importance	MRO to provide identification of sites with mineralogical evidence of habitability, and ground-penetrating radar may find evidence of groundwater and subsurface ice; Phoenix to characterize chemistry, mineralogy, and isotopic composition of evolved gases in subsurface soils and ices; MSL to provide detailed exploration of potential habitable site identified from orbit	Phoenix for evaluation of accessibility of water at high latitudes; MRO for maps of atmospheric properties; need both long- and short-term atmospheric state and variability; MSL for effects of dust on landed systems; landed mass increase from 0.2 to 1.5 metric tons; MSL for addressing human health

TABLE 3.1 Continued

Mars Exploration Architecture	Goals of NASA's Mars Exploration Program			
	Life	Climate	Geology	Human Exploration
Best next steps to meet goal	Phoenix launch in 2007 to high northern latitudes to study current hydrological cycle; MSL light-element chemistry and definitive mineralogical, geochemical, and organic surveys, look for methane; future missions to search for organics and send astrobiological package to same site; if no organics found, then extend search to other sites	Need to understand evolution of atmosphere and quantify atmospheric escape rate—Nozomi and Mars Upper Atmosphere Orbiter would have contributed; need network of 4 to 18 stations with life of 4 to 10 years as soon as affordable; need investigations of polar-layered terrains to investigate best-preserved records	In situ examination coupled with sample returns from carefully selected sites; network of landers to characterize structure, state, and processes of the interior; more rovers and more samples needed	Sample return; meteorology network to constrain atmospheric models
Committee's assessment of proposed architecture	Plan is MSL followed by AFL or Mid Rovers; the importance of sample return is not mentioned but may be only definitive technique; current proposed mission set is adequate through 2016	Network of meteorological landers and Mars Upper Atmosphere Orbiter both required for significant progress; MSTO and/or Scouts may contribute	Network of thermal flow and network of seismic stations; rover/sample return to more sites	Sample return and network of meteorological stations required for scientific progress in absence of investments by NASA's Exploration Systems Mission Directorate
Committee's suggested potential mitigation options	Need to provide better definition of cost-constrained AFL; follow through with current decision strategy; consider shifting launch of AFL to 2018 to be responsive to MSL discoveries	Need a plan for providing a network mission—put in line as an option for the 2016 mission decision	Need a plan for providing a network mission—put in line as an option for the 2016 mission decision; begin to cache samples on planned rover missions for eventual MSR; develop plan and technologies for MSR	Need a plan for providing a network mission—put in line as an option for the 2016 mission decision; begin to cache samples on planned rover missions for eventual MSR

NOTE: AFL, Astrobiology Field Laboratory; MER, Mars Exploration Rover; MSL, Mars Science Laboratory; MSR, Mars Sample Return; and MSTO, Mars Science and Telecommunications Orbiter.

[a]D.J. McCleese et al., *Mars Exploration Strategy 2007-2016*, NASA, Jet Propulsion Laboratory, Pasadena, Calif., 2006.

opportunities becomes too tight, i.e., if a technical issue with one mission has an impact on the next mission. The current architecture's diversity of missions gives it some resilience to weather misfortune and, also, to be responsive to new developments.

More Than Just Missions

A mission architecture is, however, a global strategic approach to address a multifaceted systems problem. As such, it should be viewed as involving not only the set of missions to be flown during the period 2007-2016, but also the analyses of data and supporting infrastructure to make the program successful and effective. The overall strategy for the Mars Exploration Program and its place in the Vision for Space Exploration can be viewed in a pyramidal hierarchy, with a human presence on Mars representing the apex, the ultimate form of exploration (Figure 3.1). At the base of the pyramid is the foundation provided by analyses of existing data, study of martian meteorites, development of technologies required by future missions, and other supporting research.

From this supporting base, the next level involves the definition of missions to derive a global perspective of Mars, as generally accomplished from spacecraft in orbit. Global data are used to identify locations for landed spacecraft to obtain in situ measurements and to provide ground truth for the orbiter data. In addition, lander data can contribute to global studies of the planet. Both global and local data sets are then used to identify key locations for the return of martian samples to Earth, where the full capabilities of laboratory instruments can be employed. Results gained from the supporting base and the robotic missions can then be used to develop a safe and scientifically productive role for humans on Mars.

The next four subsections highlight particular examples of non-mission activities that will contribute to the optimization of the science return from flight missions.

Basic Research: Biosignatures

The process of life detection on Mars involves two sequential steps, both of which are critically dependent on basic research activities unconnected with flight missions. The first is identification of phenomena that are or could be potential biosignatures—i.e., morphological, molecular, or isotopic features produced by either biotic or abiotic processes. The second is establishment of a definitive biosignature—i.e., a feature produced exclusively by life. Mission discoveries of potential biosignatures will lead to claims that life is or was present. Though such claims are easily made, demonstrating a definitive biosignature in situ will be the ultimate challenge. Consider the

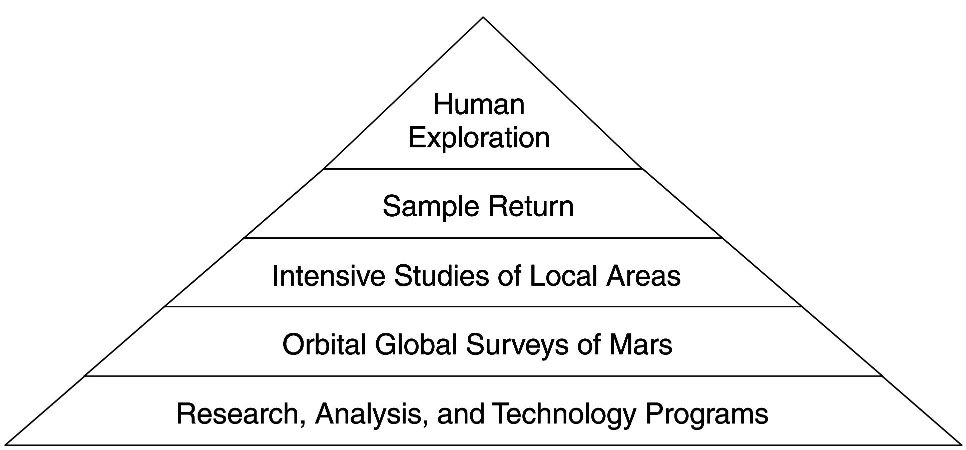

FIGURE 3.1 Schematic of the programmatic elements of an optimum Mars exploration strategy.

ongoing heated debate for claims of ancient life on Earth[7]—for which the geological and geochemical context of the deposit harboring the evidence is already known—and the likely pitfalls inherent in finding definitive biosignatures on Mars via in situ techniques become apparent. The development of biosignatures and biosignature preservation models for different potentially biologically relevant environments on Mars requires an active program of basic research informed by the most recent discoveries and findings from Mars analog and Earth-based experiments, theoretical analyses, and other activities typically supported via research and analysis (R&A) programs.

Data Analysis: Landing Site Selection

Are there geochemical or mineral traces of past environments that can guide the selection of future landing sites of astrobiological interest? Locating rock deposits that accumulated in environments in which microbial biosignatures could be preserved is critical to life detection search strategies on Mars. High concentrations of aqueously deposited minerals, such as silica, carbonate, and evaporites, are often associated with microbial communities on Earth. Many of these distinctive phases can be deposited over the full range of temperatures that support life. The detection of such materials via the analysis of orbital remote-sensing data may constitute potential signposts for past or present life. Search strategies can be optimized by selecting sites with mineralogies consistent with long crustal residence times. Clay-rich detrital sediments can also preserve organic remains on Earth if they were deposited under anaerobic conditions and were cemented by silica, carbonate, phosphate, or clays. The development of preservation models for these geochemically distinct types of deposits is essential and will have important predictive value in guiding future strategies for the search for life in various martian geological environments.

Laboratory Studies: Martian Meteorites

Since the 1980s, it has been recognized that certain classes of meteorites are probably samples of Mars. The 30+ known martian meteorites have, therefore, been extensively studied using state-of-the-art laboratory techniques in order to determine some chemical, petrologic, and chronologic information about Mars, and the early evolution of its atmosphere. For example, radiometric age measurements have yielded the timing of early planetary differentiation, crystallization ages of individual rocks (but without geological context), and dates of ejection by impact from the planet. Early atmospheric evolution has been studied through the isotopic composition of xenon derived from extinct radionuclides.[8] Identification of the martian hydrosphere has been made by measurement of hydrogen and oxygen isotopes in hydrous minerals in Mars meteorites.[9] However, there has been a general lack of communication between the Mars meteorite community and mission planners, which has been harmful to both groups. Close cooperation can be achieved by focusing on important problems of mutual interest, such as absolute dating of geological units on Mars, either by sample return or, potentially, by the development of new in situ techniques.

Technology Development

To address increasingly sophisticated questions about the origin and evolution of Mars requires the development of new technologies. Many of these technologies are required simply to execute the missions planned for the coming decade, including new entry, descent, and landing capabilities for large rovers, complex sample-handling and distribution systems, and instruments capable of, e.g., in situ organic detection and age determination. With the inclusion of a Mars sample return mission, the technical complexities multiply to include possible near-surface and deep drilling,[10] sample cache capabilities with pinpoint landing of subsequent landers, sample containment, and ascent vehicles. These technologies have long lead times and require substantial investment in development in both the near term and the far term. It seems clear that current technology development funds are insufficient to bring these missions to flight and threaten to delay a Mars sample return mission beyond what can be technologically and fiscally accomplished. More worrying still is the fact that NASA's technology development woes transcend the current budgetary climate. That is, virtually every lessons-learned study has indicated that technology funding has been a chronic problem for NASA for many years—indeed a 2003 NRC report found that for one important technology development activity, "funding was dropping dangerously close to the critical threshold."[11] The committee is not sanguine that these problems are going to get any better soon.

In addition to the technology-activities-enabling missions are the technology activities aimed at developing a particular mission's scientific instruments. Unfortunately, key programs supporting the development of instrumentation for future Mars missions—e.g., the Mars Instrument Development Program (MIDP), the Planetary Instrument Definition and Development Program (PIDDP), the Astrobiology Science and Technology Instrument Development (ASTID) program, and the Astrobiology Science and Technology for Exploring Planets (ASTEP) program—are in danger of collapse, given President Bush's budget proposals for FY 2007.[12] Indeed, the funding for MIDP and PIDDP is slated to be cut by approximately 15 percent, and the proposed cuts to the funding for ASTID and ASTEP will amount to approximately 50 percent.[13] When such potential cuts are viewed against the backdrop of the decade or longer it currently takes a PI at a NASA center or university to develop an instrument from concept to laboratory demonstration to flight hardware, it becomes all too clear that a hiatus in instrument development activities will seriously compromise future missions. The Astrobiology Field Laboratory (AFL) presents the most telling example of the potential disconnects between proposed missions and the instrument required to achieve the advertised mission goals. AFL was conceived as being able to carry a complex sample-selection and sample-handling system and a comprehensive suite of analytical instruments, designed to follow up on and exploit the potential identification of organic compounds at a particular location by the Mars Science Laboratory. The validity of this strategy is currently in some doubt because of a combination of factors including budget, overweight instruments, the dynamical characteristics of the 2016 launch opportunity, and a high probability of dust storms that will complicate AFL's entry, descent, and landing profile.[14] The importance of focused technology development as a strategic investment in the success of future missions cannot be overstated.

Ensuring Optimum Science Return

The Mars architecture as presented does not address the broad base of data analysis, the study of martian meteorites, technology development, and related activities. The committee considers these non-mission elements to be critically essential to the success of the Mars Exploration Program and the VSE. Funding for research and analysis (R&A) is vital to scientific discoveries, many of which will be enabled by data collected in the timeframe 2007-2016. Without adequate funding for R&A, the scientific return from, and long-lived public appreciation of, currently planned missions is compromised. Analysis of existing data in a timely fashion enables the definition of subsequent missions and provides a means for training the next generation of scientists in the planetary community. The committee noted that even though no new planetary exploration missions were launched for most of the 1980s, the maintenance of a healthy R&A program, based on the wealth of data obtained by the Viking project, provided the means for training some of the current leaders of the Mars science and engineering communities.

It should also be noted that the cost of support for R&A is small in comparison with the cost of a single Mars mission. R&A is, however, essential to the future of Mars exploration. Indeed, if the Mars exploration strategy is represented by a pyramid (see Figure 3.1) with basic research activities as its base, then the cost of these activities can equally well be represented by an inverted pyramid with R&A support as the least costly item, and human exploration as the most expensive item.

Similarly, adequate funding of technology is needed to ensure viable hardware, software, and communications for the current and future decades. The report *Mars Exploration Strategy 2007-2016* highlights four main "Sustaining Elements of the Strategy": planetary protection, technical heritage, telecommunications, and international cooperation. Of these, the first three all require investment in new or improved technologies. These are required for successful missions in the current decade, but investment in technology now is required for high-priority future missions such as Mars Sample Return. Given the limited availability of technology development funds, the prospect of reusing proven flight hardware on subsequent missions has its attractions. It could be argued that the most cost-effective strategy for NASA to follow would be to perform surface exploration of Mars by sending copies of the Mars Exploration Rovers to different areas, each equipped with payloads optimized to address the appropriate science questions. An exploration strategy based on the use of minimally modified technology would probably be scientifically productive. Whether or not such an approach would be cost-effective is beyond the scope of this study. What is clear is that such an exploration strategy is not likely to be capable of adequately addressing all of the non-geological and geochemical priorities identified in the SSE decadal survey and MEPAG reports. Thus, the adoption of such a strategy would represent an implicit narrowing of the scientific focus of NASA's Mars Exploration Program. If the budgetary situation continues to deteriorate, such an approach may be warranted, but the committee does not believe such a turning point has yet been reached.

It is clear, however, that the extraordinary resilience of the Mars Exploration Rovers strongly suggests that a prudent, risk-reduction strategy is to use their design as a basis for the proposed Mid Rovers. Similarly, commonalities in the design of MSL and AFL might be appropriate. The committee notes, however, that technical heritage has not, historically, been a cost-saving measure as exemplified by the Mars Observer and Mariner Mark 2 "common buses." Areas requiring technological development include entry, descent, and landing systems, pinpoint landings, drilling technology, and astrobiology instrumentation for AFL.

International Activities

The continuing success of the European Space Agency's Mars Express highlights that Mars exploration today is an international endeavor with the requisite technical know-how no longer the monopoly of one player. Given the current fiscal environment, NASA and the scientific community should optimize potential international collaborations, such that missions, payloads, and data sets are complementary, but not overlapping. The European Space Agency's rapidly solidifying plans for a rover mission, ExoMars,[15] in 2011 and much more tentative plans for a sample return mission in 2018 are cases in point.[16] The former mission is of particular interest here because it is, apparently, somewhat similar in scope to NASA's proposed Mid Rovers. Payload exchange of individual instruments or instrument suites is an area for significant international collaborations. However, the vulnerability of any nation's missions to changes in fiscal environments underscores the need to not rely on international missions to fulfill specifically Mars exploration goals, and to exercise caution regarding interdependencies. Free exchange of data, for both scientific analysis and mission planning, is important, as is the need for opportunities for international science team participation.

Summary

The committee is concerned about the absence from the Mars architecture of essential programmatic elements—e.g., support of research and analysis programs and technology development activities—which provide the foundation on which future missions are built.

RESPONSE TO QUESTION 2

In response to the question, Does the revised Mars architecture address the goals of NASA's Mars Exploration Program and optimize the science return, given the current fiscal posture of the program?, **the committee finds that it cannot definitively say whether or not the revised Mars architecture addresses the goals of NASA's Mars Exploration Program because the architecture lacks sufficient detail with respect to the science and the cost to allow a complete evaluation. The various mission options are, as stated above, incompletely defined, and the strategic approach to, and the selection criteria to distinguish among, various mission options are lacking. The presence of Mars Scout missions in the architecture is welcomed because they help to optimize the science return and provide balance. Nevertheless, the Mars architecture as a whole is not optimized, because the importance of foundational strategic elements—e.g., research and analysis programs and technology development—is not articulated.**

The committee believes that many of the concerns identified here owe their origin to a viewpoint that equates an architecture with a sequence of missions and not with a global strategy approach to address a complex, interrelated series of scientific and engineering challenges. To address this problem, the committee offers the following recommendations:

***Recommendation:* Develop and articulate criteria for distinguishing between the three options for missions to launch in 2016. Similarly, define a strategy that addresses the short lead time between science results obtained from MSL and selection of the mission to fly in 2016.**

***Recommendation:* Clarify how trade-offs involving mission costs versus science were made for the various launch opportunities to justify the rationale behind the proposed sequence of specific missions and the exclusion of others.**

***Recommendation:* Maintain the Mars Scouts as entities distinct from the core missions of the Mars Exploration Program. Scout missions should not be restricted by the planning for core missions, and the core missions should not depend on selecting particular types of Scout missions.**

***Recommendation:* Immediately initiate appropriate technology development activities to support all of the missions considered for the period 2013-2016 and to support the Mars Sample Return mission as soon as possible thereafter.**

***Recommendation:* Ensure a vigorous research and analysis (R&A) program to maintain the scientific and technical infrastructure and expertise necessary to implement the Mars architecture, and encourage collaboration on international missions.**

NOTES

1. D.J. McCleese et al., *Mars Exploration Strategy 2007-2016*, NASA, Jet Propulsion Laboratory, Pasadena, Calif., 2006, p. 9.
2. D.J. McCleese et al., *Mars Exploration Strategy 2007-2016*, NASA, Jet Propulsion Laboratory, Pasadena, Calif., 2006, pp. 9-18.
3. D.J. McCleese et al., *Mars Exploration Strategy 2007-2016*, NASA, Jet Propulsion Laboratory, Pasadena, Calif., 2006, p. 19.
4. The launch window stretches from January to April, 2016.
5. A spacecraft launched during the October-November, 2009, launch window will reach Mars between May and October of 2010.
6. National Research Council, *An Assessment of Balance in NASA's Science Programs*, The National Academies Press, Washington, D.C., 2006, p. 2.
7. See, for example, J.W. Schopf, A.B. Kudryavtsev, D.G. Agresti, T.J. Wdowiak, and A.D. Czaja, "Laser-Raman Imagery of Earth's Earliest Fossils," *Nature* 416: 73-76, 2002; and M.D. Brasier, O.R. Green, A.P. Jephcoat, A.K. Kleppe, M.J. Van Kranendonk, J.F. Lindsay, A. Steele, and N.V. Grassineau, "Questioning the Evidence for Earth's Oldest Fossils," *Nature* 416: 76-81, 2002.
8. K. Zahnle, "Xenological Constraints on the Impact Erosion of the Early Martian Atmosphere," *Journal of Geological Research* 98: 10899-10913, 1993.
9. L.L. Watson, I.D. Hutcheon, S. Epstein, and E.M. Stolper, "Water on Mars—Clues from Deuterium/Hydrogen and Water Contents of Hydrous Phases in SNC Meteorites," *Science* 265: 86-90, 1994.
10. Recent discoveries of sustained surficial water and potential biogenic gas emissions strengthen the need to characterize the subsurface environment on Mars. Because of the hostile nature of the martian surface, the capability to reach some distance (>3 m) below the surface must be provided on future missions. The capability to drill to a depth of several meters or to reach under rocks, rock ledges, or overhangs will be an important asset on missions beyond the scope of this report (e.g., Mars Sample Return). In the long term, the technology necessary to access even greater depths in the martian subsurface—on the order of tens to hundreds of meters—will be required to access putative martian aquifers.
11. National Research Council, *Review of NASA's Aerospace Technology Enterprise*, The National Academies Press, Washington, D.C., 2003, p. 82.
12. National Research Council, *An Assessment of Balance in NASA's Science Programs*, The National Academies Press, Washington, D.C., 2006, p. 18.
13. National Research Council, *An Assessment of Balance in NASA's Science Programs*, The National Academies Press, Washington, D.C., 2006, p. 20.
14. Luther Beegle, Jet Propulsion Laboratory, "Status of Astrobiology Instrument Development," presentation to the Space Studies Board's Mars Astrobiology Strategy Committee, May 11, 2006.
15. For more information on ExoMars see, for example, <www.esa.int/SPECIALS/Aurora/SEM1NVZKQAD_0.html>.
16. For more information on ESA's planning for a Mars sample return mission see, for example, <www.esa.int/SPECIALS/Aurora/SEM1PM808BE_0.html>.

4

A Balanced Mission Portfolio

Does the Mars architecture represent a reasonably balanced mission portfolio? Although the committee interpreted this question as relating primarily to scientific balance, other issues of balance are also considered.

SCIENTIFIC BALANCE

The balance of scientific questions that the proposed architecture can and cannot address was of great interest and concern to the committee. Table 4.1 outlines the three key crosscutting scientific themes defined in the SSE decadal survey and breaks them down into slightly more focused key topics. Table 4.1 also summarizes the extent to which these different topics are satisfied by the proposed missions, based on the descriptions contained in the document *Mars Exploration Strategy 2007-2016*. As noted above, the lack of sufficient definition of the missions from MSTO onward is such that considerable uncertainty exists as to exactly which topics each mission is likely to address. In particular, the likely capabilities of AFL are far from clear.

Table 4.1 clearly indicates that the theme of Mars as a potential abode of life is well served by the proposed architecture, that theme being a primary focus of the Phoenix, MSL, AFL, and Mid Rover missions. Similarly, the second theme, water, atmosphere, and climate on Mars, is also well served and is a focus for the Phoenix, MSL, MSTO, and AFL missions. The third theme, structure and evolution of Mars, is not well addressed by the proposed architecture. The MSL, AFL, and Mid Rover missions will provide some information on crustal compositions. Similarly, detection of localized methane sources by MSTO is likely to indicate ongoing geological activity. However, none of the proposed missions address issues relating to Mars's deep interior and magnetism, or its absolute chronology. Every proposed mission is focused primarily on either the first or the second of the decadal survey's crosscutting themes. No mission in the architecture has the decadal survey's third crosscutting theme as its main focus.

The next two subsections explore some of the issues associated with addressing theme three.

Network Science

Although addressing the key science questions relating to the third theme, the structure and evolution of Mars, is not a priority of the proposed architecture, *Mars Exploration Strategy 2007-2016* recognizes the importance of these questions. For instance, the strategy document comments: "The quality and value of scientific results from

TABLE 4.1 Crosscutting Themes for the Exploration of Mars Identified in the SSE Decadal Survey Compared with the Capability of Proposed Missions

SSE Decadal Survey Theme	Important Science Topics	2007 Phoenix	2009 MSL	2011 Scout	2013 MSTO[a]	2016 AFL[a]	2016 Mid Rover[a]	*2016 ML^{3}N*[a]
Mars as a potential abode of life	Does/did life exist?		X	?	X[b]	XX	X	
	How hospitable?	XX	XX	?		XX	XX	
Water, atmosphere, and climate	Water	XX	XX	?	X	XX	XX	*X*
	Present atmosphere	XX	X	?	XX			*XX*
	Long-term climate	X		?	XX	X		*XX*
Structure and evolution	Crust and activity		X	?	X[b]	X	X	*X*
	Deep interior and magnetism			?	?			*XX*
	Chronology			?[c]		?[c]	?[c]	

NOTE: The comparison is with the capability as described in D.J. McCleese et al., *Mars Exploration Strategy 2007-2016*, NASA, Jet Propulsion Laboratory, Pasadena, Calif., 2006.

Key: X, addressed by the relevant mission as it is currently conceived; XX, very well addressed by the relevant mission as it is currently conceived; ?, potentially addressed given the selection of appropriate instrumentation. Items in roman type are included and/or addressable by the proposed architecture. Items in italic type are not included and/or addressable by the proposed architecture. The ML^{3}N (Mars Long-Lived Lander Network) mission is based on the SSE decadal survey recommendation for a network of geophysical/meteorological packages. MSTO is assumed to include both aeronomy and trace-gas investigations.

[a]Missions that are poorly defined and so may eventually have capabilities somewhat different from those assumed by the committee.

[b]Potential confirmation of localized methane production.

[c]Potentially addressable via in situ techniques.

surface missions depend upon the landing site selected and the completeness of the available geological, climatological, and geophysical context. . . . A network of landers, carrying seismic sensors, heat flow probes and the capability for making high-precision geodetic measurements, is needed to better understand the structure, state and processes of the martian interior in order to ascertain thermal and geological evolution of the planet that is responsible for the surface we see today."[1]

In view of the importance of Question 3, and the current imbalance in the proposed architecture, the committee reiterates the recommendation already made to include a geophysical/meteorological network mission as a third possibility for the 2016 launch opportunity. It could be argued that the inclusion of this mission will require significant new technology investments at a time when only limited funding is available. The committee does not think this is the case. The concept of a Mars network was studied extensively by NASA in the early 1990s as part of the Mars Environmental Survey (MESUR) project.[2] A prototype of the MESUR landers—MESUR Pathfinder, later renamed Mars Pathfinder—was successfully flown and operated on Mars in 1997. Additional development work has been undertaken in the context of the Pascal Mars Climate Network mission, which has been proposed as a Discovery and a Mars Scout mission.[3] Finally, additional developmental activities have been undertaken in Europe in the context of a variety of concepts, including MARSNET, INTERMARSNET, and, most recently, NETLANDER.[4]

Although the committee has not seen detailed cost studies and is not appropriately constituted to undertake such studies itself, it is of the opinion that the cost of an adequate network mission is comparable with that of the other missions under consideration for launch in 2016. If the addition of a network mission in 2016 is not possible, then every effort should be made to make at least some of the highest-priority measurements on the landed missions that are flown in the period 2013-2016.

As outlined in Table 4.1, a network mission (envisaged to consist of four stations with seismological, meteorological, and heat flux instruments) has the capability to address the decadal survey's second and third crosscutting themes.[5] Inclusion of this mission in the Mars architecture would be consistent with the SSE decadal survey's call for the Mars Long-Lived Lander Network mission. The committee anticipates that a moderate amount of technology development (especially of entry, descent, and landing systems), or international collaboration, is required to bring such a network to fruition.

Absolute Chronology

The committee is concerned that with a Mars sample return mission relegated beyond the current budgetary and planning horizon, the issue of deciphering the absolute chronology of Mars remains unaddressed in the current architecture despite its recognized scientific necessity for unraveling the geophysical, geological, hydrological, and atmospheric history of the planet. This type of historical context is also important for focusing efforts to find life—if it did emerge—and for providing a historical framework within which to evaluate the evolution of any life or suggestions of it on Mars. Chronology can potentially be addressed coarsely through in situ analysis. Even with errors of ±500 million years, such an analysis would greatly improve our understanding of the absolute timing of key events in martian history.

Measurement of the age of rocks by a future rover is probably only possible using the potassium-argon (K-Ar) method, but the technical problems in developing such a system are huge. The sample preparation needed would be daunting, especially given the new evidence that rocks on Mars commonly have coatings. Also, the K-Ar system is so easily reset by shock, weathering, and other processes that interpretation of the measured ages will require knowledge about the sample's petrologic context. The only hope for making an easily interpretable measurement is to go to a landing site with unweathered lava flows uniformly covering a broad area (so that crater-counting data can be obtained for calibration). Unfortunately, such a site will not help to define the boundaries of the martian geological epochs (i.e., the Noachian and Hesperian boundaries are so old that lavas of this age are likely to be altered). Moreover, visiting such a volcanic site would likely require a dedicated mission. On the other hand, an in situ dating technology would find broad applicability to other solar system bodies besides Mars—especially those planets and satellites from which sample return missions cannot now be contemplated, e.g., Venus, Mercury, and the icy bodies of the outer solar system—and so serious consideration should be given to the technical feasibility of developing the appropriate instrumentation. Ultimately, a Mars sample return mission will be required to obtain high-precision dating capable of unraveling the duration of aqueous activity at any single location and the associated implications for extinct or extant life.

OTHER ISSUES OF BALANCE

The committee also identified four other issues of balance as follows:

- The balance between different mission types (landers/rovers as opposed to orbiters) was considered reasonable. The exploration of Mars is at a relatively mature stage; most of the necessary orbital measurements have been made, and it is therefore appropriate that the majority of the missions proposed for the coming decade consist of localized, in situ investigations.
- Careful consideration should be given to achieving the appropriate balance between the use of MSTO as a science platform and as a communications relay. The importance of addressing the long-term climate evolution of Mars, together with uncertainties in Mars telecommunications requirements and the availability of other orbital assets to relay communications, suggests that the balance should be strongly biased toward science. The committee is concerned that MSTO not simply serve as a telecommunications relay, especially in the absence of any quantified, hard telecommunications requirements.

- The committee notes that Scout missions provide a potential additional mechanism for adding balance to the overall architecture (subject to the caveats discussed previously). In particular, the optimum science payload for MSTO may (or may not) alter depending on the outcome of the 2011 Scout competition.
- Finally, international collaboration, as noted in the document *Mars Exploration Strategy 2007-2016*, could be another mechanism for adding balance to the Mars architecture.

RESPONSE TO QUESTION 3

In response to the question, Does the Mars architecture represent a reasonably balanced mission portfolio?, **the committee finds that in the context of the basic types of missions, the Mars architecture is a reasonably well balanced one: both landed and orbital missions are included in an appropriate mix, given the current state of Mars exploration. To the extent that the specific science objectives of the proposed missions are defined, one of the three crosscutting themes for the exploration of Mars identified in the SSE decadal survey is largely neglected, as are very high priority topics related to understanding near-surface and boundary-layer atmospheric sciences, and so, in this respect, balance is sorely lacking.** As has already been recommended (see above), a geophysical/meteorological network mission is a key to addressing both of these science areas, although some of the highest-priority science measurements could potentially be made on other surface missions (e.g., the AFL or the Mid Rover missions). These include meteorological, seismic, and heat flow measurements.

To optimize efforts to implement a balanced portfolio of missions, the committee offers the following recommendations:

Recommendation: **Include the Mars Long-Lived Lander Network in the mix of options for the 2016 launch opportunity.**

Recommendation: **If the Mars Long-Lived Lander Network cannot be implemented in the period under consideration, provide for an effort to make some of the highest-priority measurements on the landed missions that are included in the proposed Mars architecture.**

Recommendation: **Ensure that the primary role of the Mars Science and Telecommunications Orbiter is to address science questions, and not simply to serve as a telecommunications relay. This distinction is particularly important with respect to the required orbital parameters that are adopted.**

NOTES

1. D.J. McCleese et al., *Mars Exploration Strategy 2007-2016*, NASA, Jet Propulsion Laboratory, Pasadena, Calif., 2006, p. 15.
2. Solar System Exploration Division, *MFPE: Mission from Planet Earth*, Vol. 2 of *Solar System Exploration Division Strategic Plan*, NASA, Washington, D.C., 1991, pp. 18-26.
3. See, for example, R.M. Haberle et al., "The Pascale Discovery Mission: A Mars Climate Network Mission," *Concepts and Approaches for Mars Exploration*, Lunar and Planetary Institute, Houston, Texas, 2000, available at <www.lpi.usra.edu/meetings/robomars/pdf/6217.pdf>.
4. For more information about NETLANDER, see, for example, <smsc.cnes.fr/NETLANDER/>.
5. Should mission resources permit it, the inclusion of descent and/or surface imagers in each network station would greatly enhance their utility by enabling them to pinpoint the actual landing sites and to perform some assessment of the local geology. With so little information available from specific sites on Mars, the addition of information from four or more network sites would be a significant bonus.

5

Summary

As a result of its discussions and deliberations concerning the above topics, the committee finds that NASA's plans for the 2007, 2009, and 2011 launch opportunities have considerable merit. The committee does, however, have some specific concerns with the proposed mix and phasing of missions under consideration for launch in 2013 and 2016. The committee notes that the basic objectives and strategy articulated in *New Frontiers in the Solar System* (the solar system exploration decadal survey) are acknowledged and reiterated as the foundation of the program, in spite of the current fiscal constraints with which NASA is dealing. These objectives and strategy have also been recently reiterated by the Mars science community via the Mars Exploration Program Analysis Group (MEPAG), a structure that has enabled past and continuing science community involvement in, and ownership of, the Mars science process. While external forces have driven the Mars architecture to its science floor, that floor has, importantly, remained intact.

That said, the committee is concerned that the current Mars science program suffers from a lack of balance, in that two of the high-priority missions recommended by the SSE decadal survey do not appear in the 2007-2013 timeframe. An overall Mars science program that moves forward in a balanced, scientifically efficient manner can be guaranteed by undertaking the following actions:

- Better defining the scientific rationales for the 2013 and 2016 missions (via appropriately constituted mission definition teams);
- Including the Mars Long-Lived Lander Network in the mix of options for the 2016 launch opportunity;
- Maintaining the science component of the proposed MSTO and its schedule;
- Maintaining the R&A base; and
- While future technology developments may enable better in situ analysis, e.g., for chronology, the committee finds that there is no substitute for an eventual sample return mission. A strategy to implement the Mars Sample Return mission must be devised, and a program to develop the technology necessary to enable this mission should start at the earliest possible opportunity.

Appendixes

A

SSE Decadal Survey Mars Priorities

The National Research Council's solar system exploration decadal survey enunciated a comprehensive series of goals, priorities, and recommendations relating to the exploration of Mars.[1] The decadal survey also described the important role played by R&A programs, technology-development activities, and related undertakings in supporting Mars missions. The following series of extracts from the decadal survey—relating to, for example, the recommendations for small, medium, and large spacecraft missions—are relevant to the topics discussed in this letter report.

LARGE MISSIONS

Mars Sample Return

While MSR cannot replace certain crucial in situ measurements (e.g., heat flow, seismicity, electromagnetic sounding for water, analyses of labile samples, and determination of atmospheric dynamics), it is scientifically compelling in its own right, and the ground-truth acquired from returned samples will aid the interpretation and greatly enhance the value of data from orbital and robotic lander missions. Spacecraft capabilities that would contribute to effectiveness in sampling include mobility, in situ reconnaissance analytical instrumentation, and a core drilling device. (Under current conditions, it appears likely that living organisms, and more generally all organic material, would be destroyed by oxidizing conditions in the surface layer of Mars. They may be preserved only at depth in the planet. Just what depth—centimeters, meters, kilometers—is unknown.) Necessary capabilities include the ability to manipulate and document samples collected and to package them in a way consistent with requirements placed by the planetary protection protocol imposed on the mission. A radioisotope power system for the mission . . . would expand the geographic range of sites that could be sampled and would extend the mission's stay time, allowing the collection of a larger and more carefully selected suite of samples. Ample power undoubtedly will be important if drilling is contemplated.[2]

Observations by robotic orbiters and landers alone are not likely to provide an unambiguous answer to the most important questions regarding Mars: whether life ever started on that planet, what the climate history of the planet was, and why Mars evolved so differently from Earth. The definitive answers to these questions will require analysis in Earth-based laboratories of Mars samples returned to Earth from known provenances on Mars. Moreover, samples will provide the ultimate ground-truth for the wealth of data returned from remote-sensing and in situ missions. **The SSE Survey recommends that NASA begin its planning for Mars Sample Return missions so that their implementation can occur early in the decade 2013-2023.**

The Need for Sample Return to Search for Life. At our present state of knowledge and technological expertise, it is unlikely that robotic in situ exploration will be able to prove to an acceptable level of certainty whether there once was or is now life on Mars. Results obtained from life-detection experiments carried out by robotic means can be challenged as ambiguous for the following reasons:

- Results interpreted as showing an absence of life will not be accepted because the experiments that yielded them were too geocentric or otherwise inappropriately limited;
- Results consistent with but not definitive regarding the existence of life (e.g., the detection of organic compounds of unknown, either biological or nonbiological, origin) will be regarded as incapable of providing a clearcut answer; and
- Results interpreted as showing the existence of life will be regarded as necessarily suspect, since they might reflect the presence of earthly contaminants rather than of an indigenous martian biota.

The Need for Sample Return for Geochemical Studies and Age Dating. Rocks contain a near-infinite amount of information on a microscopic scale, some of it crucial to an understanding of the rock's origin and history. The constituent minerals, fluid inclusions, and alteration products can be studied chemically and isotopically, providing critical information on the age, dates of thermal and aqueous alteration events, nature of the source regions, and history of magmatic processes. In situ instrumentation will always be limited to a fraction of the potential measurement suite and lower levels of precision and accuracy. Information about the Mars climate will be found in the layer of weathering products that we expect to find on rock samples and in the soils. These products will almost certainly be very complex minerals or amorphous reaction products that will tax our best Earth-based laboratory techniques to understand. A critical unknown for Mars is the absolute chronology of the observed surface units. Precise and accurate dating of surfaces with clearly defined crater ages is best accomplished with returned samples.

The Need for Sample Return for Studies of Climate and Coupled Atmosphere-Surface-Interior Processes. Key measurements in modeling the relative loss of portions of the atmosphere to space and to surface reservoirs are surface mineral compositions and their isotopic systematics. Atmospheric loss processes (e.g., hydrodynamic escape, sputtering) leave characteristic isotopic signatures in certain elements. Loss to space and surface weathering (e.g., CO_2 to carbonate minerals) are likely to produce isotopic fractionation in different directions. $^{15}N/^{14}N$ in the martian atmosphere is understood to have evolved over the past 3.8 billion years (it is currently 1.6 times the terrestrial value), and a determination of this ratio in near-surface materials may constrain the time of their formation. Compositional and isotopic analysis of surface minerals, weathering rinds, and sedimentary deposits will establish the role of liquid water and processes such as weathering. The corresponding measurements on volatiles released from near-surface materials are likely to be more heterogeneous and may provide fossils of past atmospheric and chemical conditions that allow the past climate to be better understood.

The SNC Meteorites Do Not Obviate the Need for Sample-Return Missions. SNC meteorites have provided a tantalizing view of a few martian rocks and a demonstration of how much can be learned when samples can be examined in Earth-based laboratories; however, they represent a highly selected subset of martian materials, specifically, very coherent rocks of largely igneous origin from a small number of unknown locations. Thus, SNC meteorites are unhelpful in answering one of our outstanding questions—What is the absolute chronology of Mars?—because although these meteorites can be accurately dated, the geologic units from which they are derived are unknown. While returned samples are also a selected subset of martian materials, we will know their geologic context, and they will be from sites selected because they can provide particularly valuable information.[3]

It is essential that the site to be sampled be carefully chosen, with the choice drawing upon the large body of orbital and lander data that will be in place by the time the MSR is flown. However, no single sample-return mission will completely satisfy the need for this form of exploration, no matter how carefully it is planned. Mars is highly varied in its geology; prior to returning some martian material to Earth it may be impossible for us to understand which type of site has the highest potential for providing samples that contain evidence of life and other valuable scientific data; sample collection and return represent a new endeavor, one that may not work perfectly the first time. It will be necessary to plan for a series of MSRs over whatever span of time the budget permits.[4]

MEDIUM MISSIONS

Mars Science Laboratory

The Mars Science Laboratory (MSL) is an important mission along the path of "Seek, in situ, and sample." The science goals are to conduct detailed in situ investigations of a site that is a water-modified environment identified from orbital data. As such, this mission will provide critical ground-truth for orbital data and test hypotheses for the formation and composition of water-modified environments identified through morphological and spectroscopic investigations. The types of in situ measurements possible on MSL are wide ranging, including atmospheric sampling, mineralogy and chemical composition, and tests for the presence of organics. There currently is some debate as to whether this mission will have roving capability on the order of 10 km, or be more focused toward drilling to get below the surface, which is hostile to life. Both strategies have merit in addressing high-priority science goals, though the drilling mission puts a much greater demand on precision landing. Regardless of the ultimate design of the instrumentation, **the SSE Survey recommends that while carrying out its science mission, the Mars Science Laboratory mission should test and validate technology required for sample return (e.g., sample handling and storage in preparation for sample return and feed-forward lander design, consistent with the future use of a Mars Ascent Vehicle).** In addition, the surface operations of the Mars Science Laboratory mission should feed forward to Mars Sample Return.[5]

Mars Long-Lived Lander Network

The Mars Long-Lived Lander Network (ML^3N) is a grid of science stations that will make coordinated measurements around Mars's globe for at least 1 martian year. The highest-priority objectives for network science on Mars are the determination of the planet's internal structure, including its core; the elucidation of surface and near-surface composition as well as thermal and mechanical properties; and extensive synoptic measurements of the atmosphere and weather. In addition, atmospheric gas isotopic observations (to constrain the size of currently active volatile reservoirs) and measurements of subsurface oxidizing properties and surface-atmosphere volatile exchange processes will be valuable.[6]

The Mars Long-Lived Lander Network (ML^3N) would use passive seismometers to explore the structure and activity of Mars. Heat-flow probes also would contribute importantly to our knowledge of the martian interior, but these require the drilling of holes, and they might more logically be emplaced by MSR if that mission has drilling capability; this would avoid placing a drilling requirement on the lander network.

ML^3N should also include meteorological stations that measure pressure, temperature, relative humidity, atmospheric opacity, and wind velocity. Also included should be mass spectrometers that permit high-precision, long-lived chemical and isotopic atmospheric analysis of the chemical dynamics of C, H, and O at Mars's surface. Time variability of isotopic compositions can be interpreted in terms of sources, sinks, and reservoirs of volatiles, and atmospheric evolution. Humidity sensors would track the flux of water vapor into and out of the regolith with time of day and season, providing important insight into the water budget on Mars.

The complement of instruments on the French-led NetLander mission, the four landers distributed around the planet, and the expected lifetime of 1 martian year will be sufficient to constrain the nature and size of the core, seismic activity, seismic velocities of the crust and mantle, and atmospheric properties of pressure, temperature, humidity, and wind speed. They will also have a magnetometer and electromagnetic sounding capabilities to sense crustal structures and to search for subsurface water and ice. While this complement of instruments does not address all of the high-priority goals outlined for the ML^3N, it represents a significant step forward.[7]

SMALL MISSIONS

Mars Scout Program

The Mars Scout program consists of competed, Discovery-class, principal-investigator-led missions with $300 million [now $475 million] cost caps.[8]

Mars Scout provides an excellent opportunity for NASA to address science priorities outside the principal objectives of the Mars Exploration Program, and for the broad science community to respond to discoveries and technological advancement. **The SSE Survey recommends that the Mars Scout program be managed as is the Discovery program, with principal-investigator leadership and competitive selection of missions.** It is essential, therefore, that the measurement goals for the Mars Scout program be directed toward the highest-priority science for Mars and be selected by peer review. The missions-of-opportunity element of the Scout program is also important, as it allows for participation in foreign Mars missions. **The SSE Survey strongly recommends that the Mars Exploration Program commit equally as strongly to the Scout program as to sample return.**

While Mars sample-return missions will be expensive and consuming of the attention of the MEP, there are sufficient resources in the program as currently structured to achieve both a viable Scout program and sample return. As witnessed by the response to the recent call for Scout proposal ideas (over 40 submissions were received), tremendous enthusiasm has been stimulated by recent Mars discoveries and scientific investigations not covered by the MEP. Scout provides a mission component that is highly flexible and responsive to discovery. **The SSE Survey recommends that a Mars Scout mission be flown at every other launch opportunity.**[9]

Mars Upper Atmosphere Orbiter

Mars Upper Atmosphere Orbiter (MAO) is a small mission dedicated to studies of Mars's upper atmosphere and plasma environment.[10]

Areas to be addressed by this low-cost mission are the dynamics of the upper atmosphere; hot atom abundances and escape fluxes; ion escape; minimagnetospheres and magnetic reconnections; and energetics of the ionosphere. [MAO] can explicitly explore these issues in the present-day environment and answer a number of important scientific questions. Furthermore, such a mission could quantify present-day escape processes and allow certain backward extrapolations to earlier epochs in martian history.

The instruments needed for a meaningful attack on these questions would require no new, basic instrument development and could be installed as a partial payload complement of an orbiting spacecraft. The neutral winds can be measured by either a "baffled" neutral mass spectrometer or a Fabry-Perot interferometer. The latter instrument, along with a good ultraviolet spectrometer, could address in a meaningful way the hot atom and neutral escape flux questions. The neutral mass spectrometer would also provide neutral composition and temperature information. A plasma instrument complement consisting of a magnetometer, low-energy ion mass spectrometer (capable of measuring flow velocities and temperatures), an electron spectrometer, a plasma wave detector, and a Langmuir probe would go a long way toward resolving the questions of ion escape, minimagnetospheres and magnetic reconnections, and energetics of the ionosphere.[11]

No plans exist in the current U.S. Mars Exploration Program to address any of the scientific questions identified by previous panels in this area. The Nozomi and Mars Express missions will address them to some extent, but much more data will be needed to meaningfully elucidate these issues. The measurements required for this mission could be accommodated as a science package on an international orbiter mission or as a stand-alone mission in the Mars Scout program.[12]

RESEARCH AND ANALYSIS PROGRAMS

It is largely through the work supported by [NASA's] research and analysis (R&A) programs . . . that the data returned by flight missions are converted into new understanding, advancing the boundaries of what is known. The research supported by these programs also creates the knowledge necessary to plan the scientific scope of future missions. Covered under this line item are basic theory, modeling studies, laboratory experiments, ground-based observations, long-term data analysis, and comparative investigations. The funds distributed by these programs support investigators at academic institutions, federal laboratories, nonprofit organizations, and industrial corporations. R&A furnishes the context in which the results from missions can be correctly interpreted. Furthermore, active R&A programs are a prime breeding ground for principal investigators and team members of forthcoming flight missions.

Healthy R&A programs are of paramount importance and constitute a necessary precondition for effective missions. . . . The ratio of submitted to funded proposals is typically 3 to 1, which—the SSE Survey believes—is too high, since at this rate new proposals can rarely be funded. Also, the availability of authorized funds is often subject to delays and, in recent times, the value of the median grant has fallen to below $50,000 per annum, a level generally too small to support a researcher or a tuition-paid graduate student.

The SSE Survey agrees . . . that NASA should routinely examine the size and number of grants to ensure that the grant sizes are adequate to achieve the proposed research. The Survey supports the budgetary proposals that would steadily expand solar system exploration R&A programs. **The SSE Survey recommends an increase over the decade 2003-2013 in the funding for fundamental research and analysis programs at a rate above inflation to a level that is consistent with the augmented number of missions, amount of data, and diversity of objects studied.**[13]

Astrobiological Research

NASA's Astrobiology program has appropriately become deeply interwoven into the solar system exploration research and analysis program. **The SSE Survey encourages NASA to continue the integration of astrobiology science objectives with those of other space science disciplines. Astrobiological expertise should be called upon when identifying optimal mission strategies and design requirements for flight-qualified instruments that address key questions in astrobiology and planetary science.**[14]

Astrobiology as a theme provides a scientific organizational structure that integrates a wide subset of solar system issues and questions that span the origins, evolution, and extinction of life. This theme allows nonexperts to grasp the connections between different component disciplines within planetary science and to do so in a way that most people will appreciate as addressing core themes in human thought. Astrobiology and its connections to space science (and solar system exploration in particular) are the primary means by which NASA tries to implement one of its prime objectives—understanding life's origins and its distribution in the universe.

. . . The SSE Survey encourages NASA to continue the integration of astrobiology science objectives with those of other space-science disciplines. Astrobiological expertise should be called upon when identifying optimal mission strategies and design requirements for flight-qualified instruments that will address key questions in astrobiology and planetary science.[15]

Martian Meteorites

[The] SNC category of martian meteorites plays an important role in studies relating to martian life and the planet's structure and evolution. Studies of this small group of meteorites in terrestrial laboratories have provided invaluable, if fragmentary, information about the geochemistry and chronology of Mars. NASA, the National Science Foundation, and the Smithsonian Institution have jointly supported an Antarctic meteorite program since 1976, in which teams of experts search areas known to contain a concentration of meteorites for 6 weeks every austral summer; support of this program should continue.[16]

Laboratory Facilities

In anticipation of the return of extraterrestrial samples from several ongoing and future missions, an analogue to the data pipeline must be developed for cosmic materials. **The SSE Survey recommends that well before cosmic materials are returned from planetary missions, NASA should establish a sample-analysis program to support instrument development, laboratory facilities, and the training of researchers.**[17]

Planetary Protection

In addition, planetary protection requirements for missions to worlds of biological interest will require investments, as will life-detection techniques, sample quarantine facilities, and sterilization technologies. NASA's current administrative activities to develop planetary protection protocols for currently planned missions are appropriate.[18]

Mars Quarantine Facility

Several NRC studies outline the containment requirements for samples returned from Mars. . . . The recent NRC report on the Mars Quarantine Facility (MQF) stresses that a minimum of 7 years will be required for the design, construction, and commissioning of the MQF, and that it must be operating up to 2 years prior to the arrival of martian samples. The purpose of the MQF is threefold: to sequester unaltered samples until biohazard testing is complete, to preserve the pristine nature of the samples, and to release samples deemed to be nonhazardous to a sample curation facility for allocation for further scientific study.

The technology required for containment and testing for pathogens is well developed. Biohazard assessment must also consider the potential ecological threats posed by returned samples. Sample containment must preserve the samples in a pristine condition, without inorganic and organic contamination. Technology for the preservation of samples similar to that used for lunar samples in the Lunar Curatorial Facility at the Johnson Space Center is well developed. However, the combination of biocontainment and preservation of samples in their pristine condition requires a unique design for the MQF that no currently existing facility provides. Another important design feature should be the potential for expansion, if early findings of definite evidence of extraterrestrial life warrant the need for all studies to be performed under containment. The cost of building such a specialized quarantine facility needs to be investigated.[19]

To prevent cross-contamination between samples from different planetary bodies, the samples must be handled in separate facilities. The Mars Curatorial Facility, for example, will be required once the martian samples are shown to be environmentally safe. Construction of such a facility is considered to be consistent with current practice and experience, for example, for lunar samples and antarctic meteorites. Sample allocations from the Lunar Curatorial Facility and from the Antarctic Meteorite Laboratory are under the guidance of advisory committees (the Curation and Analysis Planning Team for Extraterrestrial Materials and the Meteorite Working Group). These advisory committees are the successors of the Lunar Sample Analysis Planning Team, which oversaw the preliminary examination of the returned lunar samples and lunar sample allocations. These committees best exemplify the advisory committee proposed above for the oversight and analysis planning for Mars samples.[20]

Sample Curation

A critical necessity in preparation for the sample returns . . . anticipated . . . from Mars . . . is support for sample curation and handling at a significantly increased level over what exists today. The proper preservation of each returned sample for future investigations is of paramount importance. The samples returned . . . will have particular handling and storage demands, which must be addressed by separate, specialized facilities. The funding for these facilities, including long-term operating costs, cannot realistically come from each mission's budget. In particular, development is required in the areas of cryocuration, robotic sample handling, and biological quarantine. The panel recommends that the facilities required for the proper analysis and curation of returned samples be developed and supported.[21]

Ground-Based Observations

Continuing telescopic observation of Mars has played a key role in demonstrating that the surface of Mars changes on a relatively short time scale (as with seasonal changes, dust storms, evolution of the polar caps). Telescopic and spacecraft data are highly synergistic, and each plays a role in supporting the other. Support for future robotic and possible manned missions to Mars will require a long climatological baseline. The long baseline, partially obtained with ground-based and HST telescopic data, will also contribute to an understanding of the water cycles between the atmosphere, regolith, and polar caps, as well as spatially resolved data on volatile cycles of water, carbon dioxide, carbon monoxide, and ozone.[22]

NASA currently provides support, in widely varying percentages, for planetary science operations at Arecibo, Goldstone, Keck, and the Infrared Telescope Facility, in collaboration with the National Science Foundation (NSF), DSN, a private consortium, and NSF, respectively. . . . [These] facilities have made major contributions both to planetary science in general and to specific flight missions. The IRTF, the only facility dedicated to NASA planetary astronomy, has provided vital data in support of flight missions. **The SSE Survey recommends that the planetary**

radar facilities, the Infrared Telescope facility and NASA support for planetary observations at large facilities such as Keck be continued and upgraded as appropriate, for as long as they provide significant scientific return and/or provide mission-critical service.[23]

Theory

Models are an essential component of any scientific endeavor. Examples of theoretical planetary studies are those that treat the geodynamics of Mars, its interior structure, atmospheric loss and fractionation, and global climate and general circulation models.[24]

OTHER PROGRAMMATIC ELEMENTS

Technology Development

The SSE Survey recommends that NASA commit to significant new investments in advanced technology so that future high-priority flight missions can succeed. Unfortunately, erosion has occurred in the level of investment in technology in the past several years. Flight-development costs have increased over projections, and investments in advanced technologies have been redirected to maintain flight-mission development schedules and performance.

For most of the history of planetary exploration, large-cost flight missions . . . have carried a large portion of the technology-development burden in their development costs. During the change in the last decade to a larger number of lower-cost flight missions, the consequent loss of technology development by large missions was compensated by adding separate technology-development cost lines to the planetary exploration portfolio . . . under an understood policy of “no mission start before its technological time.” This mechanism was intended to separate and remove the uncertainties in technological development from early flight-development costs. However, flight-mission costs have been underestimated, and development plans have been too success-oriented, resulting in erosion of technology-development lines by transfer to flight-development costs. This trend needs to be reversed in order to realize [priority] flight missions. . . .[25]

Key Technologies

In the area of spacecraft systems, the key demand is for considerable autonomy and adaptability through advanced architectures. Lower-power, lower-mass spacecraft need to be developed commensurate with realistic cost and performance for the available expendable launch vehicles. Not unrelated is the need for more capable avionics in a more highly integrated package through advanced packaging and miniaturization of electronics and with a standardized software operating system.

New and increased science measurement capability in planetary science instruments and greater environmental tolerance will be required for less mass and power. Miniaturization is the key to the reduction of mass and power requirements. . . .

As planetary exploration moves into the new century with more in situ and sample-return missions, it will be necessary to develop planetary landing systems, in situ exploration systems, and Earth-return technologies. The key requirements for landing systems are autonomous entry, descent, hazard avoidance, and precision landing systems. Once on the surface, sample gathering and analysis become key technologies, with attendant requirements for new surface science instruments, including biological measurements, and means for moving about a planet—on, above, and below the surface. Systems for accessing difficult-to-reach areas will be required.

Rover technology should advance toward long-life and long-range capability, with autonomous hazard avoidance and the ability to operate on large slopes. Drilling techniques on both terrestrial and icy surfaces will be needed, advancing toward deep-ice penetration and submarine exploration in subsurface oceans. Aerial platforms for Mars . . . will be required. . . . Advanced autonomy will need to be built into all of these mobile mechanisms.

The means to return planetary samples needs to be developed, beginning with small bodies and the Moon, advancing toward Mars. . . .[26]

Communications Infrastructure

The Deep Space Network (DSN) is suffering from insufficient communications capability and occasional failures as it ages. Limitations on downlink bandwidth restrict the return of data from spacecraft. . . . While efforts to increase the transmitter power on spacecraft are valuable, likely it will be less expensive to augment both transmitter power and communications capacity on Earth than to correspondingly increase these factors on all spacecraft. Furthermore, additional ground stations would be valuable to provide geographic redundancy for the system as a whole, and they would grant more freedom in the timing of critical spacecraft events. . . .

The SSE Survey recommends upgrades and increased communications capability for the DSN in order to meet the specific needs for this program of missions throughout the decade, and that this be paid from the technology portion of the Supporting Research and Technology (SR&T) line rather than from the mission budgets.[27]

International Cooperation

Some future endeavors are so vast in scope or so difficult (e.g., sample return from Mars) that no single nation acting alone may be willing to allocate all of the resources necessary to accomplish them, and **the SSE Survey recommends that NASA encourage and continue to pursue cooperative programs with other nations.** Not only is the investigation of our celestial neighborhood inherently an international venture, but the U.S. Solar System Exploration program will also benefit programmatically and scientifically from such joint ventures.[28]

NOTES

1. National Research Council, *New Frontiers in the Solar System: An Integrated Exploration Strategy,* The National Academies Press, Washington, D.C., 2003, pp. 67-91 and 198-201.
2. *New Frontiers*, p. 82.
3. *New Frontiers*, pp. 198-199.
4. *New Frontiers*, pp. 82-83.
5. *New Frontiers*, pp. 199-200.
6. *New Frontiers*, p. 7.
7. *New Frontiers*, p. 83.
8. *New Frontiers*, p. 84.
9. *New Frontiers*, p. 200.
10. *New Frontiers*, p. 7.
11. *New Frontiers*, p. 83.
12. *New Frontiers*, p. 200.
13. *New Frontiers*, p. 163.
14. *New Frontiers*, p. 9.
15. *New Frontiers*, p. 158.
16. *New Frontiers*, p. 89.
17. *New Frontiers*, p. 9.
18. *New Frontiers*, p. 9.
19. *New Frontiers*, p. 169.
20. *New Frontiers*, p. 170.
21. *New Frontiers*, p. 32.
22. *New Frontiers*, p. 89.
23. *New Frontiers*, p. 206.
24. *New Frontiers*, p. 89.
25. *New Frontiers*, p. 202.
26. *New Frontiers*, pp. 203-204.
27. *New Frontiers*, p. 206.
28. *New Frontiers*, p. 2.

B

MEPAG Goals and Objectives

The Mars Exploration Program Analysis Group (MEPAG) is, according to its Web page, a "community-based forum designed to provide science input for planning and prioritizing Mars exploration activities for the next several decades. . . . MEPAG regularly evaluates Mars exploration goals, objectives, investigations, and required measurements on the basis of the widest possible community outreach."[1] In other words, MEPAG is not an appointed committee. All members of the Mars science and engineering communities can attend MEPAG meetings, and whoever wants to provide input can do so. MEPAG is generally regarded as quite effective in many respects, and its open, inclusive, and proactive approach to scientific and technical issues has made it a model of community engagement, a model now emulated by the outer solar system, Venus, and lunar science communities.

MEPAG has issued its comprehensive assessment of Mars goals, objectives, investigations, and required measurements four times in the last 5 years, most recently in February 2006.[2] Some might argue that the recommendations in MEPAG assessment reports reflect the wish lists of the people who go to the meetings, and that certain parts of the Mars community are much more engaged than others. To be fair, however, MEPAG's Goals Document Committee has equal representation from four distinct groups, which parallel MEPAG's four key Mars science goals. Thus, it can be argued that the recommendations from the Goals Document Committee are more even-handed and representative of the Mars science community than is the representation of different interest groups at MEPAG meetings.

MEPAG's priorities are determined by a consensus-building process and are organized in a top-to-bottom hierarchical manner as follows:

- Goals are long-term priorities and are organized around major scientific topics. Understanding Mars as a unified system implies that progress must be made by addressing all of the goals simultaneously, and so they are regarded as coequal in priority. MEPAG's four goals are each subdivided into objectives.
- Objectives describe the strategic approaches and milestones needed to address the goals. They are prioritized on the basis of either their importance or their position in a logical sequence of activities needed to address a particular scientific question. The 2006 MEPAG priorities list eight scientific objectives and two objectives relating to safe mission operations. The objectives are each subdivided into investigations.
- Investigations are the prioritized individual activities that, taken together, are needed to address each objective. Some investigations may be amenable to studies using the data from a single instrument on a single

spacecraft, but others will require data from multiple instruments on multiple spacecraft. Investigations are further subdivided into measurements.

- Measurements constitute actions that can be undertaken by a specific instrument on a specific spacecraft.

The goals and objectives contained in MEPAG's 2006 listing of priorities are as follows:

- Goal I. Determine if life ever arose on Mars.

Objective A. Assess the past and present habitability of Mars.
Objective B. Characterize carbon cycling in its geochemical context.
Objective C. Assess whether life is or was present on Mars.

- Goal II. Understand the processes and history of climate on Mars.

Objective A. Characterize Mars's atmosphere, present climate, and climate processes.
Objective B. Characterize Mars's ancient climate and climate processes through study of the geologic record.
Objective C. Characterize the state and processes of the martian atmosphere of critical importance for the safe operation of spacecraft.

- Goal III. Determine the evolution of the surface and interior of Mars.

Objective A. Determine the nature and evolution of the geologic processes that have created and modified the martian crust and surface.
Objective B. Characterize the structure, composition, dynamics, and evolution of Mars's interior.

- Goal IV. Prepare for human exploration.

Objective A. Obtain knowledge of Mars sufficient to design and implement a human mission with acceptable cost, risk, and performance.
Objective B. Conduct risk and/or cost reduction technology and infrastructure demonstrations in transit to, at, or on the surface of Mars.

NOTES

1. See, for example, <mepag.jpl.nasa.gov/>.
2. MEPAG reports can be found online at <mepag.jpl.nasa.gov/reports/index.html>.

C

Acronyms

AFL	Astrobiology Field Laboratory
ASTEP	Astrobiology Science and Technology Instrument Development
ASTID	Astrobiology Science and Technology for Exploring Planets
DSN	Deep Space Network
IRTF	Infrared Telescope Facility
JPL	Jet Propulsion Laboratory
MAO	Mars Upper Atmosphere Orbiter
MEP	Mars Exploration Program
MEPAG	Mars Exploration Program Analysis Group
MER	Mars Exploration Rover
MIDP	Mars Instrument Development Program
ML^3N	Mars Long-Lived Lander Network
MQF	Mars Quarantine Facility
MRO	Mars Reconnaissance Orbiter
MSL	Mars Science Laboratory
MSR	Mars Sample Return
MSTO	Mars Science and Telecommunications Orbiter
NRC	National Research Council
NSF	National Science Foundation
PI	principal investigator
PIDDP	Planetary Instrument Definition and Development Program
R&A	research and analysis
SSB	Space Studies Board
SSE	solar system exploration
VSE	Vision for Space Exploration