ASSESSMENT OF NASA's MARS EXPLORATION ARCHITECTURE

November 11, 1998

Dr. Carl Pilcher
Science Program Director
Solar System Exploration
Mail Code S
National Aeronautics and Space Administration
Washington, DC 20546

Dear Dr. Pilcher:

In your letter of August 12, 1998, you requested that the Committee on Planetary and Lunar Exploration (COMPLEX) assess the approach to Mars exploration advocated by NASA's Mars Architecture Definition Team. COMPLEX understands that you need its remarks by November 15, 1998, to assist in ongoing mission planning and budget deliberations concerning the Mars Surveyor missions scheduled for launch in 2003 and 2005.

As you requested, the assessment was conducted at COMPLEX's September 15-17, 1998, meeting held at the National Research Council's Georgetown offices in Washington, D.C. The assessment was based on presentations made by members of the Mars Architecture Definition Team, including Dr. Charles Elachi (chair), Dr. Dan McCleese (Chief Scientist of the Mars Exploration Directorate at the Jet Propulsion Laboratory), and Dr. Frank Jordan (Manager of the Mars Planning and Architecture Office at the Jet Propulsion Laboratory). Additional comments and elucidation were provided by Dr. John Rummel (NASA's Planetary Protection Officer).

In the course of its study, COMPLEX reviewed material submitted by the Mars Architecture Definition Team, consulted on recent scientific and technical developments with a select group of experts representing the diverse interests of the Mars science community, reviewed prior relevant reports by COMPLEX and other National Research Council (NRC) committees (e.g., *Mars Sample Return: Issues and Recommendations* [1997], "Scientific Assessment of NASA's Mars Sample-Return Mission Options" [December 3, 1996], and *Review of NASA's Planned Mars Program* [1996]), and held extensive discussions in closed session.

NASA's presentations emphasized that the implementation aspects of the Mars exploration program will be defined in the next stage of the study. Thus, COMPLEX was unable to provide a detailed, point-by-point technical analysis of the scientific responsiveness of the proposed Mars exploration architecture. The committee was, however, able to provide a general assessment in the light of recommendations made in a variety of previous NRC reports (see attached "Assessment of NASA's Mars Exploration Architecture"). As such, both COMPLEX and the Space Studies Board (SSB) regard this current document as another step in an iterative process that has been in progress for many years and will continue with the evolution of NASA's planning for the implementation of its Mars exploration program and the program's central facet, a series of sample-return missions scheduled to begin in 2005.

As you know, COMPLEX and the SSB have consistently emphasized the importance of an intensive study of Mars by spacecraft. An important element of such a program is the return of martian samples to Earth. COMPLEX continues to support this viewpoint. The primary objectives for Mars exploration and sample-return missions have been clearly defined and prioritized by both COMPLEX and other groups. These include, among other high-priority objectives, the search for evidence of possible martian life, past or present.

The Mars Architecture Definition Team has done a fine job in designing the program. The incorporation of the return of multiple samples from a variety of diverse sites is a particular strength. Overall, COMPLEX concluded that the program to address the question of life on Mars is sound. There are, however, some concerns to address in the implementation phase as well as some concerns about possible impacts on the program's scientific return. These concerns, described in the attached assessment, led COMPLEX to make the following recommendations:

- The scientific goals and objectives of NASA's Mars exploration program must be stated in scientifically valid and reasonable terms. That is, the interpretation of biologically relevant observations can be maximized only if the data are gathered in the context of a broad framework of research aimed at understanding the origin and evolution of the martian environment. Thus, an appropriate focus for NASA's Mars program is the comprehensive goal of understanding Mars as a possible abode of past or present life. Moreover, a biologically oriented program must be conducted within the framework of appropriate safeguards against forward and back contamination to maintain scientific integrity and public trust.

- A Science Definition Team should be appointed by NASA Headquarters as soon as possible to provide oversight, guidance, and recommendations as an integral part of the implementation process. The team's responsibilities should include, among other things, devising "decision trees" based on the proposed missions' potential for scientific discoveries, assessing the scientific consequences of various descope options, and determining if proposed landing sites meet program goals.

- Plans should be formulated for integrating the myriad elements of the Mars exploration architecture. These elements include NASA (e.g., intercenter roles, responsibilities, and interfaces), the scientific community, the public, and international constituents.

• The process of sample handling (from arrival on Earth to distribution to investigators) and data analysis (from collection to distribution to the scientific community in a usable form) must be defined within the context of well-developed "end-to-end," science-driven plans. Relevant resources must also be identified for these and related activities, such as sample- and data-analysis programs, and upgrading laboratory facilities.

• The enabling and enhancing activities, such as the micromissions, the uncommitted payload mass, and operational tests, are fundamental to fulfilling the scientific objectives of the Mars exploration program because they can enhance the data return, enable new or unique measurements, provide flexibility to respond to new discoveries, and permit the optimization of surface operations based on experience from relevant preflight tests. In addition, the micromissions and uncommitted payload mass provide a potential means of addressing scientific goals not currently included in NASA's architecture (e.g., studies of martian climate change).

COMPLEX notes that it was not able to comment on those aspects of the Mars exploration architecture relating to preparations for a possible program of human exploration in the next century. The Space Studies Board points out that scientific issues relating to this topic have been and continue to be discussed by its Committee on Human Exploration and Committee on Microgravity Research. In addition, relevant engineering and technical issues are being considered by the NRC's Aeronautics and Space Engineering Board.

The Space Studies Board and COMPLEX look forward to following the future development and implementation of NASA's plans for Mars exploration and, in particular, sample-return missions. COMPLEX is particularly interested in hearing an updated presentation at the earliest opportunity, so that the committee can follow the exploration architecture's evolution into an implementation plan. COMPLEX is also interested in receiving responses on the comments contained in the attached assessment.

Sincerely,

Claude Canizares
Chair
Space Studies Board

Ronald Greeley
Chair
COMPLEX

cc: C. Elachi

Assessment of NASA's Mars Exploration Architecture

COMPLEX's ASSESSMENT OF NASA's MARS EXPLORATION ARCHITECTURE

NASA's Mars exploration "architecture" was reviewed by the National Research Council's (NRC's) Committee on Lunar and Planetary Exploration (COMPLEX) at its September 15-17, 1998, meeting in Washington, D.C. The term "architecture" is used by NASA to signify the overall technological and scientific framework within which it will conduct a program to understand the potential biological history of Mars and the search for evidence of past or present life. A focus of the architecture is the return of a series of samples and relevant data to Earth.

Presentations on the Mars exploration architecture were given by Dr. Charles Elachi (Director of Space and Earth Science Programs at the Jet Propulsion Laboratory [JPL] and chair of the Mars Architecture Definition Team), Dr. Dan McCleese (Chief Scientist of the Mars Exploration Directorate, JPL), and Dr. Frank Jordan (Manager for the Mars Planning and Architecture Office, JPL) on the strategies behind and elements of the architecture.

In addition to members of COMPLEX, leading experts on Mars from the scientific community were invited to participate in the discussion of the Mars exploration architecture (see Appendix 1). After the presentations, four working groups, each led by members of COMPLEX, discussed the scientific elements of the architecture, including exobiology, sample return, surface science, and remote sensing, in the context of recent scientific and technical developments. Results from the working groups were then discussed in open sessions of the full group.

Later, in closed session, COMPLEX deliberated on the presentations and the results from the discussions of the working groups, taking into account recommendations contained in relevant NRC reports (e.g., *Mars Sample Return: Issues and Recommendations* [1997], "Scientific Assessment of NASA's Mars Sample-Return Mission Options" [December 3, 1996], *Review of NASA's Planned Mars Program* [1996], and *The Search for Life's Origins* [1990]), and it developed and reached consensus on the conclusions and recommendations presented in this assessment.

COMPLEX regards this assessment as an incremental step in an iterative process that has been in progress for many years and will continue with the evolution of NASA's planning for Mars exploration and, in particular, sample-return missions. COMPLEX finds that the general architecture (see Appendix 2) is well thought out and is a rational approach to achieving the goals of the program. The incorporation of plans for the return of multiple samples selected at a variety of diverse sites is a substantial strength of the architecture. As such, the architecture's scientific potential appears to be very high.

Given the lack of detailed definition of the Mars missions in the post-2001 era and the lack of specifics in the presentations to COMPLEX (see Appendix 2), an assessment of "the degree to which the revised [Mars Surveyor] program is responsive to the Board's previous scientific advice" must await the completion of an implementation plan based on the architecture. However, based on discussions and deliberations, COMPLEX was able to identify three general issues that need to be addressed if NASA's Mars program is to realize its full scientific potential. These issues include:

1. Architecture design,
2. Architecture implementation, and
3. Budgetary and technology concerns.

A fourth potential category is the relationship between the architecture and possible human-exploration missions to Mars in the next century. This issue was not discussed, however, because COMPLEX did not receive any detailed information on this topic.

In the sections that follow, COMPLEX discusses pertinent issues in the three areas listed above and presents specific conclusions and recommendations.

Architecture Design

As a result of its discussions and deliberations, COMPLEX concluded that two areas of the overall architecture require attention, namely:

- The manner in which the architecture's biologically oriented goals are posed; and
- Issues relating to the integration of various facets of the architectures.

Rephrase the Objectives in the Goal Statement

The goal statement for the Mars architecture should be phrased in a fashion that maintains both excitement and scientific integrity. The goal of NASA's Mars exploration program is, according to the presentations received by COMPLEX, "[to] achieve significant advances toward understanding the biological history of Mars and [to] search for evidence of past or present life" (see Appendix 2).

Finding convincing evidence of present or past life on Mars would be a discovery of paramount significance to society. However, it is also possible that life has never existed on Mars. NASA, the scientific community, and the public must recognize that the planned program of exploration will provide valuable constraints on where and under what conditions life originates, independent of whether life is found.

In searching for evidence of past or present life on Mars, it is important to understand that either answer, positive or negative, is scientifically important and that any evidence, particularly that obtained early in the program, is likely to be somewhat ambiguous.[1] Consequently, the larger context of the evidence is key to its proper interpretation. **Thus, the scientific goals and objectives of NASA's Mars exploration program must be stated in scientifically valid and reasonable terms. The interpretation of biologically relevant observations can be maximized only if the data are gathered in the context of a broad framework of research aimed at understanding the origin and evolution of the martian environment. Thus, an appropriate focus for NASA's Mars program is the comprehensive goal of understanding Mars as a possible abode of past or present life.**

To the extent possible, information must be obtained on the global martian environment in order to understand the events in the history of the martian samples and of the planet in general.[2] The missions outlined in the Mars exploration architecture will provide some of this information through the course of site selection, in situ surface observations, and analysis of returned samples.

One consequence of a biologically oriented program is a heightened awareness of issues related to planetary protection. As a result, maintenance of both the scientific integrity of returned samples and the public's trust demands that the program be conducted within the framework of appropriate safeguards relating to forward and back contamination.[3,4]

Develop Plans to Integrate the Program Elements

One of the greatest strengths of the Mars exploration program is the breadth and depth of its support. The exploration of Mars is a high priority for the scientific community,[5] it is a major programmatic goal for NASA,[6] and it is a prime policy goal of the Clinton Administration.[7] Mars is also of great interest to the public and is the next obvious target for human exploration beyond the Earth-Moon system.[8]

These collective constituencies support Mars exploration for different reasons, and the exploration architecture will, necessarily, be a compromise reflecting diverse goals and aspirations. Integrating the various rationales for Mars exploration is a challenge for NASA, the nation, and the international community.

Internally, NASA must integrate the diverse interests of three primary constituencies:

1. The traditional planetary science community;
2. The human exploration community; and
3. The increasingly important biological and life sciences communities.

The roles, relationships, and interfaces among these interests and associated constituencies in various NASA centers must be articulated to avoid confusion and misunderstanding and to ensure that the scientific goals for the exploration of Mars are not compromised by competing goals and objectives.[9]

At the national level, NASA's Mars exploration architecture must be responsive to other goals. The program must integrate:

1. The public's profound interest in exploration;
2. The desire of the scientific community to generate new knowledge;
3. The interest of engineers and technologists in advancing their arts; and
4. Policy stakeholders' interest in using the program to advance educational goals, promote industry, and enhance national prestige.

The incorporation of a significant degree of international cooperation in the Mars exploration program raises new integration issues. International partnerships significantly enhance the program elements that can be undertaken, leverage scarce resources, optimize the limited launch opportunities, and promote the vitality of the worldwide scientific and engineering communities. International cooperation, however, exposes the program to uncertainties related to the domestic forces driving the space programs of the participating nations. If insufficient care is taken to define the roles and responsibilities of the various participants, any ensuing problems will threaten the benefits of the collaboration and have a chilling effect on future cooperation.[10,11] International participation makes a given project much more difficult. The advantages can, however, certainly justify the added difficulty, but they need to be carefully analyzed to ensure that the justifications are valid.

Plans should be formulated for integrating the myriad elements of the Mars exploration architecture. These elements include NASA (e.g., intercenter roles, responsibilities, and interfaces), the scientific community, the public, and international constituents.

Architecture Implementation

As planning for the implementation phase of the Mars exploration program begins, several key issues must be taken into account. These include:

1. Contingencies, discoveries, and descope options;
2. The role of a Science Definition Team;
3. Ensuring valid sample and science return;
4. Accessing high-priority landing sites;
5. Promoting enabling and enhancing activities;
6. Planning for activities related to sample return and data analysis; and
7. Integrating public outreach and educational activities.

Consider Contingencies, Discoveries, Descopes, and the Role of a Science Definition Team

Two elements of planning need to be incorporated in the implementation plan deriving from the proposed Mars exploration architecture. These are its potential for scientific discoveries and the impact of possible descope options (i.e., reductions in capabilities required as a result of unforeseen problems in the implementation of the program).

The scientific potential of the missions outlined by the Mars Architecture Definition Team is very high, and a wealth of scientific discoveries can be expected. The Mars exploration program should capitalize on this potential and retain sufficient flexibility to respond to discoveries.

NASA's sample-return strategy is, for example, centered on the exploration of various manifestations of past or present aqueous environments.[12] But if the first site selected for sample return fails to yield evidence of aqueous environments or, alternatively, presents convincing evidence of extinct or extant life, does the basic strategy (including subsequent site selections and instrumentation) remain the same, or does it change? If so, how would the strategy be revised? Because the time between missions and the time for analysis of results are limited, the potential changes in strategy must be considered and debated by the scientific community in advance as a part of the decision-making process.

The proposed architecture is, however, very complex, involving multiple mission elements, many of which have not flown previously in planetary projects. Because of the inherent risks in these elements and limitations in funds and schedule, it is essential that various *descope options* and *contingencies* be defined for each major element of the program and that the *scientific consequences* of the descopes be clearly identified.

The Space Studies Board has consistently maintained that scientists should be involved in flight programs from the earliest possible opportunity.[13] Thus, **a Science Definition Team should be appointed by NASA Headquarters as soon as possible to provide oversight, guidance, and recommendations as an integral part of the implementation process. The team's responsibilities should include, among other things, devising "decision trees" based on the proposed missions' potential for scientific discoveries, assessing the scientific consequences of various descope options, and determining if proposed landing sites meet program goals.** Members of this team should include scientists who have direct experience in handling extraterrestrial samples.

Ensure Valid Sample and Science Return

The focus of each Mars lander scheduled for launch between 2003 and 2013 is, according to the architecture, the collection and return to Earth of diverse materials from sites for which basic geomorphic, mineralogic, petrologic, and chemical information has been gathered. Detailed study of the materials and the accompanying information will be conducted in terrestrial laboratories. As outlined, these missions are responsive to the scientific rationale for Mars sample-return missions established by COMPLEX and other groups.[14-18]

Each lander is equipped with a rover significantly more capable than that carried by Mars Pathfinder. Together, the rover and lander must deliver the maximum allowable mass of rock and soil to the sample-return container. Although the landers may be capable of collecting their own samples (with the aid of an arm and, perhaps, a drill) and conducting geological observations, the rover's mobility is the key to ensuring that the samples selected at each landing site represent the full diversity of materials present.[19-24] Each rover must, therefore, carry instruments that can characterize the rocks as well as the environments within which the rocks are found.

To meet the goals of in situ determination of geomorphology, mineralogy, petrology, and chemistry for each landing site, the standard rover instrument complement for these missions should provide images of the terrain at scales ranging from panoramic to microscopic; mineralogical analysis for accurate determination of rock types; major-element chemical analyses of selected samples; and detection of organic or reduced inorganic carbon if either is common and abundant (>1%) in the rocks at the site.[25-28]

Proper geological characterization of each site is required not only to provide local context for collected samples, but also to obtain new information about the surface of Mars independent of the sampling activity. This latter purpose must always be fulfilled so that each mission will be scientifically successful even if unforeseen circumstances prohibit samples from being collected or returned to Earth. These basic goals should be met by each mission within the 2003 to 2013 suite; other goals may be accommodated but should not interfere with the core activities of any mission or jeopardize future missions.

Maintain Flexibility for Accessing High-Priority Landing Sites

Several issues related to landing-site selection and implementation directly affect the ability to search for evidence of martian life. Current engineering constraints appear to rule out many sites of exobiological interest, based either on their latitude (which must be between 5 degrees, north, and 10 degrees, south,) or their elevation (which must be below an altitude of 2.5 km). It is important that decisions not be made that would unnecessarily constrain the ability to land in a given location. Moreover, because the size of currently achievable landing-error ellipses is far greater than the distances that current rovers can be expected to traverse, there is no certainty that some discrete sites of high scientific interest can actually be reached.

Information necessary to identify sites of particular interest will be obtained on early missions, particularly Mars Global Surveyor and Mars Geochemical Mapper (scheduled for launch in 2001). In this regard, participants in COMPLEX's discussions were concerned over two issues: first, the plan to reduce the operational life of the Mars Geochemical Mapper from 1 martian year to 1 year, and second, the absence of scientific instruments on subsequent U.S. orbiters. These decisions mean that the imaging and other remote-sensing data from the European Space Agency's Mars Express (scheduled for launch in 2003) are critical for site selection and general science. This is true not only for the increased coverage provided by Mars Express, but also for the near-infrared mapping data that would not otherwise be obtained.

Promote Associated Enabling and Enhancing Activities

The Mars exploration architecture outlines a framework within which it should be possible to conduct a highly focused program of martian exploration. COMPLEX notes that it should be possible to enhance various aspects of the scientific activities that can be conducted within this framework. COMPLEX focuses on three areas: the proposed micromissions, the 100-kg uncommitted payload mass on the landers, and operational tests associated with surface science.

Micromissions

Micromissions can contribute directly to the science goals of the Mars exploration program in a variety of ways. For example, the network of communication satellites, described as one option, not only would enhance the return of science data to Earth and enable more robust rover operations,29 but also has the potential to act as a navigational aid to enable very precise landings at targets of high scientific interest.

Micromissions are also recognized as enabling the flight of various low-altitude aerial platforms, such as aerobots, aircraft, and gliders. Such platforms could provide imaging data with resolutions of 10 cm, bridging the gap between data obtained from orbit and the surface. These data not only would provide the potential for new science, but also would enable and enhance planning for surface operations such as rover traverses, as well as avoidance of hazards. Moreover, the data could provide unique information to meet program objectives. For example, the low altitudes at which micromissions could be flown would enable searches for water on scales of a kilometer (using neutron spectroscopy); such observations cannot be performed by orbiters. Moreover, they could survey much larger areas than is possible with surface experiments.

Uncommitted Payload Mass

As a means to accommodate additional instruments designed to address unanticipated results and discoveries, the uncommitted lander-payload mass provides flexibility to the Mars exploration program. Currently, there are no funds for additional instruments, but potential international payloads and contributions from NASA's human-exploration program could be added to address the scientific goals of the Mars program not directly addressed in NASA's program (e.g., studies related to martian climate change), while simultaneously maintaining flexibility.

Operational Tests

Many elements of the architecture include new, untested technologies. It is imperative that the current plans for scientific testing of these elements and for gaining associated operational experience (such as field testing of rovers) be fully supported and documented.[30] This approach will ameliorate potential operational problems on Mars and enhance the potential return of scientific data.

Enhancements and Descope Options

There is the danger that enabling and enhancing activities such as the micromissions, the uncommitted payload mass, and operational tests might be viewed as "reserves." **COMPLEX views these elements as fundamental in fulfilling the scientific objectives of the Mars exploration program because they can enhance the data return, enable new or unique measurements, provide flexibility to respond to new discoveries, and permit the optimization of surface operations based on experience from relevant preflight tests. In addition, the micromissions and uncommitted payload mass provide a potential means of addressing scientific goals not currently included in NASA's architecture (e.g., studies of martian climate change).** The position of these enhancing and enabling activities in a hierarchy of potential descope options cannot be determined until the post-2001 Mars program is more clearly defined and the scientific consequences of their retention or deletion can be assessed more easily.

Plan for Activities Related to Sample Return and Data Analysis

The returned samples are the most important product of the program, but the value of the science to be derived from them depends critically on how well the record that they contain is preserved in its pristine condition. The presentations given to COMPLEX explained that significant resources will be made available for planetary-protection activities. Planning for what happens to the samples after they reach Earth appears much less clear.

Using the lunar sample curation activities as a model, sample handling must include the safe transportation of the samples to an appropriate facility or facilities for testing for biohazards, curation, storage under pristine conditions, preliminary characterization sufficient to permit scientists to request samples and to plan for their analysis, and the distribution of samples to the scientific community.

Similar arguments apply to in situ and remote-sensing data collected during Mars missions. These data must be calibrated and archived in such a way that they are readily available to, and usable by, the scientific community. **Thus, the process of sample handling (from arrival on Earth to distribution to investigators) and data analysis (from collection to distribution to the scientific community in a usable form) must be defined within the context of well-developed "end-to-end" science-driven plans. Relevant resources must also be identified for these and related activities, such as sample- and data-analysis programs, and upgrading laboratory facilities.**

Integrate Public Outreach and Science Activities

Mars has long been a topic of fascination to the public. The extraordinary interest and response demonstrated during the Pathfinder Mission in 1997 argue that significant educational and outreach activities should be an integral part of the Mars exploration program. The complexity of defining and then conducting rigorous scientific investigations of possible past or present life on another world needs to be explained to the public carefully, thoroughly, and in an engaging manner.

The Mars Pathfinder experience demonstrates that the optimum use of Internet capabilities on a near-real-time basis is crucial to this task. Yet, the extremes of either trivial involvement or interference with scientific activities need to be addressed early in the planning in order to avoid potentially harmful complexities or unrealistic expectations by the public, educators, or the media. The planetary-science community should be actively involved in educational and public-outreach activities associated with the Mars exploration program. Such outreach and educational activities might be funded through NASA's current education grants. A relatively few dollars, wisely spent, could yield enormous benefits to the nation's educational system.[31]

Budgetary and Technology Concerns

Better Definition of Program Costs

Overall, COMPLEX viewed the architecture as an aggressive plan that, according to the Mars Architecture Definition Team, was consistent with available resources, but COMPLEX's level of confidence in the estimated costs for program development and implementation was low. Given the constrained funding for the program, COMPLEX believes that the estimated costs for the program need to be much better defined if NASA is to accomplish its stated science objectives.[32,33] Furthermore, mechanisms to accommodate identified, but uncosted, components of the architecture to be supplied by, for example, NASA's human-exploration program will require careful attention to minimize potential impacts on the science objectives.[34]

Reduce Risk in the Sample-Return Process

The proposed strategy to return martian samples to Earth involves a chain of new and, apparently, untried technologies and operational procedures; failure of a single link in the chain could lead to a failure to return the samples and thus compromise the goal of sample return. The proposed elements that COMPLEX views as high risk include the transfer of the sample cache from the rover to the Mars Ascent Vehicle, the ascent and orbital insertion of the sample payload, capture of the payload in orbit by the transfer vehicle, return of the transfer vehicle to Earth, and delivery of the samples to the surface via high-speed (12-km/s) reentry through Earth's atmosphere. Although the redundancy of having two sample caches in orbit available for capture reduces some of the risk, there remain significant concerns for technology development and the impact of development delays on schedule and cost.

Ensure That the Program Is Driven by Science

The amount budgeted to reduce the data to a form usable for mission planning and usable by the scientific community may be inadequate to support the goals of the Mars program. The aggressive schedule will require rapid reduction and release of data for science analysis and mission planning. The tight requirements for technology development over the course of the program may put additional pressure on the resources budgeted for data analysis. In addition, the resources required for the preliminary characterization of the returned samples and their delivery to the appropriate curatorial facilities are specifically excluded from the Mars program. Also excluded are funds necessary to upgrade laboratories to prepare them for the analysis of martian samples. It is imperative that these essential functions be accommodated and that these and other requirements of the Mars program (e.g., sample- and data-analysis programs) not put additional pressure on NASA's Research and Analysis programs.[35,36] A full discussion of all the relevant issues will require a separate study.

Conclusions and Recommendations

As a result of its assessment, COMPLEX concluded that the architecture is a well-thought-out and rational approach to achieving NASA's programmatic goals for Mars exploration. Nevertheless, although the scientific potential is high, COMPLEX has some concerns about possible impacts on the Mars program's scientific return. These concerns, as outlined above, led COMPLEX to offer the following conclusions and recommendations:

- The scientific goals and objectives of NASA's Mars exploration program must be stated in scientifically valid and reasonable terms. That is, the interpretation of biologically relevant observations can be maximized only if the data are gathered in the context of a broad framework of research aimed at understanding the origin and evolution of the martian environment. Thus, an appropriate focus for NASA's Mars program is the comprehensive goal of understanding Mars as a possible abode of past or present life. Moreover, a biologically oriented program must be conducted within the framework of appropriate safeguards against forward and back contamination to maintain scientific integrity and public trust.
- A Science Definition Team should be appointed by NASA Headquarters as soon as possible to provide oversight, guidance, and recommendations as an integral part of the implementation process. The team's responsibilities should include, among other things, devising "decision trees" based on the proposed missions' potential for scientific discoveries, assessing the scientific consequences of various descope options, and determining if proposed landing sites meet program goals.

- Plans should be formulated for integrating the myriad elements of the Mars exploration architecture. These elements include NASA (e.g., intercenter roles, responsibilities, and interfaces), the scientific community, the public, and international constituents.
- The process of sample handling (from arrival on Earth to distribution to investigators) and data analysis (from collection to distribution to the scientific community in a usable form) must be defined within the context of well-developed "end-to-end," science-driven plans. Relevant resources must also be identified for these and related activities, such as sample- and data-analysis programs, and upgrading laboratory facilities.
- The enabling and enhancing activities, such as the micromissions, the uncommitted payload mass, and operational tests, are fundamental to fulfilling the scientific objectives of the Mars exploration program because they can enhance the data return, enable new or unique measurements, provide flexibility to respond to new discoveries, and permit the optimization of surface operations based on experience from relevant preflight tests. In addition, the micromissions and uncommitted payload mass provide a potential means of addressing scientific goals not currently included in NASA's architecture (e.g., studies of martian climate change).

[1]Space Studies Board, National Research Council, "Scientific Assessment of NASA's Mars Sample-Return Mission Options," letter report to Jurgen Rahe, NASA, December 3, 1996, page 2.

[2]Space Studies Board, National Research Council, "Scientific Assessment of NASA's Mars Sample-Return Mission Options," letter report to Jurgen Rahe, NASA, December 3, 1996, page 4.

[3]Space Studies Board, National Research Council, *Biological Contamination of Mars: Issues and Recommendations*, National Academy Press, Washington, D.C., 1992, pages 9-11.

[4]Space Studies Board, National Research Council, *Mars Sample Return: Issues and Recommendations*, National Academy Press, 1997, pages 3-5, 27-29, and 36.

[5]Space Studies Board, National Research Council, *An Integrated Strategy for the Planetary Sciences: 1995-2010*, National Academy Press, Washington, D.C., 1994, page 8.

[6]Office of Space Science, NASA, *The Space Science Enterprise Strategic Plan: Origins, Evolution, and Destiny of the Cosmos and Life*, NASA, Washington, D.C., 1997, pages 21-22.

[7]National Science and Technology Council, Executive Office of the President, *National Space Policy*, The White House, Washington, D.C., 1996, page 2; available online at www.whitehouse.gov/WH/EOP/OSTP/NSTC/html/fs/fs-5.html.

[8]Advisory Committee on the Future of the U.S. Space Program, *Report of the Advisory Committee on the Future of the U.S. Space Program*, U.S. Government Printing Office, Washington, D.C., 1990, page 6.

[9]Space Studies Board, National Research Council, *Science Management in the Human Exploration of Space*, National Academy Press, Washington, D.C., 1997, pages 2 and 27.

[10]Space Studies Board, National Research Council, *An Integrated Strategy for the Planetary Sciences: 1995-2010*, National Academy Press, Washington, D.C., 1994, pages 32-33.

[11]Space Studies Board, National Research Council, and European Space Science Committee, European Science Foundation, *U.S.-European Collaboration in Space Science*, National Academy Press, Washington, D.C., 1998, pages 39-41.

[12]Mars Expeditions Strategy Group, NASA, *The Search for Evidence of Life on Mars*, Jet Propulsion Laboratory, Pasadena, California, 1996, page 2.

[13]Space Studies Board, National Research Council, *Managing the Space Sciences*, National Academy Press, Washington, D.C., 1995, pages 74-75.

[14]Space Studies Board, National Research Council, "Scientific Assessment of NASA's Mars Sample-Return Mission Options," letter report to Jurgen Rahe, NASA December 3, 1996.
[15]Space Studies Board, National Research Council, *Review of NASA's Planned Mars Program*, National Academy Press, Washington, D.C., 1996, pages 10-11.
[16]Space Studies Board, National Research Council, *An Integrated Strategy for the Planetary Sciences: 1995-2010*, National Academy Press, Washington, D.C., 1994, page 104.
[17]Space Studies Board, National Research Council, *1990 Update to Strategy for Exploration of the Inner Planets*, National Academy Press, Washington, D.C., 1990, page 5.
[18]Space Science Board, National Research Council, *Space Science in the Twenty-First Century: Imperatives for the Decades 1995 to 2015—Planetary and Lunar Exploration*, National Academy Press, Washington, D.C., 1988, pages 8-9 and 17.
[19]Space Studies Board, National Research Council, "Scientific Assessment of NASA's Mars Sample-Return Mission Options," letter report to Jurgen Rahe, NASA December 3, 1996, pages 3-4.
[20]Space Studies Board, National Research Council, *Review of NASA's Planned Mars Program*, National Academy Press, Washington, D.C., 1996, page 23.
[21]Space Studies Board, National Research Council, *An Integrated Strategy for the Planetary Sciences: 1995-2010*, National Academy Press, Washington, D.C., 1994, page 104.
[22]Space Science Board, National Research Council, *Space Science in the Twenty-First Century: Imperatives for the Decades 1995 to 2015—Planetary and Lunar Exploration*, National Academy Press, Washington, D.C., 1988, page 93.
[23]Space Science Board, National Research Council, *Strategy for Exploration of the Inner Planets: 1977-1987*, National Academy of Sciences, Washington, D.C., 1978, page 44.
[24]Space Science Board, National Research Council, *Post-Viking Biological Investigations of Mars*, National Academy of Sciences, Washington, D.C., 1977, pages 14 and 23.
[25]Space Studies Board, National Research Council, "Scientific Assessment of NASA's Mars Sample-Return Mission Options," letter report to Jurgen Rahe, NASA, December 3, 1996, page 4.
[26]Space Studies Board, National Research Council, *Review of NASA's Planned Mars Program*, National Academy Press, Washington, D.C., 1996, pages 22 and 25.
[27]Space Studies Board, National Research Council, *An Integrated Strategy for the Planetary Sciences: 1995-2010*, National Academy Press, Washington, D.C., 1994, page 104.
[28]Space Science Board, National Research Council, *Space Science in the Twenty-First Century: Imperatives for the Decades 1995 to 2015—Planetary and Lunar Exploration*, National Academy Press, Washington, D.C., 1988, page 93.
[29]Space Science Board, National Research Council, *A Scientific Rationale for Mobility in Planetary Environments*, National Academy Press, Washington, D.C., 1998, in preparation.
[30]Space Science Board, National Research Council, *A Scientific Rationale for Mobility in Planetary Environments*, National Academy Press, Washington, D.C., 1998, in preparation.
[31]Space Studies Board, National Research Council, *The Role of Small Missions in Planetary and Lunar Exploration*, National Academy Press, Washington, D.C., 1995, page 21.
[32]Space Studies Board, National Research Council, *Managing the Space Sciences*, National Academy Press, Washington, D.C., 1995, page 63.
[33]Space Studies Board and Aeronautics and Space Engineering Board, National Research Council, *Reducing the Cost of Space Science Research Missions*, National Academy Press, Washington, D.C., 1997, pages 4-5 and 10-14.
[34]Space Studies Board, National Research Council, *Science Management in the Human Exploration of Space*, National Academy Press, Washington, D.C., 1997, pages 30-32.
[35]Space Studies Board, National Research Council, *Supporting Research and Data Analysis in NASA's Science Programs: Engines for Innovation and Synthesis*, National Academy Press, Washington, D.C., 1998, page 9.
[36]Space Studies Board, National Research Council, *An Integrated Strategy for the Planetary Sciences: 1995-2010*, National Academy Press, Washington, D.C., 1994, pages 29-30.

Assessment of NASA's Mars Exploration Architecture

Appendix 1
PARTICIPANTS IN COMPLEX's MARS ARCHITECTURE REVIEW

Committee and Invited Participants

1. Boynton, William *	University of Arizona
2. Calvin, Wendy *	United States Geological Survey
3. Drake, Michael	University of Arizona
4. Farmer, Jack	Arizona State University
5. Frey, Herb	Goddard Space Flight Center
6. Greeley, Ronald *	Arizona State University
7. Haskin, Larry *	Washington University
8. Head, James	Brown University
9. Jakosky, Bruce *	University of Colorado
10. Mendillo, Michael *	Boston University
11. Mustard, Jack *	Brown University
12. Rummel, John	Marine Biological Laboratory
13. Spudis, Paul	Lunar and Planetary Institute
14. Treiman, Allan	Lunar and Planetary Institute
15. Wanke, Heinrich	Max-Planck Institute for Chemistry

Presenters

1. Elachi, Charles	Jet Propulsion Laboratory

2. Jordan, Frank Jet Propulsion Laboratory

3. McCleese, Dan Jet Propulsion Laboratory

Working Groups

Exobiology:	**Surface Science:**	**Sample Return:**	**Remote Sensing:**
Jakosky**	Calvin**	Haskin**	Boynton**
Farmer	Frey	Drake	Mendillo
Rummel	Head	Treiman	Mustard
Spudis	Wanke		

*Member of COMPLEX.
**Group leads.

Assessment of NASA's
Mars Exploration Architecture

Appendix 2
KEY ASPECTS OF NASA'S MARS EXPLORATION PROGRAM ARCHITECTURE

COMPLEX performed its assessment of NASA's Mars Exploration Program Architecture based on the following understanding of the program and its background.

Charge to Mars Architecture Definition Team

NASA's Mars Architecture Definition Team was charged to develop a schematic plan which, over the period 2000 to 2011, should:

- Achieve significant advances toward understanding the biological history of Mars and search for evidence of past or present life; and
- Lay out the technological and scientific groundwork for Mars exploration in the following decade.

Constraints on the Architecture

The Mars Architecture Definition Team was asked to formulate its response subject to the following constraints:

- The budget profile for Code-S-related activities is defined and should be adhered to;
- The budgets for Code-M- and Code-U-related Mars activities are defined for the 2001 missions and are to be determined for later missions;
- Plan for a series of diverse samples from multiple sites, with the first sample-return mission targeted for launch in 2005 (2008 return) or earlier;
- Assume that the French Space Agency, CNES, will provide an Ariane 5 launcher (and, possibly, an orbiter) for the 2005 mission and enable micromissions (as secondary payloads on commercial Ariane 5 launches) as early as 2003;
- Assume that Mars Express, a joint mission of the European Space Agency (ESA), and the Italian Space Agency (ASI), will fly in 2003; and
- Accommodate the *Athena* payload originally selected through peer review for inclusion on the 2001 rover and later deferred to 2003.

NASA's Strategy for the Search for Life on Mars

The basic approach adopted by the Mars Architecture Definition Team in outlining a program for the search for past or present life on Mars was the approach recommended by NASA's Mars Expeditions Strategy Group in its 1996 report, *The Search for Evidence of Life on Mars*. That is, a program for the search for life on Mars should be directed at those environments most favorable to life. These include:

- Ancient ground-water environments;
- Ancient surface-water environments; and
- Modern ground-water environments.

Mars Exploration Program, 1996-2001

NASA's key Mars exploration missions in the period from 1996 to 2001 were defined prior to the work of the Mars Architecture Definition Team. The principal goals of the NASA missions, the Mars Surveyor program, are to recover the science lost by the failure of Mars Observer in 1994 and to initiate a program of surface exploration leading up to a sample-return mission in 2005. To do this, NASA plans to launch an orbiter and a lander at each possible launch opportunity. In addition to NASA's missions, this phase of Mars exploration includes the launch of one Russian and one Japanese spacecraft.

1996 Launch Opportunity

Mars Pathfinder was launched on December 4, 1996, and landed in the Ares Vallis region of Mars on July 4, 1997. The principal payload of this technology-demonstration mission consisted of a stereo camera, a meteorology/atmospheric science package, and the minirover, *Sojourner*.

Mars Global Surveyor was launched on November 7, 1996, and entered orbit about Mars on September 11, 1997. Its payload consists of backup copies of five (Mars Orbiter Camera, Thermal Emission Spectrometer, Mars Orbiter Laser Altimeter, Radio Science package, and the Magnetometer and Electron Reflectometer) of Mars Observer's seven instruments. Problems associated with a damaged solar panel have slowed the pace of the aerobraking maneuvers necessary for the spacecraft to reach its final, mapping orbit.

Mars '96, a large and sophisticated orbiter, was launched by Russia on November 16, 1996. Unfortunately, it failed to reach orbit and was destroyed while reentering Earth's atmosphere. Many of its instruments, supplied by Western partners, may be reflown on the Mars Express (see below) mission in 2003.

1998 Launch Opportunity

Mars Climate Orbiter is scheduled for launch on December 10, 1998, and will enter orbit about Mars on September 23, 1999. Its payload consists of the Pressure-Modulator Infrared Radiometer (one of the two remaining Mars Observer instruments) and the Mars Color Imager, an integrated medium- and wide-angle camera.

Mars Polar Lander is scheduled for launch on January 3, 1999, and will land in Mars's southern polar region on December 3, 1999. Its primary payload is the Mars Volatile and Climate Surveyor, an integrated science package consisting of a mast-mounted stereo imager and meteorological instruments, a thermal- and evolved-gas analyzer, and a 2-m-long robotic arm equipped with a sampling device and a microscope camera. The lander also carries a descent imager, a microphone experiment, and a lidar experiment provided by the Russian Space Agency. The lander also acts as the bus for the Deep Space 2 microprobes (see below).

Deep Space 2 is a technology demonstration project designed to deliver two micropenetrators to the martian surface. After separating from their carrier, the Mars Polar Lander, prior to its entry into the martian atmosphere, they follow independent trajectories to impact sites in the southern polar-layered terrain. Capable of penetrating up to 2 m into the surface, each micropenetrator will carry accelerometers, temperature and pressure sensors, and a water-detection experiment.

Nozomi is Japan's contribution to the current phase of Mars exploration. It is a small, spin-stabilized spacecraft (formerly known as Planet B) that was launched by Japan's Institute of Space and Astronautical Sciences on July 3, 1998. It is scheduled to enter an elliptical orbit about Mars in October 1999. Nozomi carries an array of instruments, including a NASA-supplied neutral mass spectrometer, designed to characterize Mars's upper atmosphere and interactions with the solar wind.

2001 Launch Opportunity

Mars Geochemical Mapper is currently scheduled for launch on March 7, 2001, and to enter orbit about Mars on December 10 of that year. Unlike its predecessors, which used propulsive braking and/or aerobraking to enter orbit, it will employ aerocapture. The spacecraft's scientific payload will consist of the Gamma-Ray Spectrometer (the last of the spare Mars Observer instruments) and the Thermal Emission Imaging System. An additional instrument, the Martian Radiation Environment Experiment, is being provided by NASA's human-exploration program.

Mars Reconnaissance Lander is scheduled for launch in April 2001 and to land on Mars in January-February 2002. As originally configured, this mission was to carry an advanced rover equipped with the *Athena* science package. Following a recent descoping, this mission will now carry the *Athena* Precursor Experiment (APEX), a Mössbauer spectrometer, a robotic arm, and, possibly, *Sojourner's* backup, the rover *Marie Curie*. The lander-mounted APEX consists of a mast-mounted camera and the mini-Thermal Emission Spectrometer. In addition, the lander carries three experiments provided by NASA's human exploration program. These are the Martian Radiation Environment Experiment, the Mars In-Situ Propellant Production facility, and the Mars Environment Compatibility Assessment instrument.

Mars Exploration Program, 2003-2013, According to Mars Architecture Definition Team

The Mars Architecture Definition Team has suggested the following sequence of missions in the period from 2003 to 2013.

2003 Launch Opportunity

Mars Sample-Return Lander 1 is schedule for launch in 2003. Its payload will consist of a solid-fueled, mini-Mars Ascent Vehicle (mini-MAV), an advanced rover carrying the *Athena* science payload, and, possibly, a sample acquisition package (a NASA/ASI collaboration) consisting of a robotic arm and a drill capable of penetrating to depths of a meter or more. In addition, there is 100 kg of spare capacity for additional experiments that have not yet been defined or budgeted. The landing precision is expected to be <10 km.

The mission profile is for both the lander and the rover (equipped with a coring drill) to collect a total of some 0.5 kg of rock and soil samples and then transfer them to the mini-MAV. This vehicle then ascends into orbit about Mars to await collection by the 2005 Mars Return Orbiter (see below).

Mars Express is a proposed cooperative mission between the European Space Agency and the Italian Space Agency (ASI). Its payload, as currently defined, includes a high-resolution stereo camera, an infrared spectrometer, a planetary Fourier spectrometer, a surface/subsurface sounding radar (an ASI/NASA experiment), and, possibly, a small (60-kg) lander. Many of Mars Express's instruments are expected to be spares or copies of experiments that were included on Russia's ill-fated Mars'96 mission (see above). Mars Express is expected to act as a back-up communications relay between Earth and NASA's 2003 and 2005 landers. The communications system will be provided by ASI. Mars Express may also use its high-resolution stereo camera to perform an optical

search-and-tracking experiment in Mars orbit to validate the sample-capture technique to be used by the 2005 sample-return mission (see below).
ESA gave formal approval for Mars Express in November 1998, and a cooperative agreement between NASA, ESA, and ASI is expected in the near future.
Micromissions are a fundamental component of the NASA-CNES partnership that is central to NASA's Mars exploration architecture. They provide a mechanism by which small (tens of kilograms), focused payloads can be launched to Mars, at no cost to NASA, as secondary payloads on commercial Ariane-5 launches. NASA will provide the micromission bus, and it is expected that the payloads will be selected by open competition. Although only one micromission might be launched at this opportunity, more will be sent at subsequent launch opportunities.

2005 Launch Opportunity

Mars Sample-Return Lander 2 and Mars Return Orbiter (see below) are scheduled for launch in August 2005 on an Ariane 5 provided by CNES. The lander and its mission profile are basically the same as those for 2003. After landing on Mars in August 2006, the lander and its rover will collect a diverse set of samples and then cache them in orbit to await collection and return to Earth by the Mars Return Orbiter.
Mars Return Orbiter 1 is designed to search for and rendezvous with the sample-return capsules cached in martian orbit by the 2003 and 2005 landers, and return one or both capsules to Earth. The capsules will be tracked optically using the orbiter's cameras. Return of the samples collected in 2003 and 2005 will enhance the possibility that samples will be successfully returned to Earth in 2008.
It is anticipated that the 2005 orbiter will be provided by CNES but that NASA will supply its rendezvous and docking equipment and the Earth-return capsule.
Micromissions are anticipated, by this time, to have become an established feature of the Mars exploration program, with the launch of at least two micromissions at each launch opportunity.

2007 Launch Opportunity and Beyond

Mars Sample-Return Landers will be launched on NASA-provided boosters (Delta-3 class) at each possible launch opportunity (i.e., 2007, 2009, 2011, and 2013) or at every other opportunity, depending on the desired pace of the program and the balance between sample-return and micromissions after the first samples have been returned to Earth. Whatever the flight rate, the landers, their rovers, and the collection and caching strategy will be the same as for the 2003 and 2005 missions. The landing precision is expected to be ~1 km.
Mars Return Orbiter will launch on NASA-provided boosters (Delta-3 or -4 class) at every other launch opportunity (i.e., 2009 and 2013) to collect and return samples from the two preceding sample-return landers.
Micromissions will be dispatched at each launch opportunity.

NASA's Expectation

The Mars Architecture Definition Team expects that in the period from 2002 to 2012, the Mars exploration program will achieve the following:

- Acquire and return the first martian samples to Earth by 2008;
- Acquire and return at least three sets of samples by 2012;
- Provide a continuous flow of scientific information about Mars's present and past history

- Allow for the injection of new technologies and scientific investigations every 2 years;
- Enable strong international buy-in and participation; and
- Engage the public with an evolving "Mars exploration story."

In the same period, the architecture will provide the opportunity to:

- Attempt to return two samples from two different regions to Earth by 2008 as a means to enhance the likelihood of successfully returning one sample;
- Acquire carefully selected surface samples and samples from a few meters below the surface;
- Conduct a number of scientific investigations from landers (as many as five) and micromissions (at least five small orbiters, landers, or aerobots); and
- Demonstrate key technologies needed for future human exploration.

With a new initiative (estimated at some $300 million), the architecture will allow the establishment of a long-term, high-capacity (~1-Mbps) Earth-Mars "internet" for continuous communication with assets on the surface and in orbit around Mars.

Unbudgeted Items in Mars Surveyor Program

A number of key items related to NASA's Mars exploration architecture are not currently included in the budget for the Mars Surveyor program. These include:

- The handling of samples after they are returned to Earth;
- Upgrades to laboratories to prepare them for the analysis of martian samples;
- Communications infrastructure (e.g., low- and aerostationary-orbit communications satellites) to facilitate the Earth-Mars internet concept;
- Potential payloads from Codes U and M on spacecraft launched after 2001; and
- An advanced aeroshell to permit more precise targeting of interesting landing sites.

French and Italian participation in NASA's Mars exploration program will be on the basis of no exchange of funds.

Assessment of NASA's
Mars Exploration Architecture

Membership

COMMITTE ON PLANETARY AND LUNAR EXPLORATION

Ronald Greeley, Arizona State University, *Chair*
Richard P. Binzel, Massachusetts Institute of Technology
William V. Boynton, University of Arizona
Wendy Calvin, U.S. Geological Survey
Larry Haskin, Washington University
Bruce Jakosky, University of Colorado, Boulder
Kenneth Jezek, Ohio State University
Karen J. Meech, University of Hawaii
Michael Mendillo, Boston University
John Mustard, Brown University
J. William Schopf, University of California, Los Angeles
Everett Shock, Washington University

David H. Smith, Study Director
Erin C. Hatch, Research Associate
Sharon S. Seaward, Project Assistant

SPACE STUDIES BOARD

Claude R. Canizares, Massachusetts Institute of Technology, *Chair*
Mark R. Abbott, Oregon State University
Fran Bagenal, University of Colorado, Boulder
Daniel N. Baker, University of Colorado, Boulder
Robert E. Cleland, University of Washington
Gerald Elverum, Jr., TRW Space and Technology Group
Marilyn L. Fogel, Carnegie Institution of Washington
Ronald Greeley, Arizona State University
Bill Green, Former Member, U.S. House of Representatives
Christian Johannsen, Purdue University
Andrew H. Knoll, Harvard University
Jonathan I. Lunine, University of Arizona
Roberta Balstad Miller, Ciesin-Columbia University
Gary J. Olsen, University of Illinois, Urbana
Mary Jane Osborn, University of Connecticut Health Center
Thomas A. Prince, California Institute of Technology
Pedro L. Rustan, Jr., United States Air Force (retired)
George L. Siscoe, Boston University
Eugene B. Skolnikoff, Massachusetts Institute of Technology
Edward M. Stolper, California Institute of Technology
Norman E. Thagard, Florida State University
Alan M. Title, Lockheed Martin Advanced Technology Center

Raymond Viskanta, Purdue University
Peter Voorhees, Northwestern University
John A. Wood, Harvard-Smithsonian Center for Astrophysics

Joseph K. Alexander, Director

COMMISSION ON PHYSICAL SCIENCES, MATHEMATICS, AND APPLICATIONS

Peter M. Banks, Erim International, Inc., *Co-chair*
W. Carl Lineberger, University of Colorado, Boulder, *Co-chair*
William Browder, Princeton University
Lawrence D. Brown, University of Pennsylvania
Marshall H. Cohen, California Institute of Technology
Ronald G. Douglas, Texas A&M University
John E. Estes, University of California, Santa Barbara
Jerry P. Gollub, Haverford College
Martha P. Haynes, Cornell University
John L. Hennessy, Stanford University
Carol M. Jantzen, Westinghouse Savannah River Company
Paul G. Kaminski, Technovation, Inc.
Kenneth H. Keller, University of Minnesota
Margaret G. Kivelson, University of California, Los Angeles
Daniel Kleppner, Massachusetts Institute of Technology
John R. Kreick, Sanders, a Lockheed Martin Company
Marsha I. Lester, University of Pennsylvania
M. Elisabeth Paté-Cornell, Stanford University
Nicholas P. Samios, Brookhaven National Laboratory
Chang-Lin Tien, University of California, Berkeley

Norman Metzger, Executive Director