
Stepping-Stones to the Future of Space Exploration

A Workshop Report

NATIONAL RESEARCH COUNCIL

Stepping-Stones to the Future of Space Exploration: A Workshop Report

DETAILS

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Stepping-Stones to the Future of Space Exploration

A Workshop Report

Aeronautics and Space Engineering Board

Division on Engineering and Physical Sciences

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Preface

The Office of Space Flight's Human Exploration and Development of Space (HEDS) Exploration Program within the National Aeronautics and Space Administration (NASA) has so far focused on long-term objectives such as the human exploration of the solar system.[1] One previous effort in the Office of Space Flight was Technology for Human/Robotic Exploration and Development of Space (THREADS), which focused on three main areas of investment: (1) systems analysis and advanced concepts, (2) HEDS-enabling advanced research and technology, and (3) technology flight demonstration projects. THREADS was a new framework for space technology investment described as being driven by science and addressing NASA's largest challenges. The National Research Council (NRC) was tasked in the summer of 2001 with providing a multiyear review of the requirements, priorities, process, and content of the THREADS roadmaps. The THREADS project, canceled by NASA Headquarters in September 2001, was perceived by many as the only means for strategic planning for space technology development within the HEDS portfolio. The NRC study was also canceled at that time.

However, responding to the need for increased external input into its planning processes, NASA's Office of Space Flight asked the Aeronautics and Space Engineering Board (ASEB) at NRC to plan a series of open workshops on issues important to technology development for human and robotic exploration and development of space (see Appendix A for the statement of task). Issues surrounding this topic include the development of specific processes to guide technology development, the need for pervasive strategic planning for technology development at NASA, increased synergy between NASA and other government agencies in technology development, and the need to address the development of space in a manner that involves the stakeholders. Key to this effort was the planning of a series of workshops to investigate related issues within a new framework, similar to the THREADS framework but entitled Advanced Systems, Technologies, Research, and Analysis (ASTRA).

The National Academies convened a steering committee to plan the workshops (see Appendix B for biographies of steering committee members). The first workshop focused on general policy issues concerning the development and demonstration of space technologies. The second workshop, still in the planning stage, will focus on the interrelationship between government and industry in the development of advanced space systems.

The first workshop took place February 23-24, 2004, in Washington, D.C. Participants included government, industry, and academic stakeholders in space technology policy, and the open discussions centered on four main topics— the rationale

[1]On January 14, 2004, President George W. Bush announced a new space exploration vision (see http://www.whitehouse.gov/news/releases/2004/01/20040114-1.html). In response, NASA has reorganized many resources and programs to better meet the requirements for this vision. Most programs related to human and robotic technology are now within the new Office for Exploration Systems (Code T).

for space exploration and development, technology and capability transformation,[2] risk mitigation, and international cooperation. The workshop agenda is presented in Appendix C and the list of participants in Appendix D.

The workshop was intended to provide a forum for various stakeholders to discuss technology policy issues related to long-term cultivation of advanced space systems. This report represents a factual summary, prepared by the committee with staff assistance, of the proceedings of the workshop. The workshop report is not a comprehensive report on technology policy issues surrounding human and robotic exploration and development of space, but rather a synopsis of the presentations by individual panelists and speakers and discussion at the workshop. It should not be taken as a consensus report of the ASEB or the National Research Council.

The intent of this workshop was to provide a broad overview of issues related to human and robotic space exploration. Although the direction of several speaker's presentations appeared focused on the human aspect of space exploration, the focusing questions provided to the panelists were balanced in their treatment of the topic. Though not an agenda item, the reorganization of NASA following the January 14, 2004, announcement by President George W. Bush of a new vision for space exploration was discussed by most panelists during their remarks. The announcement noticeably affected discussion at the workshop. The steering committee was not tasked with analyzing or commenting on the new vision and the accompanying reorganization. However, the new organizational structure at NASA does affect the environment in which space technology is developed at NASA and the context in which the workshop was held.

This report is organized as follows: Chapter 2 provides an introduction to the workshop's topic. Chapter 3 discusses the rationale for human and robotic exploration of space. Chapters 4 contains an overview of the new NASA organization and a proposed framework for space technology development. Chapters 5 through 7 cover the remaining three workshop topics—technology and capability transformation, risk mitigation, and international cooperation.

Darrell R. Branscome
Chair, Steering Committee for
Workshops on Issues of Technology
Development for Human and
Robotic Exploration and
Development of Space

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[2]Transformation, as used in this workshop, suggests a change that shifts a paradigm. For example, the transportation paradigm has been shifted several times, including by the invention of both the automobile and the airplane.

Acknowledgment of Reviewers

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 National Research Council'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. We wish to thank the following individuals for their review of this report:

Howard Baum, National Institute of Standards and Technology,
Joseph Fuller, Futron Corporation,
Noel Hinners, Lockheed Martin (retired),
Simon Ostrach, Case Western Reserve University,
Thomas Prince, California Institute of Technology, and
Ian Pryke, George Mason University.

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 Thomas Sheridan, Massachusetts Institute of Technology. Appointed by the National Research Council, 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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Summary

The National Research Council's (NRC's) Aeronautics and Space Engineering Board (ASEB) was asked by the National Aeronautics and Space Administration's (NASA's) Office of Space Flight to convene a series of workshops on technology policy issues related to the interrelationship between government, industry, and other stakeholders in advancing human and robotic exploration and development of space (see Chapter 2 for more detailed information on the policy context and planning of the workshop). By design, the first workshop focused on policy issues concerning the development and demonstration of space technologies, specifically those related to a proposed new framework for space technology and systems development—Advanced Systems, Technologies, Research, and Analysis (ASTRA) for Future Space Flight Capabilities. The rationale, from the perspective of different stakeholders, for the long-term cultivation of advanced space systems was also a main topic.

In addition to a discussion of the ASTRA framework, the steering committee chose to focus on four policy topics during the first workshop—the rationale for human and robotic space exploration, technology as a driver for capability transformation,[1] risk mitigation and perception, and international cooperation and competition. While other policy issues are also important to the formulation of a space exploration technology program, the steering committee felt these were topics that needed to be discussed in further detail in relation to the proposed ASTRA framework. The sections below set forth the main points from each panel discussion and provide a summary of the ASTRA framework. Each of these sections is discussed in further detail in the chapters which follow. The committee chose to present the material in the order of discussion at the workshop.

RATIONALE FOR SPACE EXPLORATION

Panel members provided various rationales for the exploration and development of space by humans and robots, including scientific discovery, economics, security, and exploration of the unknown. One panelist suggested that space exploration was necessary to increase our knowledge of space and to develop the means to use it to our advantage. The majority of panelists believed that robots should be used when they can do the job effectively and humans used only when necessary. Robots were also described as the tools for exploration. A few panelists and attendees suggested that instead of

[1]Transformation, as used in this workshop, suggests a change that shifts a paradigm. For example, the transportation paradigm has been shifted several times, including by the invention of the automobile and the airplane.

arbitrarily partitioning funding between robotic and human exploration, a systems study of the appropriate roles of both kinds of efforts should be performed and an optimum ratio between the two determined. Two panelists recalled how effective the combined robotic and human exploration effort had been in the Apollo program.

In discussing the various roles of industry and government in space exploration, several panelists agreed that government's role is to invest in the high-risk areas—programs that would be impossible to achieve elsewhere—while industry must focus on what can be profitable. Gary Martin suggested that industry's role was to provide innovation and creativity. One panelist, Donna Shirley, mentioned the emerging role of wealthy individuals as investors in space technology (e.g., participants in the X-PRIZE foundation) and suggested that more private enterprise be brought into the space exploration effort.

Panelists at various times mentioned several technology investments that would be needed to enable space exploration beyond low Earth orbit. This is not an exhaustive or prioritized list nor one developed through a systematic process, but is a set of top-level technologies and issues, as suggested by various panelists, which the government should investigate:

- Smarter robotics,
- Launch and vehicle costs,
- Human factors (survival and effectiveness, unknown effects of long-duration spaceflight, etc.),
- Nuclear propulsion,
- Communications, and
- In-space construction.

The role of the public in deciding the future of space exploration was also a topic of discussion. Several panelists believed that the public should be directly involved in the debate and included in the process. As echoed in the panel discussion on international cooperation, these panelists believed that NASA must improve its credibility before the public (or international partners) will become engaged.

NASA EXPLORATION SYSTEMS AND ARCHITECTURES

NASA provided an overview of the new space exploration vision and a framework for technology development and systems analysis. Several previous architecture studies for lunar and Mars missions were also presented to the workshop participants. The new vision was described as a means to implement a sustained and systematic exploration of the solar system using an integration of humans and robotics to extend the human presence beyond Earth orbit. The development of technologies, systems, and processes to do this is part of the vision. Both the NASA speaker, Rear Admiral (Ret.) Craig Steidle, and other participants noted that possibly the biggest risk to the vision was the ability to sustain it through several administrations and Congresses.

A strategy-to-task-to-technology process[2] was presented wherein modeling and simulation would be used to focus technology investment on critical operational environments and to guide critical trade studies. Spiral development[3] would be used to insert advanced technologies and evolve architectures. The new NASA organization, the Office of Exploration Systems (Code T), was described. The office will rely on lessons learned in NASA and the Department of Defense (DOD) about large projects and systems and will employ incentives and opportunities in a manner unique to NASA. The need for technology was discussed by the steering committee and presenters. Steidle said there was a huge role for technology development within the new vision and that he would be looking to industry to fulfill many technology needs.

John Mankins, director of human and robotic technology in the Development Programs Division of Code T, presented an overview of the Advanced Systems, Technologies, Research, and Analysis (ASTRA) framework. ASTRA is a "collection of road maps, priorities, gap analysis results, and metrics for the development of future spaceflight capabilities for human and robotic exploration."[4] Dr. Mankins said that successful implementation and pursuit of the new vision will require advances in diverse technology areas, and that a resilient, adaptive process is necessary to plan and execute investments in space technology.

Steering committee and audience members mentioned the need for infusion of new, innovative technologies external to NASA into the ASTRA plan. Dr. Mankins and other participants acknowledged that there was no good means to bring new, nontraditional ideas into the NASA procurement process, and that a better means is necessary.

TECHNOLOGY AS A DRIVER FOR CAPABILITY TRANSFORMATION

This panel session focused on the various ways that technology can be used to transform[5] current capabilities. Panelists provided input on the topic from their

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[2]The strategy-to-task technique is "an approach used to develop low-level, often system-specific, requirements for a system or capability through a process of decomposition." (Michael Bathe and Jeremy Smith. "A Description of the Strategy to Task Technique and Example Applications," *Journal of Battlefield Technology*, Vol. 5, No. 1, July 2002.) The strategy-to-task-to-technology process goes one step further by combining this technique with prioritizations of technology.

[3]The spiral model of development was a term coined in 1988 by Barry Boehm, a member of the software community, in response to software development failures. Boehm formally defines the spiral development model in a 2000 report (Spiral Development—Experience and Implementation Challenges, Carnegie Mellon University (CMU)/SEI-2000-SR-006, February 9-11, 2000, p. 9); however, the DOD commonly uses the following definition:

> An iterative process for developing a defined set of capabilities within one increment. This process provides the opportunity for interaction between the user, tester, and developer. In this process, the requirements are refined through experimentation and risk management, there is continuous feedback, and the user is provided the best possible capability within the increment. Each increment may include a number of spirals. (Under Secretary of Defense (AT&L), memorandum dated April 12, 2002).

[4]John Mankins, NASA Headquarters, "Advanced Systems, Technologies, Research, and Analysis to Enable Future Space Flight Capabilities and Realize the U.S. Vision for Space Exploration," presented to the steering committee on February 23, 2004.

[5]Transformation and transform, as used in this workshop, suggests a change that shifts a paradigm. For example, the transportation paradigm has been shifted several times (e.g., the invention of the automobile and the airplane).

respective areas of expertise and experience—global positioning system, fuel-cell research for automobiles (FreedomCAR), joint government-agency programs (National Polar-orbiting Operational Environmental Satellite System (NPOESS)), small business, NASA, and the DOD. The Defense Advanced Research Projects Agency (DARPA) model was described by panelist Joseph Guerci as a bridge between current and near-term armed services science and technology programs and long-term fundamental research programs. DARPA's lean management structure and short project timelines were given as examples of why DARPA is successful. Bradford Parkinson, during his presentation on the GPS transformation of navigation technology, defined "disruptive" as something that used to be really hard and is now taken for granted. His message boiled down to three key enablers for technology: focus, time, and leadership. Christine Sloane presented a model for technology development in the automotive industry.

David Hardy, in his presentation from the perspective of the DOD Space Experiments Board, suggested two key barriers to timely technology development: (1) timescales for technology development and (2) the process through which thought is converted into an operational system. He also mentioned the difficulties of working in a cross-agency environment due to cultural and organizational differences. Jacqueline Haynes provided a small business perspective. She mentioned several concerns that the small business community might have with the new exploration vision, including (1) the perceived inability of small businesses to break into NASA's new programs in the face of existing relationships between NASA and larger companies and (2) their difficulty of developing new lines of communication and relationships with NASA.

The interagency program NPOESS was highlighted as an example of a joint program among many federal agencies. According to Stanley Schneider, the success of this program comes from the staff's ability to work in a unified manner and to leave behind all previous loyalties to their respective employing agency. Another unique part of the program is the sharing of responsibility for the systems engineering program with contractor TRW. NASA's New Millennium Program was presented by Christopher Stevens as an example of a program used to explicitly accelerate the infusion of technologies into NASA science missions at lower cost and risk.

RISK AVERSION—FLYING IN THE FACE OF UNCERTAINTY

Risk, in its various forms, was also discussed by the workshop participants and panelists. Panel moderator Molly Macauley pointed out that something that is uncertain is not necessarily risky, and that risk need not result from that which is uncertain. Risk can result from a lack of care or from poor management decisions even in informed, familiar situations, and it can be managed in a variety of ways. Panelists provided varied input to the discussion of risk and the need for its treatment within a technology development program in which many kinds of risk inhere. Allen Mazur discussed risk from a sociological viewpoint, suggesting that sociological models of accident events reveal different dimensions affecting media coverage and public perception from those revealed by engineering models.

John Barry discussed the Columbia Accident Investigation Board (CAIB) report and emphasized that human spaceflight is not routine and has many risks associated with it.

He stated that the CAIB findings are just as relevant to the new exploration vision as to the space shuttle program. Many in the audience agreed that although NASA is a risk-averse organization, it does not appear to have learned lessons from the Challenger accident. Panelists also discussed issues of communication and agency integration. Joseph Fuller addressed the idea of management risk in addition to technical risk. He stated that the ASTRA plan presented to the workshop does not address risk. He also mentioned that perception of risk is a function of the level of how much is known about a program or technology. While making informed decisions is key and risk assessment is necessary, Fuller noted that probabilistic risk assessment is not the only method available for consideration.

Gregg Hagedorn cited the Naval Sea Systems Command as an example of an organization that has experience with day-to-day management of risk associated with its fleet. Hagedorn commented that the public understands risks to humans but has less appreciation of risks to technology. There is a challenge in separating programmatic and technical risks to avoid conflict of interest. Leadership is also necessary to encourage people to admit when mistakes have been made.

The U.S. Congress, as had been mentioned by Neil Armstrong in the first panel, is ultimately responsible for seeing that the federal government acts in the best interest of the public. Richard Obermann stated that Congress understands risk and deals with decisions that must be made quickly, often based on a limited amount of information. He also commented that members of Congress perceive risk based on past experience with NASA and are therefore likely to view cost estimates with skepticism.

Michael Stamatelatos of NASA's Office of Safety and Mission Assurance described the use of probabilistic risk assessment at NASA in various programs. He agreed that there is a need to improve risk awareness organizationally and develop in-house expertise to understand probabilistic risk requirements.

Several participants mentioned that the use of probabilistic risk assessment in a vacuum is short-sighted. Understanding NASA's culture and the institutional barriers within the agency are key to the effective treatment of risk.

INTERNATIONAL COOPERATION/COMPETITION—WHY, HOW, WHEN?

The panel began with an overall discussion of the rationale for and history of international cooperation and competition. Panelists agreed that international cooperation is not altruistic but instead is enacted because the individual partners conclude that they can benefit in some way. They also mentioned that cooperation would most likely increase the complexity and cost of the overall project but could make its pursuit more affordable for the individual partners. The International Space Station (ISS) was cited as an example of a scientific and engineering program becoming a foreign policy tool. However, Ian Pryke cautioned that a project could also become hostage to foreign policy.

Most panelists mentioned in their remarks that President Bush had decreed that the new exploration vision would involve international cooperation of some kind.[6] The questions are when and how. Panelists also stressed that any cooperation on the

[6]NASA, *The Vision for Space Exploration*, February 2004.

implementation of this new vision should begin sooner rather than later in the process. Panelists warned that other nations might decide not to participate but instead to form their own cooperative space exploration programs without the United States. There are also several types of international involvement that could be pursued in implementating the vision, including program interdependence (e.g., ISS) and coordination (e.g., NPOESS). Several panelists agreed that the U.S. needs to meet its commitments on the ISS before other countries will agree to be involved in the new exploration vision. Legal issues surrounding the end of the ISS program were also discussed. International cooperation is not mentioned explicitly in the ASTRA framework. Although she recognized the need for infrastructure, Joan Johnson-Freese said the framework appears to be linear—that is, it assumes an equal-increment progression from step 1 to step 2 to step 3. This progression seems improbable and concerns were expressed that NASA might emphasize process at the expense of product.

The legal and international issues entailed in space exploration are usually resolved as necessary. Panelists felt that the current treaties adequately address any near-term issues and that the current legal environment is based on past precedents involving technology. When asked about examples of multinational cooperative efforts in industry, panelists cited several examples, including pan-European industry consolidation and new private agreements between various global industrial partners.

2

Introduction

This chapter provides a discussion of the state of space technology and space exploration policy at the time of the workshop's planning and actual convening. During this 2-month period, vast changes in policy occurred that directly affected the topics discussed at the workshop. Chapter 3 presents the discussion in the first panel session, on the rationale for human and robotic exploration and the development of space. Chapter 4 provides a short overview of the presentations made by the National Aeronautics and Space Administration (NASA) during the workshop. Chapters 5, 6, and 7 provide an overview of the proceedings during the final three panel sessions.[1]

CONTEXT FOR THE WORKSHOP

During the past two decades, several studies have suggested the need for a clear goal for the exploration and development of space—in particular, for human exploration[2]—and a national aerospace policy.[3] This debate continued after the Columbia accident[4] and has been debated in many forums, including a workshop hosted by the Space Studies Board and the Aeronautics and Space Engineering Board of the National Research Council.[5] That workshop report discusses much of the debate in greater detail.

Because the nation's vision for space exploration was not fully defined following Apollo, technology researchers have looked for various ways to make strategic investments in new space technology. NASA's Office of Space Flight's Human Exploration and Development of Space (HEDS) Exploration Program was focused on long-term objectives, such as human exploration, while NASA's Offices of Space and Earth Sciences were focused on robotic and remote sensing missions, whose goal was scientific discovery. One previous effort in the Office of Space Flight was Technology for Human/Robotic Exploration and Development of Space (THREADS), which focused on three main areas: (1) systems analysis and advanced concepts, (2) HEDS-enabling advanced research and technology, and (3) technology flight demonstration projects.

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[1]Workshop presentations can be found online at <http://www7.nationalacademies.org/aseb/Space_Tech_workshops.html>. Accessed March 1, 2004.

[2]Advisory Committee on the Future of the U.S. Space Program, *Report of the Committee on the Future of the U.S. Space Program,* December 1990, Washington, DC: U.S. Government Printing Office.

[3]Commission on the Future of the United States Aerospace Industry, *Final Report*, November 2002. Available online at <http://www.aerospacecommission.gov/AeroCommissionFinalReport.pdf>. Accessed March 17, 2004.

[4]Columbia Accident Investigation Board, *Report,* Volumes I-VI, August 2003, Washington, D.C.:. U.S. Government Printing Office. Available online at <http://www.caib.us/news/report/default.html>. Accessed March 17, 2004.

[5]NRC, *Issues and Opportunities Regarding the U.S. Space Program: A Summary Report of a Workshop on National Space Policy,* Washington, D.C.: The National Academies Press, 2004. Available online at <http://books.nap.edu/catalog/10899.html>. Accessed on May 5, 2004.

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THREADS was a new framework[6] for space technology research and development investment described as being driven by science and addressing NASA's grand challenges.[7] The new strategy was to be incremental (e.g., it described stepping-stones of investment), to leverage partnerships, and to emphasize education, all in a cost-effective manner.

The National Research Council was tasked in the summer of 2001 with providing a multiyear review of the requirements, priorities, processes, and content of the THREADS roadmaps. The THREADS project, canceled by NASA Headquarters in September 2001, was perceived by many as the only means for strategic planning of space technology development within the HEDS portfolio. The NRC study was also canceled.

The need for strategic planning in space technology at NASA continued despite the cancellation of the THREADS project. NASA then contracted with the National Research Council to plan and host a series of workshops on the topic, including one with a focus on the interrelationship between government, industry, and other stakeholders in advancing human and robotic space exploration and development

During planning for the first workshop, one major event occurred that changed the policy climate with regard to space exploration. On January 14, 2004, President George W. Bush announced a new national vision for space exploration.[8] This new vision provides a set of goals in human and robotic exploration by which technology development timelines and investments can be created and managed. While debate continues on the new vision in the Congress, technology sectors, the U.S. public, and abroad, this new climate could, at least for the short term, focus technology investments at NASA on more specific challenges than before the vision was announced. In response to the new vision, NASA has reorganized its programs in space exploration to better focus its work on the new vision.[9] The Office of Exploration Systems was "established to set priorities and direct the identification, development, and validation of exploration systems and related technologies."[10] Subsequently, on January 30, 2004, President Bush created, by executive order, the President's Commission on Moon, Mars and Beyond to make recommendations to the administration on realization of the new vision and to advise NASA on issues related to long-term implementation.[11]

The workshop reported on in this document did not specifically address the new vision or NASA organization. While most speakers did mention the new vision in their remarks in some manner, future workshops in the series should instead—as this

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[6]John C. Mankins, Manager, Advanced Concepts Studies, Advanced Programs Office/Office of Space Flight, NASA, "Technology for Human/Robotic Exploration and Development of Space [THREADS]: An Overview," presented to the NRC Committee on Technology for the Human/Robotic Exploration and Development of Space (THREADS) on July 14, 2001.

[7]National Aeronautics and Space Administration, *2003 Strategic Plan*. Washington, D.C.: National Aeronautics and Space Administration.

[8]George W. Bush, "A Renewed Spirit of Discovery: The President's Vision for U.S. Space Exploration," presented to the nation at NASA Headquarters, Washington, D.C., on January 14, 2004. Available online at <http://www.whitehouse.gov/space/renewed_spirit.html>. Accessed on May 5, 2004.

[9]NASA, *The Vision for Space Exploration*, February 2004.

[10]NASA Announces New Headquarters Management Alignment – NASA Press Release, January 15, 2004.

[11]Executive Order Creating the Presidential Commission on Implementation of United States Space Exploration Policy, January 30, 2004.

workshop did—contribute to the public discussion of technology policy for human and robotic exploration and development of space.

A framework for space technology investment and development, Advanced Systems, Technologies, Research, and Analysis (ASTRA), has been under development within the NASA human exploration of space organization. The framework, discussed in greater depth in Chapter 4, is intended to establish technology investment planning for space technology. When presented this framework at its December 2003 planning meeting, the steering committee deliberately chose to focus the first workshop in the series on specific policy issues that might need further treatment in the framework. The committee also planned input from other industrial sectors and government programs known for their innovative technology development processes. The committee recognized that many policy and technology issues could have been addressed in connection with the framework but decided that limiting the discussion to a few areas, including risk assessment and mitigation, international participation, and timelines and models for technology development; would allow for a more focused dialogue at the 2-day workshop.

ORGANIZATION OF THE WORKSHOP

The workshop agenda was divided into five discussion topics, including four panels and a series of NASA presentations:

- Panel on the Rationale for Human and Robotic Space Exploration;
- NASA exploration presentations—NASA Exploration Systems Office overview; Advanced Systems, Technologies, Research, and Analysis (ASTRA) for Space Flight Capabilities; and recent lunar and Mars architecture studies and technology drivers;
- Panel on Technology as a Driver for Capability Transformation;
- Panel on Risk Aversion—Flying in the Face of Uncertainty; and
- Panel on International Cooperation/Competition—Why, How, When?

Several speakers were asked to serve as panelists on four of the topics. Each panelist was asked to provide a short oral presentation on the topic, after which session moderators directed the discussions. The first session centered on the rationale for civil human and robotic exploration and development of space and included discussions of specific roles for humans and robots (Chapter 3). The second session (Chapter 4) featured presentations by NASA personnel related to the new space exploration vision and NASA's new organizational structure. Also presented at this session were system architectures for lunar and Mars missions. The third session examined the role of technology as an agent for organization and capability transformation (Chapter 5) and covered both barriers to and catalysts for transformation in various sectors. The fourth session focused on different aspects of risk and risk management as they relate to space exploration and technology management (Chapter 6). The final session discussed various issues involved in international cooperation in space exploration (Chapter 7).

3

The Rationale for Human and Robotic Space Exploration

Charles Walker, of the Boeing Company and a former astronaut (the first and only astronaut sponsored by industry), moderated the panel. Walker introduced the Panel on the Rationale for Human and Robotic Space Exploration by remarking that it is in our nature to explore. As we develop technologies, they are applied to create tools that assist us in the pursuit of space exploration. Over time, the instruments we create have become complex. One researcher in the field, he said, has suggested that our robotic instruments have three characteristics: programmability, mechanical capability, and flexibility.[1] These, of course, mirror or attempt to imitate, even expand, human capabilities. So, cognizant of the great challenges of space exploration and development, the committee asked the following focusing questions of the panelists:

- What are the compelling reasons for human or robotic presence in space?
- What are the appropriate roles for robotic exploration and human exploration and development of space?
- What technological barriers must be overcome?
- What role should the U.S. government, industry, academia, and private citizens have in this exploration and development of space?
- How best do we establish and sustain public support for such endeavors?

The panel included National Academy of Engineering member and former astronaut Neil Armstrong; staff director of the U.S. House of Representatives Committee on Science David Goldston; planetary scientist Wesley Huntress, director of the Carnegie Institution's Geophysical Laboratory and former NASA senior executive; executive director of the U.S. Chamber of Commerce Space Enterprise Council David Logsdon; NASA's Space Architect Gary Martin; and former Mars Exploration Program manager for the Jet Propulsion Laboratory, Donna Shirley, director of the Experience Science Fiction Museum.

Neil Armstrong opened his remarks with a quote from the 5th century B.C. Greek Antisthenes: "The beginning of wisdom is calling things by their correct names." He noted the lack of linguistic standards or enforcement in American English and suggested that the establishment of such standards for engineering terms would be a worthy pursuit. Engineering requires careful use of language since errors in communication can have devastating consequences. Armstrong noted that the term "robot" was created by Czech writer Josef Capek and his playwright brother, Karel Capek, for a 1920 play entitled *Rossum's Universal Robots*. Named after the Czech word *robota,* meaning forced work,

[1]Roger Clarke, Asimov's laws of robotics: Implications for information technology, *IEEE Computer 26(12)*, pp. 53-61, 1993.

the robots in that play were defined by their autonomous behavior. Armstrong then observed that although spacecraft do not live up to that original definition of the term, their onboard programming and ability to be remotely controlled from Earth have made for valuable accomplishments.

Armstrong said that the Apollo program benefited from early probes sent by the United States to map the Moon and test the lunar surface. He also noted that these probes have accumulated 13 successes and 16 failures, not unlike the (almost) 1 in 3 Mars probe success rate. Increasing the success rate of future probes through increased autonomous capability, he thought, would depend on extended systems reliability and performance range. As their separation from Earth increases, spacecraft need more autonomy. Summarizing his view on the rationale for space exploration, Armstrong said it is to increase our knowledge of space and to develop the means to use it to our advantage.

Answering a question from moderator Charles Walker about the relative roles of government and industry, Armstrong observed that while industry is willing to engage in enterprises incurring very short-term financial losses, it does so only if it sees those losses leading to longer-term profitability,which limits the role it can perform. Perhaps not-for-profit corporations can exercise somewhat more business flexibility, he suggested, but the principle is similar.

Another question about Armstrong's view on appropriate roles of humans and robotics in space exploration and development elicited the reply that NASA should have kept human spaceflight and robotics investments together, working toward common mission goals. Mission accomplishment is the overriding goal in Armstrong's view; achieve that, and safety will usually follow.

The final question, from Darrell Branscome, asked how public support can be increased. Armstrong's response was that publicly funded endeavors are proposed by the presidential administration and then approved and funded by the Congress, which is supposed to reflect the public will. But the public will is elusive. Because most people do not have the information at hand to make informed decisions, they rely on the Congress to make the best decision possible.

David Goldston began his remarks by noting that they were his own, not those of particular members of Congress or a congressional committee. He said the rationale for human spaceflight was less clear than the rationale for science-driven robotic missions. The latter missions are well defined by virtue of the peer review process. In Washington, D.C., he said, the rationale for human missions is fuzzy, and most explanations cannot survive rigorous scrutiny. He summarized the basic reasons for space exploration as follows:

- *Science.* While science is often cited as a rationale for human missions, much science can be conducted robotically, and there are no clear criteria for determining when sending humans on science missions is worth the additional expense and risk. In proposing its space exploration vision for NASA, the White House has carefully stated that it is not science-driven but informed by science. Goldston thought that was an honest position, but NASA is not using the same language in its discussions of the new vision and should be doing so.
- *Education and public excitement*. In Goldstein's opinion, this is the most commonly stated rationale but the weakest one. He noted that U.S. education was

Stepping Stones to the Future of Space Exploration: A Workshop Report

not likely to suddenly improve just from the excitement of a human space mission. He noted that the launch of the first Sputnik satellite prompted the federal government to put money not only into space programs, but also into education programs. The greatest excitement at this time is being generated by unmanned programs; examples he gave were the Mars rovers and the Hubble Space Telescope. He concluded that the ability of human spaceflight to stir up excitement is not really a valid rationale.

- *International security*. Goldston reflected on this as a valid rationale for Project Apollo in the 1960s but not in the first decade of the new century. He suggested that some may hope that the newly inaugurated Chinese manned spaceflight capability will provide some momentum for the new space exploration vision. Goldston noted further that the administration has framed its vision in terms of international cooperation, not of security.
- *Commerce*. He called this rationale for human exploration an intriguing one but one not well developed by the White House. It seemed to him that no actions had been proposed or taken to get the commercial sector involved.
- *Far reaching ideas*. Goldston said that ideas such as beaming energy from the Moon to Earth were often cited in passing, but seemingly without real thought or effort behind them.
- *Human destiny and exploring the unknown*. Goldston called this the most legitimate rationale but also a complicated one. There is a public will to explore, but expanding our understanding of the world can be done with unmanned space probes. He said that the Lewis and Clark analogy doesn't quite work, because expanded human understanding of the solar system can occur without human missions. While concluding that this rationale needs more thought, Goldston said that Congress and the public may find it difficult to prioritize a mission motivated primarily by "human destiny."

Goldston continued by addressing the question of appropriate roles for human and robotic exploration. He supported the administration's notion of dropping the walls between human and robotic programs, but cautioned that even if the programs are intertwined they will continue to compete for money, so it is important not to sacrifice unmanned for manned missions. Goldston said that unmanned missions must continue to be assessed as they are now, with open, competitive peer review. They also should not be slaves to manned missions. There are legitimate goals for unmanned space exploration. Manned space missions should not be justified by designing robotics that must be maintained and supported by humans; use humans only when necessary. Politics should not drive the design of space exploration.

Goldston then spoke of public support for spaceflight. It has always been iffy, he said. There needs to be open, public discussion without hype. Goldston felt that NASA should have such a dialogue, especially about cost, and that this could improve NASA's credibility. He encouraged the panel and the workshop to so inform NASA. He concluded his remarks by noting that in a recent hearing before the House of Representatives' Committee on Science, NASA was unclear about how much the new space exploration vision would cost.

Charles Walker asked Goldston what was necessary for sustaining a program of exploration over the long term. Goldston replied that it begins with being upfront about costs and risks, both to humans and mission success. He said that NASA had been unwilling to do this for the International Space Station program, with life sciences research replacing the old mix of reasons for the station's existence.. He added that we must understand the state of our knowledge, then learn as we go along and change as needed.

Wesley Huntress began his remarks by defining robots as tools. He referred to the Mars exploration rovers, Spirit and Opportunity, now operating on the surface of Mars, and suggested that they would be ten times more effective if there were a human operator controlling them from Mars orbit providing virtually instant feedback rather than from Earth, with delays of more than 10 minutes.

Huntress then went into his presentation, drawn from a study done under the auspices of the International Academy of Astronautics, beginning with a strategy for science-driven exploration. Guiding principles were presented: addressing broad public and scientific interest, starting with a goal, establishing the destination and a plan, then utilizing robots where possible and humans where necessary. Desired outcomes would follow, in his strategy, through a systematic plan with goals established first, then destinations. The strategy would be flexible, affordable, and sustainable. Huntress made the point that there are also cultural and political imperatives for space exploration. Science alone is not a sufficiently strong imperative. Further, he contended that scientific objectives or goals come from fundamental human questions—What is our origin? What is our future? Are we alone? To explore these objectives we have four destinations, he said: the Sun-Earth Lagrangian point (L2),[2] the Moon, near-Earth objects, and Mars. Huntress then elaborated on the scientific activities and technical exploration architectures appropriate for each of those destinations. He summarized his remarks by saying that a successful architecture for exploration should use a stepping-stone approach extending outward from Earth.

In answer to a question about what technologies critically need advancing, Huntress replied that he believed almost all of these things could be done with technologies now in hand. He did note, however, a few technology advances that would be a great help. One is nuclear propulsion, especially nuclear-electric, for transporting cargo at reduced risk and in shorter times. Project Prometheus is therefore a critical program. Huntress continued, saying that optical communications technologies are needed to increase bandwidth, and added that the satellites on which the optical communications are installed could also carry systems to help with surface navigation. An Internet node at Mars might also be a good thing. Finally, he noted that heavy-lift launch to space and in-space construction technology also might be good investments. But he advised that these technological investments should not be made if we can get by without them.

David Logsdon provided the workshop with prepared remarks. The Space Enterprise Council of the U.S. Chamber of Commerce addresses space issues across the full

[2]The Sun-Earth Lagrangian point, L2, is one of five Lagrangian points (or libration points) in the Sun-Earth system discovered by mathematician Joseph Louis Lagrange. Each Lagrangian point is a location in space at which the gravitational forces between two large bodies are completely balanced. A third body of negligible mass, located at this point, would be stationary relative to the two larger bodies. The L2 point has been mentioned by many as an optimal location for the operation of space probes or observatories.

spectrum of American industry. Logsdon said his remarks, based on the Council's views, were inspired by a common dedication on the part of member companies, despite their diversity, to the promotion of commerce on the ground and in space. These members support an integrated approach to human and robotic space exploration that takes advantage of the strengths of both and that will evolve as knowledge and technology advance.

Regarding the compelling reasons for space exploration, Logsdon reflected on the large-scale, government-backed expeditions of the past—for example, the Spanish-backed discovery of this continent and the Lewis and Clark exploration of the American West. He saw a lesson in those endeavors—namely, that while the impact might not be seen in the short run, in the longer run it is profound. He then spoke of drawing inspiration from human heroes and the exploration of new frontiers that created them. Our nation's industries have been bolstered over the past several decades by a government and private sector workforce that, motivated by our nation having been first on the Moon, took up the science, mathematics, and engineering disciplines. Logsdon extended this point to international competition: As evidenced throughout the history of aviation technology and business, "if we don't do it, they will."

Regarding barriers to new programs of exploration, he spoke of the unknown effects of long-duration spaceflight, the need for a new launch vehicle, cost uncertainties, and, finally, political uncertainties. In the absence of a political imperative like we had in the 1960s, Logsdon made a clear call for the American public to support space exploration. To rally this support, the White House would have to be involved, perhaps through a body like a national space council. Another way to gain support would be to make space exploration a course of study during the middle school and high school years. Other ways of rallying public support for space exploration included coalitions of stakeholder industries that would campaign for space and efforts by American's movie and video game entertainment industries. He concluded by saying that it is essential for the benefits of space exploration and development to be articulated in terms of everyday life.

Charles Walker asked Logsdon if there should be legislation to further encourage industry to participate and invest in space exploration. Logsdon replied that the Commercial Space Act legislation applied. Panelist David Goldston added that the House Science Committee added amendments in February 2004 to ensure that industry is not jeopardized. This bill may be voted on by the House of Representatives soon.

Gary Martin opened by referring to the public's support of NASA while acknowledging that the agency cannot point to specifics to prove this support. To the public there is no single NASA strategy: the space shuttles, unmanned probes, Earth science, all these pieces exist without an overarching framework. NASA needed the President's vision for national space exploration, he said. It is the framework, the context, and the long-term picture. It will depend on sustained growth and will be accomplished through a sequence of steps, human and robotic missions, to the Moon, Mars, and beyond. The requisite characteristics of a national policy for space exploration were contained in the President's directive, which calls for a step-wise increase in capability but on no particular timetable. For this, a strategic and systematic process is necessary. Recently, the role of the International Space Station has come into question. Now it has a focused set of goals because it is an important stepping-stone in a larger strategy. Martin elaborated, saying the ISS is not going to be everything to everybody but acknowledging that it had previously been promoted as such.

Martin said that exciting science, such as peering beneath the ice and into the oceans of the moons of Jupiter, requires a lot of power. NASA's Project Prometheus will provide that power, first for robotic missions. Nuclear reactor technology for surface power on planets needs research before it can be used in this application. Nuclear propulsion will be necessary as well. For instance, nuclear thermal propulsion can reduce the mass of a crewed vehicle to Mars to almost one-half that of a crewed vehicle using chemical propulsion. And, Martin continued, employing aerobraking technology at Mars will reduce the mass another 40 percent or so. He listed other important technologies such as bioastronautics and heavy-lift space transportation.

On the respective roles of government and industry, Martin said the government's is to make the large investments and take the big technology risks, thereby enabling science. Industry will bring creativity and innovation. He hoped that entrepreneurs will be able to get involved and expressed a need for industry to benefit from this participation. Academia will be the source of peer-review, science goals, and mission planning and will teach the next generation of workers and researchers. Martin closed his remarks by saying that private citizens should be the ultimate beneficiaries of this new exploration vision. They should be able to understand what their national space program has under way and be inspired. According to NASA-sponsored research, the public is supportive of NASA programs, he said, but the public would like to understand the larger context of those programs and desired more information about NASA missions.

Donna Shirley began her remarks by saying she intended to be terribly pragmatic. She echoed other panelists in saying that robotics should be used when they can do the job and humans used only when necessary. The Hubble Space Telescope was designed for servicing by astronauts, but a robotic servicer could probably be built and flown for about the cost of a shuttle launch. Shirley contended that we don't need to make arguments for people to go to space—they want to go! The popularity of science fiction about humans in space, including the mythic Star Wars movie series, shows that humans want to go into space. She thought that one fruitful technology area is to increase the autonomy of telerobotics, making the machines more capable of operating with less human supervision. On the matter of technology barriers, she mentioned the current state of robotics, saying we need smarter robotics and that the research is being done in universities today. Robots need not mimic humans but have been successful by imitating insect behavior. Shirley mentioned Rodney Brooks of the Massachusetts Institute of Technology's Computer Science and Artificial Intelligence Laboratory as one of those university researchers. Shirley went on to say that launch costs must be reduced. Human survival and effectiveness of human work in space require more study, and the ISS is the place to do that, but she observed that astronauts do not like to be test subjects because they believe any weaknesses found will prevent them from flying again. Finally, on the topic of technology, Shirley stated that nuclear power and propulsion are necessary. Space exploration will not go far without them, and we don't want our missions to be slaves to the diurnal and seasonal variations on planetary surfaces, as they are when hardware is powered by photovoltaics.

Shirley, turning to the role of government, told the workshop that the government should do what cannot be done anywhere else. Industry needs to do what is profitable, but incentives need to be put in place that will make companies eager to invest in particular areas. She added that more private enterprise needs to be introduced to the space business, noting that many wealthy individuals had become interested in space launch. Shirley specifically named Paul Allen of Scaled Composites, Elon Musk of SpaceX, Dennis Tito, and the investors in Armadillo Aerospace. She noted that Federal Aviation Administration licensing of human spaceflight is an enormous hurdle for private companies, and the regulations are arcane.

Returning to government space programs, Shirley said, that the truth must be told about costs. The new national space exploration vision should not be treated as a jobs program. Observing that this is the approach NASA has often used to sell its programs to Congress, she contended it is not the best way to develop an exploration program. She was also concerned that the problem of how cargo will be returned from orbit after the shuttle's retirement is not being considered, but it should be.

Shirley opined that the congressional habit of earmarking programs is "killing us," taking needed program funding to pay for politically motivated local projects. She also commented on the NASA organization, pointing out that the Jet Propulsion Laboratory succeeds because it is a contractor, not a government entity. She thought that NASA should look into privatizing its centers in order to motivate them to be more efficient and competitive.

Shirley asked for the public to be made part of the process. The public must feel ownership before it can advocate space exploration. She referred to Mark Craig, of NASA Johnson Space Center, as having attempted to get feedback from the public on space exploration. NASA has not really worked at this, she said, calling its public affairs approach an attempt to sell the public on what NASA wants rather than engaging it in formulating the programs. Finally, she told the workshop that the Moon as a destination is a diversion from Mars, not a stepping-stone on the way. If it is to be a goal, it should be sold as one separate from the goal of reaching Mars.

The panel discussion began with Molly Macauley suggesting that the dividing line between humans and robotics is not as clear as the panel members had just made it out to be. She asked how one determines what the discrete role of each is—what are the trade-offs? Wes Huntress replied that first each case must be studied and that the answer will always be relative. David Goldston responded that this was the right question to be asking, and that from a policy perspective neither NASA nor the White House had been clear in answering it so far. The NASA budget request, he said, muddles things by merging human and robotic programs. According to Goldston, the question we need to be asking is, When are humans absolutely necessary, and for what? Gary Martin stated that NASA is looking at what goals the science enterprises are setting as their highest priorities and is then determining what technologies are needed to accomplish those goals. Once the technologies are determined, they will be developed.

In a follow-up question to panel members, Charles Trimble wanted to know what they thought of having a set ratio of human to robotics efforts in program budgets, with the human efforts including physiological studies. Donna Shirley did not think much of having such a ratio. Set a goal—where we want to go and what we want to do there—then decide on the costs and the allocation of budget, she said. Asked if robots could do everything, she responded no: there is science that can be done most cost effectively by robots, but robotics can't do it all. How, then, is a budget to be set for the human imperative, asked Trimble? David Goldston responded that NASA had set aside a share of its budget for humans and a share for robot-conducted science. This established partitioning is good for robotic science and keeps it from being devoured by the human spaceflight programs, but he said he was nervous about setting an arbitrary dollar figure. A program should prove that human spaceflight content is necessary to its good. Goldston, observing that when Congress considers the budget, NASA competes with other federal science institutions like the National Science Foundation, asked for public input on the proposition that we need human spaceflight for its own sake and on the value that should be attached to such flight. Neil Armstrong then opined that had the space station program been allowed to proceed as originally planned, without congressional delays, the station would now be complete and at a fraction of the present cost.

Dava Newman then suggested that the question, Should we separate the human and robotic efforts? is the wrong question to ask, that we're confusing the issue. Are not humans and robotics part of a whole system needing integration? she asked, suggesting that systems analysis be used to study exploration opportunities and architectures be allowed to determine what the roles are and how they are best performed. Goldston responded that he believed Congress would like to see this done. There are enormous and artificial divisions within the NASA culture inhibiting this integration, said Shirley, who has written an article on the subject.[3] Huntress believed that the Apollo program—which landed the first humans on the Moon—would never have succeeded had the human and robotic elements not been totally intertwined. When that program ended, robotics found a customer in the science community and did well. Now it has two customers: the same science community and the human support function. That division of labor needs to be made clearer. Goldston responded that, although such division is a good idea, it would not decouple the “what” from the “when.” Gary Martin interjected that in the Mars exploration program the robotic missions will look for water, the source of life as we know it. The human missions that ensue will do science that follows up those robotic explorers. Humans can recognize something out of the ordinary, something interesting, which is, he said, a unique ability. Donna Shirley disagreed with that statement, saying that robots merely extend human senses in distance and wavelength. Armstrong contended that, by Capek’s definition, we really have not had robots yet. Quoting from the plant manager in Capek’s play *Rossum's Universal Robots*, he joked that “Robots remember everything but think of nothing new. They would make very good university professors.” Eric Rice asked the final question of the session: How can implementation of the new exploration policy better engage the public? Donna Shirley responded that NASA had looked into that and that Mark Craig, at the Johnson Space Center, should be asked. Gary Martin concluded by saying that NASA was having surveys done—listening to what the public says on the subject to better understand what that public would like to see from its space program.

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[3]D.L. Shirley, The myths of Mars: Why we’re not there yet, and how to get there, Workshop on Concepts and Approaches for Mars Exploration, Lunar and Planetary Institute, Houston, Tex., July 18-20, 2000.

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NASA Exploration Systems and Architectures

OVERVIEW OF OFFICE OF EXPLORATION SYSTEMS (CODE T)

Rear Admiral Craig E. Steidle (Ret.), the associate administrator of NASA's Office of Exploration Systems, presented an overview[1] of key elements of the recently announced Nation's Vision for Space Exploration. He is the first to hold this position, since the office was created only in January 2004. The Office of Exploration Systems (Code T) was "established to set priorities and direct the identification, development, and validation of exploration systems and related technologies."[2] The Nation's Vision for Space Exploration, announced by the President on January 14, 2004, included 18 elements, several of which are outside the responsibilities of the Office of Exploration Systems. The key objectives of the Nation's Vision for Space Exploration[3] were described as follows:

- Implement a sustained and affordable human and robotic program
- Extend human presence across the solar system and beyond
- Develop supporting innovative technologies, knowledge, and infrastructures
- Promote international and commercial participation in exploration.

Steidle noted that perhaps the greatest challenge would be the program's sustainability throughout several administrations and Congresses. Major milestones have been established to guide planning for implementation of the exploration, including initial flight testing of a crew exploration vehicle, launch of the first lunar robotic orbiter, and the first human mission to the Moon in over 30 years, among others.

Steidle emphasized that the Office of Exploration Systems plans to use findings from the 1986 President's Blue Ribbon Commission on Defense Management,[4] which looked at lessons learned from major Department of Defense acquisitions and how they served as drivers in formulating the Exploration systems program. The lessons learned included bringing operators and technologists together to leverage cost-performance trades, applying technology to lower the cost of systems, maturing technology prior to

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[1]Craig Steidle, NASA Headquarters. "Office of Exploration Systems: Program Overview," briefing to the steering committee on February 23, 2004.

[2]NASA press release: NASA Announces New Headquarters Management Alignment, January 15, 2004.

[3]George W. Bush, "A Renewed Spirit of Discovery: The President's Vision for U.S. Space Exploration," presented to the nation at NASA Headquarters, Washington, D.C. on January 14, 2004. Available online at <http://www.whitehouse.gov/space/renewed_spirit.html>. Accessed on May 5, 2004.

[4]The President's Blue Ribbon Commission on Defense Management (also referred to as the Packer Commission) was chaired by David Packer. The final report is entitled *Quest for Excellence: Final Report to the President from the President's Blue Ribbon Commission on Defense Managemen*t, Washington, D.C., Government Printing Office, June 1986.

embarking on engineering and systems development, and developing partnerships with industry to identify innovative solutions. He also noted an additional important finding of the more recent Young report, conducted by the Defense Science Board/Air Force Scientific Advisory Board, which said that definition and control of requirements are dominant drivers of cost, schedule, and risk in space systems development programs.[5]

He described a strategy-to-task-to-technology process (see Figure 3-1) that uses modeling and simulation throughout the life cycle process. Initially the modeling and simulation will focus technology investment on critical operational environments and guide critical trade studies to enable the preparation of system requirements documents. Later in the process, the modeling and simulation will focus on the investment plan to achieve affordable system design and development.

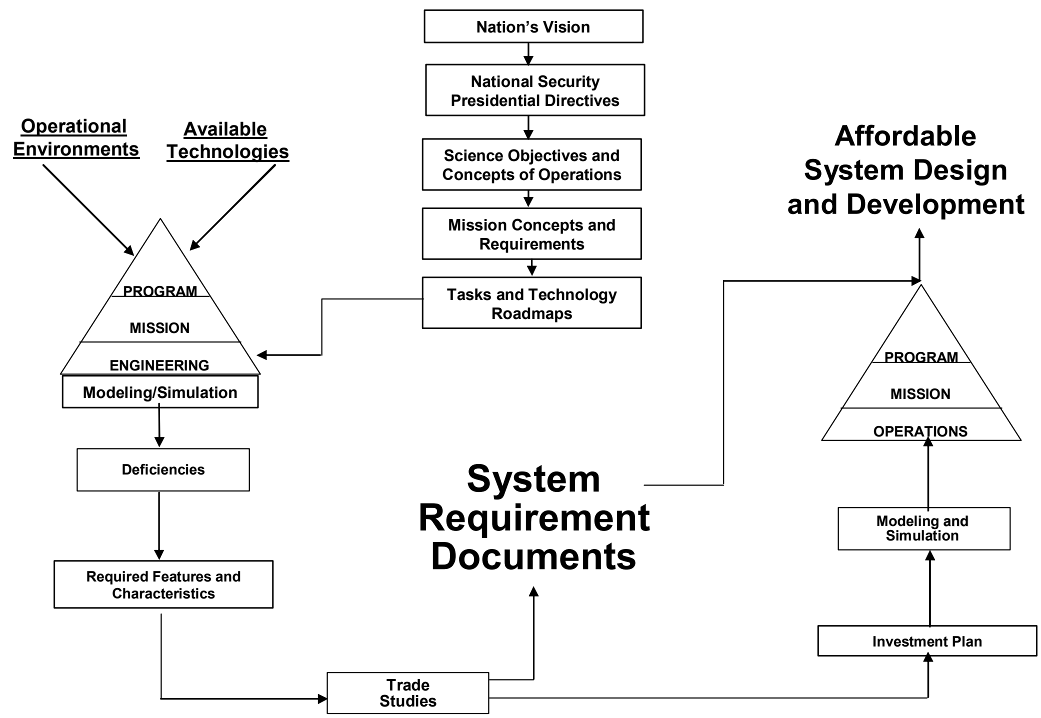

FIGURE 3-1: Strategy-to-task-to-technology process. SOURCE: Craig Steidle, NASA Headquarters, "Office of Exploration Systems: Program Overview," briefing to the steering committee on February 23, 2004.

[5]Defense Science Board and Air Force Scientific Advisory Board, *Report of the Defense Science Board/Air Force Scientific Advisory Board Joint Task Force on Acquisition of National Security Space Programs*, Washington, D.C.: Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics, May 2003.

Steidle noted that the Office of Exploration Systems is reliant on other NASA program offices for significant activities that are critical to achieving the complete vision. The Office of Space Science plans several lunar and Mars precursor projects that intend to accomplish important science objectives and gain engineering data needed to support design decisions for human spaceflight to both destinations. Additionally, one role of the Office of Biological and Physical Research will be to conduct life science research to help understand and mitigate the health hazards associated with human spaceflight to deep space destinations.

Steidle expects to bring his past Department of Defense acquisition experience in spiral development[6] to bear on the acquisition of hardware elements necessary to achieve the exploration vision. A Project Constellation timeline has been established to reflect the initial spiral phase to achieve the first flight of the unmanned crew exploration vehicle (CEV) in the 2011 time frame and the second spiral phase to achieve the first manned CEV flight in the 2014 time frame. Follow-on spirals will be needed to achieve crewed flights to Mars in the far-term.

Steidle presented the new Office of Exploration Systems, which consists of three divisions: the business operations division, the requirements division, and the development programs division. The business operations division will focus on acquisition strategy and business management, program assessment, resource management, and information management and dissemination. The requirements division will be responsible for requirements formulation, systems integration, and exploration analysis. The development programs division has responsibility for human and robotic technology, exploration transportation systems (Project Constellation), and nuclear systems development (Project Prometheus). The divisions will coordinate their work with a hand-off from requirements to development. Level 0 and Level 1 requirements are formulated within the requirements division with the help of an embryonic project team, and later the project teams are transitioned and discipline engineers added to carry projects through remaining development cycles.

Steidle stressed the need to provide competitive incentives and opportunities to come up with the technology development necessary for the new vision. Centennial Challenges is a feature of the new Exploration Vision that will use cash awards to stimulate innovation and competition in technical areas of interest to civil space and aeronautics. Specifically, the Centennial Challenges is a low risk program designed to (1) encourage innovation in ways that standard federal procurement cannot, (2) enrich NASA research by reaching new communities, (3) help address technology pitfalls, (4) promote returns that outweigh the investment, and (5) educate, inspire, and motivate the public.

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[6]The spiral model of development was a term coined in 1988 by Barry Boehm, a member of the software community, in response to software development failures. Boehm formally defines the spiral development model in a 2000 report (*Spiral Development—Experience and Implementation Challenges*, CMU/SEI-2000-SR-006, February 9-11, 2000, p. 9); however, the DOD commonly uses the following definition: An iterative process for developing a defined set of capabilities within one increment. This process provides the opportunity for interaction between the used, tester, and developer. In this process, the requirements are refined through experimentation and risk management, there is continuous feedback, and the user is provided the best possible capability within the increment. Each increment may include a number of spirals. (USD(AT&L), memorandum dated April 12, 2002)

Steidle also discussed the major objectives in the Office of Exploration Systems for the remainder of 2004 and its current status. Included in these objectives are a study of lessons learned from the Orbital Space Plane and Next Generation Launch Technology Program, developing relationships with industry by setting aside special days for interaction with industry representatives, and completing a preliminary requirements analysis, among other things.[7]

Discussion with Steidle continued after the presentation. Brad Parkinson mentioned that in systems technology, surprises occur and sometimes requirements cannot be met because of immature technology. Steidle said that once the requirements are established, any modifications to the plan must be approved by NASA's Deputy Administrator after following a strict process to petition for change, backed up with a strong justification. Darrell Branscome mentioned that the workshop's focus was technology as a transformer and asked Steidle to comment on the role of technology in the program. Steidle mentioned that there is an important role for technology to play as it fills gaps in the plan. The current budget provides $300 million for technology development. Steidle would like industry to assist in fulfilling these technology requirements. He hopes to begin an open dialogue with industry to develop the necessary relationships. The technology maturation process in place will have milestones throughout its tenure, providing off-ramps for unsuccessful technology.

Discussion continued on the Centennial Challenges effort. Steidle mentioned that the effort begins with $20 million per year in fiscal year 2005. The program is still defining areas for the solicitation. Molly Macauley asked as to why previous Department of Defense managers were chosen to lead two of the three divisions within the Office of Exploration Systems. Steidle replied that NASA wanted proven leaders who had experience with system-of-systems and large-systems work; had managed large, ambitious programs; and had experience with congressional briefings and the budget process. This combination was most likely to be found within the Department of Defense. The slots needed to be filled quickly, and NASA did not specifically solicit industry for candidates.

Eric Rice asked about the future of the Small Business Innovative Research (SBIR) program, whose management was moved to the new Office of Exploration Systems. Steidle acknowledged that the management had been shifted to his office and that those programs would remain. He mentioned the possibility of redirecting those efforts in the future, but said all of the current projects would continue. He wants to make sure that the technology programs are not liquidated to support other missions.

The Moon was mentioned as a testbed by Charles Trimble, who asked if it was also considered a place to be explored. NASA already has certain requirements, including geology mapping and communications systems, that need to be demonstrated for exploration. Steidle wants to demonstrate those capabilities and will evaluate the Moon as a testbed for exploration technologies.

Charles Walker asked how spiral development would affect the relationship between NASA headquarters and the field centers. Steidle mentioned that no specific field centers are associated with Code T; however, the nodes of expertise at each center are essential,

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[7]Craig Steidle, NASA Headquarters. "Office of Exploration Systems: Program Overview," briefing to the steering committee on February 23, 2004.

and Code T will be linked to those nodes. The centers will be able to respond to broad agency announcements and contract with Code T as appropriate. Offices have been set up at five centers and are ready to facilitate this relationship.

Joanne Gabrynowicz asked about the influx of defense expertise at NASA and wondered if there had been any discussion about whether NASA would remain a civil agency. Steidle confirmed that the agency would remain civil and public in nature. Dava Newman commented on the failure to mention universities in the Code T presentation. Steidle admitted that he doesn't yet know what is available in the academic community and that no programmatic decisions have been made. He is open to ideas but doesn't know yet how they will be used. David Hardy asked a similar question about coordinating efforts between NASA and the DOD space community. Steidle said that DARPA and NASA are starting a new partnership and that cooperation on lift technologies was ongoing. These partnerships could be expanded as appropriate.

OVERVIEW OF ADVANCED SYSTEMS, TECHNOLOGIES, RESEARCH, AND ANALYSIS FOR FUTURE SPACEFLIGHT CAPABILITIES

John C. Mankins, director of human and robotic technology in the Development Programs Division of the NASA Office of Exploration Systems, presented an overview of the Advanced Systems, Technologies, Research, and Analysis (ASTRA) framework. Mankins briefly reviewed the goals and objectives of the nation's new vision for space exploration, including the key role that innovation and technology would play in achieving this vision. As background, he noted that past U.S. achievements in space had led to the development of technologies that have widespread applications to problems on Earth. He further noted that in preparation for future human exploration, we must advance our ability to live and work safely in space and, at the same time, develop the technologies to extend our reach to the Moon, Mars, and beyond. The new technologies required for further space exploration also will benefit our nation's other space activities and may lead to applications that could be used to address problems on Earth.

The President's announcement stated that NASA would develop the innovative technologies, knowledge, and infrastructure to explore space and support decisions about the destinations for human exploration. Mankins expected that preparing for exploration and research would accelerate the development of technologies that are important to the economy and national security. The space missions in this exploration plan require advanced systems and capabilities that will accelerate the development of many critical technologies, including those for power, computing, nanotechnology, biotechnology, communications, networking, robotics, and materials. The President's announcement points out that these technologies will underpin and advance the U.S. economy and help ensure national security. NASA plans to work with other government agencies and the private sector to develop space systems that can address civil and commercial needs. NASA will also pursue opportunities for international participation to support U.S. space exploration goals. Mankins reviewed the NASA vision, mission, and goals that are outlined in the 2003 NASA Strategic Plan.[8]

Mankins noted that the most significant transformational space systems and concepts emerged in the first two decades of the space age, including expendable launch vehicles, intercontinental ballistic missiles, the deep space network, geostationary communications satellites, the first- and second-generation global positioning systems (GPS), the space shuttles, and Viking, among others.[9] More recent transformational systems include the third-generation GPS, science observatories such as the Hubble Space Telescope, the Gamma Ray Observatory, the Advanced X-ray Astronomical Facility, the Space Infrared Telescope Facility, the International Space Station, and Mars landers, including Sojourner, Opportunity, and Spirit. He noted that further transformational systems and concepts might include optical communications, nuclear space propulsion and power, and deep space outposts.

Mankins mentioned a number of selected issues and questions that he is focusing on in his new set of responsibilities, including close coordination with and engagement of the research and development community as requirements are formulated, concepts are defined, and new systems and infrastructures are developed.[9] He also noted that previous studies had identified a number of technical challenges that the technology investment plan would address—for example, low-mass, deployable modular thermal systems; redundant and self-reconfigurable modular electronics; high-strength, low-mass materials for modular structural systems; highly mobile, dexterous, self-sufficient robotics; affordable, space-maintainable and evolvable extravehicular activity (EVA) systems; cryogenic fluid/propellant storage, management, and transfer; medical care beyond low Earth orbit; and others.

For the remainder of the presentation, Mankins focused on his current approach for human and robotic technology planning—a framework called Advanced Systems, Technologies, Research, and Analysis (ASTRA). ASTRA is a collection of 10- to 25-year road maps, priorities, gap analysis results, and metrics for the development of future spaceflight capabilities for human and robotic exploration.[9] This stepping-stone approach is intended to

- Establish technology investment planning systems that enable focused choices,
- Work from clear concepts of operations for technology,
- Create a forecast of future events,
- Use a comprehensive taxonomy as a basis for gap analyses and partnering, and
- Establish an annual process for assessing results and updating planning.

The planned strategic technology and systems model focuses on the NASA technology readiness level (TRL) definitions. Generally, at the lower TRLs (i.e., basic research), many diverse, competing technologies are funded at low levels. As the competition continues, various technologies that have advanced up the TRL scale are

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[8]National Aeronautics and Space Administration, *2003 Strategic Plan*, Washington, D.C.: NASA Headquarters, 2003.

[9]John Mankins, NASA Headquarters, “Advanced Systems, Technologies, Research, and Analysis to Enable Future Space Flight Capabilities and Realize the U.S. Vision for Space Exploration,” presented to the workshop, February 23, 2004.

selected for continued support with a more moderate level of funding. Over time, as higher technology readiness levels are achieved and technologies are matured, the number of competing technologies is reduced to one or two. Funding of each concept increases considerably as the technology is matured through system-level ground and flight demonstrations to support decisions to proceed with system development.

Within the ASTRA framework, Mankins expects to use the national space exploration vision,[10] including science goals and requirements, to guide the technology systems analysis for supporting the formulation of the human and robotic technology plan. This plan will, in addition to NASA investments, also reflect investments by other organizations. The investment portfolio will include a balance of general and focused technology, in-house and external peer-reviewed competitions, and interim technology testbeds and demonstrations.

ASTRA also incorporates a set of ground rules and processes for the integration of technology information and a strategy-to-task approach.[11] Standardized terminology and common frameworks permit a systematic evaluation of spaceflight technology research and development. The framework supports the Advanced Technology Life-cycle Analysis System (ATLAS) methodology by forming the basis of a Technology Tool Box (TTB), which is a database of technology-related inputs for the ATLAS model. Both ASTRA and ATLAS are mechanisms for efficiently applying multidisciplinary expert knowledge to the challenge of improving spaceflight capabilities.

ASTRA involves both a five-level hierarchical approach and an organizational structure focused on self-sufficient space systems; space utilities and power; habitation, bioastronautics, and EVA; assembly, maintenance, and servicing in space; surface exploration and expeditions; space transportation; in-space instruments and sensors; and information and communications.

Mankins concluded his presentation by observing that the new vision for human and robotic exploration represents a long-term, strategic focus for the nation's civil space activities. Successful implementation and pursuit of the new vision will require advances in diverse technology areas. He stated that a resilient, adaptive process would be necessary to plan and execute these investments.

Molly Macauley inquired about examples of transformation and rapid innovation achieved outside space programs and asked if the effort planned to leverage other technology developments. Mankins, who has commissioned a series of workshops on transformational systems concepts in space, answered by saying that was exactly what was being done—bringing emerging technologies from outside the space sector or from outside NASA. He said NASA was trying to prevent the program from becoming insular and trying to leverage different disciplines and systems concepts. The workshops are being held mainly at NASA centers and universities. Code T is also sponsoring several industry days to solicit industry for ideas and participation in new areas. Macauley suggested that NASA needs to move beyond its interaction with the "usual suspects and venues." Eric Rice mentioned that, in formulating the original idea for a space station

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[10] NASA, *The Vision for Space Exploration*, February 2004

[11] The strategy-to-task technique is "an approach used to develop low-level, often system-specific, requirements for a system or capability through a process of decomposition." (Michael Bathe and Jeremy Smith. "A Description of the Strategy to Task Technique and Example Applications," *Journal of Battlefield Technology*, Vol. 5, No. 1, July 2002.)

program, NASA held workshops around the country, getting input from individuals, organizations, and companies in all locales. He suggested that a similar set of workshops could be productive here.

In response to a question about the future of NASA's Small Business Innovative Research (SBIR) program, Mankins replied that SBIRs were being made more relevant to the technology needs of government. Decisions on SBIRs would not be driven by commercializing space, he said.

Charles Walker asked what specific mechanisms other than the Centennial Challenge Mankins and Code T had in mind to identify and bring new innovations into the program. Mankins stated that the process was still in development in Code T but that it would include many opportunities for competition. These opportunities will be oriented to accomplishment and will be applicable to all TRLs.

Branscome asked what lessons could be learned from Steidle's Joint Strike Fighter experience. Steidle stated that the technology selection process involved a gap analysis. Specific technologies and affordability were concerns. There was a need for new manufacturing capabilities, business models, design methods, integrated subsystems, and health management and prognostics. The technology selection process worked well for the Joint Strike Fighter; its first success was the bunker-busting bomb.

Donna Shirley asked about incorporating nontraditional systems concepts in the process. Space elevators were an example. She suggested that there did not seem to be any opportunity for major innovation in the overall systems concepts being discussed that day. Mankins said the problem was that big, new ideas do not integrate well into NASA or elsewhere because there is no mechanism to take in system-level ideas and often no support. Some mechanism needs to be devised for far-term work, he concluded, but the greater responsibility of Code T is to make things happen successfully in the present. Pulling big, new ideas in has not worked well in the past. The NASA Institute for Advanced Concepts and the Revolutionary Aerospace Systems Concepts, both programs within NASA's former Aerospace Technology Enterprise (Code R), provide a mechanism to pull in new ideas. Mankins mentioned that Code T plans to better synthesize the ideas discovered through these two programs with technology investments and systems.

RECENT ARCHITECTURE STUDIES AND TECHNOLOGY DRIVERS AT NASA

James Geffre, NASA Johnson Space Center, provided an overview of recent studies on space system architecture and necessary technologies for both lunar and martian exploration that have been performed by the Advanced Development Office. He mentioned early in the presentation that not enough emphasis is placed on how to implement an architecture to suit a wide range of future missions and goals. Major challenges in light of the new exploration vision will include safety, performance/flexibility, risk, and cost effectiveness.

Geffre also suggested that NASA needs to develop an "interstate highway" for space that employs reusable, efficient space transportation systems. Future missions will also need propellant on demand and more robust capabilities. The mission strategy should establish building blocks and use a modular spiral development approach.

Four possibly transformational conceptual elements of spaceflight were presented:[12]

1. Lunar elevators would be a reusable, space-based chemical propulsion transport system for payloads from low Earth orbit (LEO) to the Moon or beyond. The elevators would refuel at their destination and never need to return to Earth. One advantage would be mass-efficient lunar exploration with a one-person vehicle.
2. Solar-electric-propelled freighters would integrate high-performance, efficient electric propulsion into a vehicle to propel payloads from LEO to high-energy orbit. Advantages include the potential reduction in beyond-LEO transportation costs and required launch vehicle capacity.
3. Cryogenic propellant depots would provide an on-orbit reserve of cryogenic chemical or electric propulsion propellant, decoupling the launch of propellant from that of hardware.
4. Orbital maneuvering vehicles are autonomous orbital maneuvering, rendezvous, and docking vehicles that can transfer propellant launch packages to tankers, move payloads, and safely de-orbit hardware.

The team looked at a variety of missions and architectures and concluded that human lunar return is one of the most important to study because its trade space of implementation options includes technology elements of other missions. The team also attempted to include options in its analysis that would answer questions such as, Where should in-space staging be done? Where should the primary vehicle be located? Do vehicles stay in orbit all the time, or do they return to Earth after every mission? NASA is investigating this entire trade space and also considering mass as a metric in the design. Geffre did point out that mass and cost are usually interconnected in such a trade space. One example of this interconnection was a comparison between the mass of Apollo (approximately 130 tons) and the mass of these new architectures (on the order of 150 to 200 tons). One important difference between the old and new designs is that a larger fraction of the mass in the new architectures is reusable (that is, is not a propellant).

The team also looked at payload capabilities for use by other government entities, including other NASA enterprises and DOD. The studies emphasized the cost-benefit of not having to launch propellant each time a vehicle is launched. Additional autonomous activity was also considered in the scenarios studied. Geffre said that Mars architecture studies have been ongoing for last 15 years; however, the team is using a newer set of transformational space infrastructures. The goal of this architecture is to improve performance and affordability relative to what is achievable with more traditional approaches.

Geffre ended his presentation by mentioning briefly key capabilities and technology needs that have been identified during these mission and architecture studies. They fall into five areas: (1) advanced space transportation, (2) Earth-to-orbit transportation, (3)

[12]James Geffre, NASA Johnson Space Flight Center, "A Summary of Recent NASA Exploration Architecture Studies: Transformational Space Infrastructure Strategies," presented to the workshop on February 23, 2004.

planetary habitation, (4) advanced extravehicular activity, and (5) cross-cutting capabilities.[13]

During the discussion period, Donna Shirley mentioned that the architecture studies presented here looked like the same types of studies that have been done for the last 20 years. She thought that the outcomes of the studies would all be the same if the technologies one is looking at are the same. Shirley asked if NASA was looking at architecture studies for a variety of scenarios, some—e.g., the space elevator—more transformational than others. Geffre said that the team had not yet looked at space elevators or other radically transforming capabilities, but there was a need to do so and to infuse new ideas into NASA.

Joseph Guerci asked how the team budgets for technologies that would one day succeed. Geffre said that the team does not wait until all technologies are available before using their predicted performance metrics in system studies. The new transformational space infrastructures would instead allow NASA to choose and carry out the most ambitious of the missions based on projections of when the enabling technologies are expected to be ready. If certain technologies are unavailable, mission designers can then fall back on more traditional technologies. An incremental set of capabilities is funded as more resources become available.

[13]Cross-cutting capabilities, in this sense, are those that apply to both robots and humans in both near-Earth orbit and planetary exploration. Examples include intelligent systems, high-bandwidth communications, advanced navigation, and advanced power systems and storage.

Stepping Stones to the Future of Space Exploration: A Workshop Report

5

Technology as a Driver for Capability Transformation

The afternoon session began with a presentation by Joseph Guerci on DARPA's space activities and their role in transforming technology used by the armed services. Two panel sessions followed in succession. Both covered technology and transformation of capabilities. The first was moderated by steering committee member Charles Trimble, the second by Dava Newman. Members of the first panel were Brad Parkinson, Stanford University; Christine Sloane, General Motors; and David Hardy, Air Force Research Laboratory. The second panel has as members Jacqueline Haynes, Intelligent Automation, Inc.; Stanley Schneider, National Polar Orbiting Operational Environmental Satellite System; and Christopher Stevens, NASA's New Millennium Program. All the speakers were asked to address a half dozen focusing questions in their short presentations:

- What, briefly, is the role of technology as an agent for organization and capability transformation, specifically as related to your organization?
- What other factors must be present to facilitate technology as an agent for transformation?
- What are the obstacles that hinder using technology to accomplish capability transformation?
- What are the important barriers that must be overcome in using technology to facilitate capability transformation?
- What are the challenges to achieving technology insertion into capability development?
- What are the appropriate time templates to use for technology-driven innovation?

Joseph Guerci, deputy director of the Special Projects Office at the Defense Advanced Research Projects Agency (DARPA), presented information about DARPA's space activities, vision, and technology transition. He began his presentation by providing an overview of the creation, purpose, and mandate of the agency. DARPA was created by President Eisenhower in 1958 in response to the Sputnik threat. Its role is to bridge the gap between current and near-term armed services science and technology programs and fundamental research made up of long-term investments. Each project funded by DARPA is given a short timeline—3 to 5 years—to accomplish its goal. Guerci stressed that this constraint, in addition to a lean management structure, is DARPA's way of keeping fresh ideas flowing.

Technology is transitioned out of DARPA in one of three ways:

- DARPA contracts directly with the industry base, which then produces the technology for use by the government. Guerci mentioned that this is the most effective transition mechanism for DARPA.

- DARPA funds small systems or prototypes through armed services science and technology programs, which then advance the new technology by means of various armed service funding mechanisms and bring it into full production.
- DARPA enters into a formal transition with a transition partner (usually a branch of the DOD), which submits to it a program objective memorandum (POM). Stealth technology was transitioned in this manner.

As a result of recommendations from the Commission to Assess United States National Security Space Management and Organization (the Rumsfeld Commission),[1] a larger percentage of DARPA's budget is invested in space now than in the recent past. According to Guerci, the report stated that U.S. space systems are vulnerable to attack, the space industrial base is weak, and the systems are aging. DARPA was subsequently directed to focus on the access and infrastructure questions related to space. There are three types of DARPA research in space:

- Direct access (example: affordable launch vehicles and access to space),
- Both direct and indirect access (example: microsatellites), and
- Indirect access (example: payload compression).

Guerci mentioned the need to change the space research and development process by using a new paradigm to reduce the cost and increase the frequency of space deployments. A paper given by James Wertz at the American Institute of Aeronautics and Astronautics and the Utah State University Conference on Small Satellites was referenced as an example.[2] Collaboration between various space agencies is also critical, according to Guerci. There is a lot of excess capacity in launches, especially military launches, that could be used. The issue is that individuals and programs do not want to introduce additional risk into their missions even when they have extra space. Guerci suggested that the government mandate that excess capacity be used.

Steering committee member Molly Macauley asked if the Moon-Mars mission should be done by DARPA instead of NASA. Guerci replied that DARPA does not typically handle large acquisition projects well. Its focus is on proof-of-concept demonstrations. NASA has tremendous capability as well as resources that do not exist in DARPA, and there is also a lot of synergy between industry and NASA. Macauley then asked about risk at DARPA. Guerci said that DARPA fails often and may even try several times. But when a project finally succeeds, its payoff can be immense (e.g., stealth technology, the Internet).

FIRST PANEL

Brad Parkinson, Stanford University, began by discussing the Global Positioning System and its role as a transformer of capabilities, first for the military and then for the

[1]Commission to Assess United States National Security Space Management and Organization, *Final Report*, January 2001. Available online at <http://www.defenselink.mil/pubs/space20010111.html>. Accessed May 7, 2004.

[2]James Wertz, Microcosm, Inc., Changing the Paradigm of Space Testing: The FAST Program, 15th Annual AIAA/USU Conference on Small Satellites, Logan, Utah, August 13-16, 2001.

general public. Parkinson described GPS as a just-in-time technology that was really a collection of new technologies, all of which were necessary to develop the final product. The constituent technologies included spaceborne atomic clocks, spread-spectrum ranging, and inexpensive, low-power computing, among others. He provided examples of GPS successes. GPS had allowed the tracking of sheep and the accurate automated landing of aircraft; it had also led to an understanding of crustal motion and earthquakes.

Parkinson defined "disruptive" as something that used to be really hard but is now taken for granted. His message boiled down to three key enablers: focus, time, and leadership. For technology to be useful it needs to have the focus of a mission. The focus needs to have substance. One example of substance is reliability—not simply performance, but instead the reliability of the mission itself. Technology development has a natural rhythm. It takes time to mature technology appropriately. For example, a baker cannot double the temperature at which a cake is baking and then halve the baking time to achieve a baked cake. There is also a need for leadership from someone who understands how much time it will take to achieve a disruptive technology and who has the courage to stand up to the mainstream world, which is saying it can't be done. This person is not the advocate and does not lead by committee. For example, GPS was cancelled by the Air Force on four separate occasions. Fortunately, civil leaders with more authority stepped in to prevent that from happening.

Moderator Trimble mentioned that the new Code T process is driven by requirements, while GPS was driven mainly by the capability itself. Parkinson confirmed that there had not really been any requirements for GPS. Because the Air Force did not think it wanted the capability, he could design to what he thought was achievable within constraints of cost and time. In a development program, one has to change requirements in a feedback loop once one realizes that a technology is not feasible. Parkinson also mentioned that the idea of a capability is more helpful than the idea of a requirement, because often requirements are defined so rigidly that they can never be achieved at a reasonable cost.

Newman asked how long technology development typically takes. Parkinson said that it depended on the mission. Typically, a technology planner can add 25 to 50 percent to the time an advocate says he needs to provide the technology. Accurate estimates require concrete and specific knowledge.

Christine Sloane, General Motors, began by describing her role in the Partnership for the Next Generation of Vehicles and the new Freedom Cooperative Automotive Research (FreedomCAR) research effort. FreedomCAR is designed to accelerate the development of technologies for new, energy-efficient vehicles and for hydrogen fuel and use them to transform an existing infrastructure (in this case, petroleum-fueled automobiles, or, more broadly, passenger transportation). The biggest challenge to inserting technology into the automobile industry and the fuel industry is acceptance of the new technologies by the marketplace and the public. Key to achieving that acceptance are cost, familiarity, performance, and durability (including tolerance for abuse by the consumer). She believed that these issues are probably less applicable to space travel, since the equipment and vehicles are all funded, assessed, operated, and maintained by professionals, not the marketplace. Technology insertion in the automotive industry must also take into account customer preferences at the point of purchase. Since the societal benefits of energy efficiency, such as reducing petroleum dependence or greenhouse emissions, may be more important than the personal benefits, Sloane believed the government needs to support the long-term research (over 10 years in the automobile industry) required to achieve such efficiency. There is a conflict in the marketplace when purchasers decide whether to spend incremental dollars for a personal benefit (such as a tape deck) or for a societal benefit Because personal benefits have historically dominated purchase decisions, technology insertion is needed.

FreedomCAR is a government program in which industry is a partner. A key industry role is to set research targets that reflect the comprehensive requirements of the automotive marketplace and real-world driving so that fundamental technology developments from this research will take into account industry's engineering challenges in technology insertion. The FreedomCAR partnership is focused on transforming the automotive sector's nearly total dependence on petroleum by giving it the flexibility to use diverse fuels. The major research focus is therefore on energy-efficient systems powered by hydrogen fuel cells. Beyond the engineering performance of these systems, their affordability is key. Affordability can be seen as a technical challenge because it requires achievements such as material substitution, parts integration, and innovative manufacturing processes. Insertion of these technologies into the automobile industry marketplace will likely require market incentives to overcome customer hesitancy to adopt a new technology, infrastructure incentives to stimulate deployment of the new refueling system coincident with vehicle introduction, and the development of commercial codes and standards, none of which are required in the space industry.

Sloane mentioned several obstacles to the successful completion of a long-term program to develop the hydrogen fuel cell automotive technology that the space exploration program may not face. They included commitment to the long-term vision; retirement of existing infrastructure; codes and standards; public acceptance; and affordability. There are also difficulties associated with the introduction of a new automotive vehicle into the marketplace, including durability of the inserted technology, timescales for infrastructure development, market acceptance, and cost, especially for the small number of vehicles that will initially be sold. Trimble asked if the introduction of a new vehicle was feasible from an engineering standpoint. Sloane said that it was feasible and that the companies engaged in developing the technology are optimistic enough to continue to invest in the new technology and to operate demonstration vehicles. General Motors has six fuel cell cars being driven in the Washington, D.C., area that are performing very well. The key remaining challenges are to make them more affordable and durable. Macaulay asked about the time needed to develop the infrastructure. (For example, the current infrastructure for space exploration includes the space shuttles and the ISS.) How does the industry figure out how long it will take? Sloane responded that in the fuel/automotive marketplace, a key element will be the coincident development of opportunities for the energy and automotive industries to invest in that will bring a return on the investment. That will require not only technology readiness but it also requires that the government coordinate simultaneous deployment by energy and vehicle companies and that it encourage the vehicle-buying public to switch to the new technology. General Motors has spent over $1 billion on new technologies for these next-generation vehicles and expects to market them in the next decade. The technical issues surrounding fuel cells for automobiles are therefore expected to be solved by 2010. The energy industry, meanwhile, is preparing for the availability of the technology by exploring opportunities for improved hydrogen production and deployment and by demonstrating hydrogen infrastructure technologies to bring them both to the same stage of readiness as fuel cell technology. Cost and public acceptance will be key to a successful introduction into the consumer marketplace.

An audience member suggested that there is a need to invest in interoperability (codes/standards) for the space program. Charles Walker mentioned systems engineering for large systems and asked how the introduction of cars powered by hydrogen fuel cells will be different from the introduction of a new model car. Is the FreedomCAR transformational or evolutionary? Sloane replied that it is a disruptive technology, not an evolutionary technology. The infrastructure will be substantially different for both the automotive companies and the energy companies. In the FreedomCAR, the "engine" is being completely reinvented, whereas new model cars always entail evolutionary improvements on earlier designs and are manufactured using traditional casting and machining technologies and catalyst hardware, for example. The supply base for the fuel will also be totally different, no longer relying principally on petroleum feedstocks. To the driving public, the vehicle should look attractive enough to inspire the purchase of a new, less familiar vehicle system. For example, for a fuel cell vehicle, which is a completely electric vehicle, there is no need for a traditional engine compartment. The General Motors fuel cell vehicle Autonomy demonstrated one possible use of the design freedom offered by fuel cell power systems—it had a skateboard chassis that had under it the entire power system and all the vehicle controls.

David Hardy, Air Force Research Laboratory, provided a DOD perspective on the focusing questions and described the DOD Space Experiments Review Board**.** DOD has been given incredibly difficult goals, including launch on demand, the ability to hit any target anywhere in the world in 60 minutes, the ability to track objects anywhere at any time, and a global information grid, among others. The development of new technologies is the one way to achieve these goals, and also DOD leadership understands that. However, in the current fiscal environment, capabilities must also be a "good buy." Missions and programs must analyze the problem, determine the technology needed to solve it, and then start a new program if necessary. Obstacles to this process include the long times for technology development and the complexity of the process by which ideas are converted into an operational system. These obstacles are partly inherited from the time when space systems were originally developed, when requirements and technology were not evolving as rapidly as they are today.

Hardy believes that the TRL system to determine technology maturity is too subjective. It leads one to think that systems are more technologically advanced than they really are, especially when researchers become advocates for specific technologies and overstate technology readiness, letting managers make decisions based on overly optimistic numbers.

There are many players in the space technology arena, including, on the military side, the National Reconnaissance Office, DARPA, the Air Force, and—to some extent—the Navy. On the civil side, the space technology arena includes NASA, the Department of Energy, and the National Oceanic and Atmospheric Administration (NOAA). This is a rather large community, with many cultures and different organizational structures. It is hard to work together. For example, lift requirements do not mesh easily for historical and organizational reasons and because the organizations have fundamentally different missions. Launches are expensive. For the Air Force, cheaper access to space is a huge driver.

Hardy also believes that the space infrastructure is currently fixed, static, and predictable. The military would like to see it much more flexible and robust. If the entire space infrastructure of the United States were to be wiped out, the military would not be able to rebuild it. Hardy also said that the Air Force has no incentive to support humans in space, so it is developing unmanned vehicles. However, when it comes to responsiveness and affordability, in space, one can find much in common between NASA and DOD.

Joanne Gabrynowicz asked if the military would be interested in experiments on the Moon. Hardy said that this was unlikely. The military likes to look down at Earth from space and to do so at the lowest possible altitude. It might have some interest in low Earth orbit and the L2 Sun-Earth Lagrangian point, but not in exploration. He said there might be some overlap with capabilities demonstrated by the Clementine mission.[3] The DOD might be interested in rendezvous with other objects in space or in very close operations. In general he felt that there was no utility in joint DOD and NASA missions. Hardy also commented on terrestrial defense against near-Earth asteroids, saying that there is high risk but low probability. There is some interest on the part of DOD, but not enough to spur any action. Terry Allard, NASA, asked Hardy which technologies would be worth exploring through joint DOD and NASA programs or missions. Hardy replied that interagency plans are difficult, and that sometimes the only result of the partnership is to justify the research of each agency. He is skeptical of interagency working groups, even though real synergies can be achieved

SECOND PANEL.

Jacqueline Haynes started the second panel, continuing the theme "Technology as a Driver for Capability Transformation" and providing her perspective as the owner of Intelligent Automation, Inc. (IAI), a small, woman-owned business focused on advanced artificial intelligence applications and technology innovation. Answering the question about the role of technology as an agent of organization and capability transformation, she said flexibility was paramount. Flexibility was mentioned as key in the small business community, whose members are typically organized around technologies in which they are already invested through their personnel. As for the other factors that must be present for technology to achieve transformation, Haynes observed breakthrough scientific achievements come from a combination of vision, motivation, and funding. She presented as an example a three-dimensional model of ballistic identification.

Haynes suggested that small businesses might have special concerns about new NASA programs. Among the concerns were these:

- Small businesses might not be able to break into NASA's new programs because of the existing relationships between NASA and large companies.

[3]Clementine was a joint mission between the DOD and NASA in 1994 to test the effects of extended space exposure on sensors and spacecraft components. Although its primary mission was to test new lightweight satellite technology, mapping of the Moon was a secondary mission.

- Limited time and costs would make it hard to establish new relationships and new communication channels.
- Businesses might be hesitant to participate because they are not confident that the program will outlast the administration.

She also suggested that two important barriers must be overcome in using technology to facilitate capability transformation—namely, negative perceptions of engineers and scientists, causing young people to opt for the other careers, and a poor public understanding of space missions. She declared that education in science and engineering was important, saying, "the universities are not producing the scientists needed now, and the prognosis [for the future] is worse." She then broadened her point to include educating the public and enhancing communication between scientists and the public.

When asked what the main contribution of her business was, she cited active participation in the small business innovative research (SBIR) program (50 percent of her company's portfolio) and providing applications of basic theoretical sciences. Her company does not directly sell products but licenses some technology. It is not difficult for small businesses to enter the SBIR program, which she saw as attractive. She supports the SBIR and the Small Business Technology Transfer (STTR) programs in pushing innovation but is concerned that the programs are becoming overly focused on accomplishing program objectives.

Stanley Schneider, associate director for technology transition in the National Polar-orbiting Operational Environmental Satellite System (NPOESS) Integrated Program Office, provided the perspective of a federal interagency program. NPOESS is a collaboration by DOD, the Air Force, NOAA, and NASA. A recommended model for a robust risk reduction program was presented involving both hardware and software. User buy-in was mentioned as necessary for success, as was the involvement of all stakeholders. Flying all the instruments beforehand was a way to further reduce risk.

NPOESS needs several new technologies for making various measurements. Schneider said that a guideline that calls for setting aside 25 percent margin of payload space in the satellites for technology testing is being followed. Payload mass, volume, and data rate are reserved for new technologies that will be piggybacked for testing.

In answering the focus question on the role of technology as an agent for organization and capability transformation, Schneider described a unique contracting arrangement whereby NPOESS contracts, primarily with Northrop Grumman Space Technology, under a "shared system program responsibility" model. Northrop Grumman and NPOESS consider themselves partners, and this model was suggested as a way to reduce risk. Everyone works under the same roof and in the same office at NPOESS regardless of which government agency employs them. The operational mentality is that you "leave your badge at the door." In this way NPOESS has created its own identity. One of the benefits is that the people there think outside the box, working together to create success. Performance-based requirements were implemented, and the contractor presented a processing timeline where data needs are met in 30 minutes. The SafetyNet architecture was the innovative industrial solution.[4] Schneider reported that instrumentation accounted for about a third of the entire NPOESS budget, which was development oriented.

Moderator Newman asked Schneider how the message had got out about the success of the NPOESS model of agency collaboration and cooperation? The answer was to have a lot of community interaction and numerous briefings, as well as special sessions at relevant programmatic, science, and engineering conferences and symposia. He was also asked what NPOESS's international role was, especially in light of existing international polar-orbiting satellites. NPOESS will be bringing in data from European systems and vice versa, but there is no exchange of instrumentation. The European group sits on the NPOESS advisory group, which meets quarterly.

Christopher Stevens, manager of the NASA New Millennium Program (NMP) at the Jet Propulsion Laboratory (JPL), provided the final perspective.[5] The objective of NMP is to accelerate the infusion of revolutionary technologies into NASA science missions by validating them in space, to provide new and lower cost capabilities for Earth and space science missions and reduce the risks to the first users. The NMP is similar to the proposed Code T Technology Maturation program, but the NMP is sponsored by the Earth (Code Y) and Space Science (Code S) Enterprises. The NMP helps fill the gap between low-TRL work and the science missions. NMP was set up when the Earth and space science programs realized that the technology capabilities needed to accomplish Earth and space science goals would not be available without further investment. Approximately $35 million of the annual budget for the NMP comes from the Earth Science Enterprise and $80 million, from the Space Science Enterprise.

When discussing the relationship between ASTRA and NMP, Stevens noted that the technology validation projects in the NMP program fit the ASTRA model in the "applications pull" area. The NMP program conducts two types of technology flight tests: (1) stand-alone subsystem validations and (2) integrated system validations. He spoke of multiple applications and potential dual use opportunities as well as NMP's education and outreach efforts.

A 5- to-8-year period before launch was suggested as the time typically needed for mid-TRL technologies to be developed. A 10-year period for technology development from lower TRLs was mentioned, and a shorter period, 3 to 5 years, was suggested for subsystems.

Someone asked how the NMP fits into NASA's ASTRA or a Moon-Mars initiative. Stevens responded that there is no formal relationship. It was his understanding that there were discussions at NASA about whether the NMP should be moved to Code T. When Code T was formed, NASA decided that was not appropriate to move NMP into the new organization. NMP is specifically addressing the needs of Codes S and Y, but the attributes and processes of NMP may be suitable to Code T's plans, particularly where the capabilities needed by Code T for robotic exploration of the Moon and Mars are also needed for future space and Earth science missions. Macauley reminded everyone that Deep Space 1's original objective was to validate technologies. Later, the emphasis

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[4]SafetyNet is a data routing and retrieval architecture built by Northrop Grumman Space Technology. Information available at <http://www.st.northropgrumman.com/media/SiteFiles/mediagallery/factsheet/NPOESSSafetyNetFactSheet.pdf> accessed March 17, 2004.

[5]Christopher Stevens, NASA Jet Propulsion Laboratory, "New Millennium Program: Technology as a Driver for Capability Transformation," presented to the steering committee on February 23, 2004.

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seemed to be on a combination of technology validation and science. Now it seems that the effort has returned to the original objective. Stevens said that the program had been restructured to focus on technology. When asked how the NMP program had changed over the years, Stevens replied that the program emphasizes enabling future capabilities rather than allowing projects to morph into quasi-science missions.

At the close of the second panel discussion, steering committee member Rice commented that small businesses are an important asset, as most technology innovation has come from the small businesses. Stevens's reply was that the NMP's challenge has been how to help small businesses determine what the needs are. The interdisciplinary aspect of small businesses is a good model, Gabrynowicz said, NMP's seamless integration of different cultures and its attention to different populations of scientists, engineers, and social scientists is very useful and can be a good model. Sharon Traweek, an anthropologist, has researched the anthropology of science and technology.

6

Risk Aversion—Flying in the Face of Uncertainty

The session was moderated by committee member Molly Macauley, a senior fellow at Resources for the Future, a research organization in Washington, D.C. The panelists were General John Barry, a member of the Columbia Accident Investigation Board; Joseph Fuller, founder and president of Futron Corporation, a technology management-consulting firm headquartered in Bethesda, Maryland; Gregg Hagedorn, with the Naval Sea Systems Command (NAVSEA); Allan Mazur, a sociologist, engineer, and professor of public affairs in the Maxwell School of Syracuse University; Richard Obermann, the Democratic professional staff member on the House Committee on Science; and Michael G. Stamatelatos, NASA Director for Safety and Assurance Requirements.

The panelists for this session were asked to address the following questions:

- What lessons might be shared about differences in risk perception by the public, the Congress, and the agency (NASA)? How are perceptions influenced by risks that are low probability but high cost?
- The NASA model under discussion (ASTRA) omits explicit treatment of risk. Risk can be defined in many ways—it can, for example, include economic, technological, and political uncertainty—but no matter how it is defined, the model does not explicitly include it. Specifically, the model does not (1) incorporate the consequences of failure to meet milestones, (2) identify decision points at which technology development might be terminated because of cost, engineering problems, or obsolescence, (3) illustrate the cost impacts of failure or redirection of technology development, or (4) include fallback strategies. What modeling techniques might you suggest that would enable the model to incorporate probabilistic treatment yet remain tractable?
- Among the arguments against including probabilistic treatment in the model are that it renders the model more difficult for decision makers to comprehend, and can undermine the political ability to sell the technologies. How significant are these concerns and how can they be addressed? Lessons learned from the development of other technologies (for instance, nuclear power generation, the superconducting supercollider, synthetic fuels) might be useful if you can share them.

Molly Macauley introduced the topic by offering some perspective on how to treat risk. The intent of the session was to provide an overview of risk, which is not explicitly treated in the ASTRA model, in various forms. She pointed out that something uncertain is not necessarily risky, and that risk need not result from something uncertain. In other words, uncertainty—for instance scientific, engineering, or technological uncertainty or any other thing that is intrinsically unpredictable or stochastic—is not necessarily risky. Risk can result from careless management decisions even in informed, certain situations.

Risk can be technological, political, or financial. Macauley noted that in Steidle's presentation the previous day, Steidle had commented that sustaining a long-term program through successive presidential administrations, Congresses, and budget cycles might be the greatest risk facing human space exploration.

Macauley also noted that neither uncertainty nor risk is necessarily bad and that to some degree, both can be managesd. In some cases, uncertainty can be reduced through additional research and development, as we learn by doing. Risk can be managed in a variety of ways, including private insurance for activities that take place in the private sector. In the case of government programs, however, the government typically self-insures, so the public bears the risk.

Macauley observed that risks that are voluntarily undertaken are usually perceived differently from risks that are involuntary. Low-probability, high-consequence risk is usually perceived differently from high-probability, low-consequence risk. Loss of life is typically seen as a greater risk than loss of property, even if the property loss involves billions of dollars.

Mazur commented that deaths associated with spaceflight, if they are highly publicized, become symbolic and therefore have a much greater effect on public policy than a body count from a probabilistic risk assessment. He said that deaths of aerospace industry workers, even of astronauts, have little impact on public sentiment if they occur outside the public eye. But even one highly visible death in flight can greatly affect a program, causing long delays or even cancellation, or even an increase in funding if that seems to offer a solution. He stated that probabilistic risk assessment goes out the window when astronaut deaths make the headlines. Mazur noted that there were many more news stories covering the Challenger and Columbia accidents than the Apollo fire. As result, NASA was able to investigate the Apollo accident in-house and quickly resume the program. Because of increased media attention and the attendant public anguish, independent commissions were set up to investigate the two shuttle accidents, and these produced far longer delays in the program and severe criticism of the agency.

He pointed out that a sociological model of accident events differs from an engineering model and reveals aspects of the accidents that influence media coverage and public perception. According to Mazur, the engineering model focuses on the proximate causes of a disaster (e.g., frozen O-rings, broken foam) and their precursors (e.g., rushed launch schedules, NASA's culture of risk). If engineers and risk analysts consider media coverage at all, they treat it peripherally, focusing on things like fairness and accuracy of the reporting. A sociological model treats an accident as a social event, the public reaction to which is greatly affected by the quantity and tone of news coverage. Just as the physical accident has precursors, journalistic coverage is also affected by important factors that precede or accompany the accident.

That a teacher was on Challenger, and that the accident itself was captured by the camera—the photo of the explosion is now iconic—reinforced the news coverage and contributed directly to President Reagan's decision to form an investigative committee independent of NASA. (Mazur suggested how different the accident would have been, as a social event, had it occurred 1 minute later, out of camera range.) Because the Columbia accident came after September 11, 2001, and had an Israeli astronaut on board it was immediately interpreted as a possible terrorist event. The shuttle's disintegration, also captured on film, was shown repeatedly in the days following the accident. Mazur, using the example of the Cassini mission, said that the sociological model applies as well to unmanned missions, such as space probes carrying radioactive material, that are perceived to present a risk to the public. The public controversy over the Cassini mission was familiar from other public controversies over risky technologies. The argument of opponents and proponents lead to balanced media coverage, with each side given a voice. Soon the controversy itself became newsworthy, which heightened the level of news reporting. With doubts about the safety of the mission featured in the newspapers and on television, public concern was aroused and opposition to the mission increased. Attempts by Cassini proponents to correct the news reports amounted to throwing gasoline on a fire, increasing the level of news coverage and therefore of public concern.

Asked by a panel member if NASA could influence the amount of media attention to human spaceflight, Mazur replied that coverage will be extensive if an accident is linked with an event such as having a schoolteacher on board. An unmanned flight can also escalate into a big media story if the flight itself is controversial (this could happen with future missions using technology developed in NASA's Prometheus).

General John Barry began his summary of key points from the Columbia Accident Review Board (CAIB) report by noting that the patch honoring Apollo 1, Challenger, and Columbia on the back page of the report avows that exploration will continue in the face of adversity. In this context, he said, "adversity" can almost be replaced by "risk." The CAIB found that the shuttle is not inherently unsafe—rather, it is a developmental vehicle, which has inherent risks, not an operational vehicle. An incorrect mindset both inside and outside NASA—namely that the shuttle is operational—contributed to safety problems, according to the CAIB.

Barry also pointed out that it was the first time the nation had used aging vehicles—the space shuttles—in an R&D environment, which presents a new challenge. The CAIB looked at both technical issues (for example, problems with the shuttle's external tank foam insulation) and management/cultural issues inside NASA and then sought to make projections about high-risk areas associated with human spaceflight. The Columbia accident represents a turning point for NASA—impelling a new debate about the nation's commitment to human spaceflight and a new vision for that commitment.

Barry emphasized that human spaceflight is not routine and has many risks. A risk-averse organization like NASA needs constant learning, but NASA did not go to school on Challenger. The U.S. Navy used the findings of the Challenger accident investigation as an example of how, after an accident, to learn from mistakes, but NASA did not. For instance, the same people controlled schedules for costs, testing, maintenance, flight, and so forth, yet the agency needed more checks and balances. Barry also discussed the tendency for the agency to normalize deviance—that is, when a mistake occurs more than once, the tendency is to accept it (for example, the repeated loss of foam became acceptable when it should not have). In addition, he said that when an issue is first raised, the agency's approach is to prove that there is *no* problem but that after launch, the approach is to prove that there *is* a problem, making the agency reactive rather than proactive about risk.

One of the CAIB recommendations is that NASA needs to be a better-integrated organization. The agency's shuttle program integration office did not really serve this purpose; rather, it was much like a specialty shop for particular expertise. Process had become too important. For example, how photos of the accident were requested became more important than the photos themselves and the reason for wanting them.

On the issue of improved communication, Barry observed that the use of e-mail has changed the way we communicate. He also criticized the propensity for PowerPoint presentations without written reports to back them up. Barry said that the safety program at NASA tends to be silent, yet the agency needs more effective data collection, trend analysis, and analysis of anomalies.

During the question and answer period, Barry affirmed that the CAIB recommendations are just as relevant to President Bush's new vision of the human exploration of the Moon, Mars, and beyond. Asked how we can be sure that NASA implements the CAIB recommendations, Barry acknowledged that culture change is difficult and hard to measure and needs consistent, sustained leadership at the top. Asked about the value of human interaction relative to engineering interaction or systems interface, Barry emphasized the need for improved communication with a system of checks and balances in place.

In prepared remarks, Joseph Fuller discussed other kinds of risk besides safety risk. He pointed out that management risk is also important, and if poorly addressed, can result in failure and degraded performance. Fuller found that the ASTRA model fails to address any kind of risk. Because ASTRA is a systematic evaluation of technical or investment options, its use in a corporate setting would naturally include risk assessment. Fuller suggested an analysis of networked technology portfolios from which planners could generate systems and missions and perform system-of-systems analysis. He noted the difficulty of performing such analysis for ASTRA because of the absence of risk assessment standards and the limited capability for risk analysis within the community. Fuller observed that the aerospace industry is underperforming owing to a lack of leadership in creating the complex risk capabilities required for the future.

Fuller agreed that the public appears to accept reasonable risk and that it expressed strong interest in continuing spaceflight after the Challenger and Columbia accidents; bureaucrats, however, appeared much less willing to assume the same risk. Fuller commented that perception of risk is a function of the knowledge one has about a program or mission; those who are closest perceive the risk as highest. NASA needs to provide better information on risk to the public—it needs to explain why and how decisions are made. Not all risk assessment needs to be probabilistic—there are other methods—but risk assessment of some kind is necessary.

Gregg Hagedorn discussed the NAVSEA experience with day-to-day management of the risk associated with its fleet (such as aircraft carriers, submarines). He said that the public understands risks to humans but has less appreciation of risks to technology. At present, the Navy's Chief of Naval Operations is telling NAVSEA to take more risks. In modeling risk, Hagedorn pointed out the challenge of separating programmatic and technical risks to avoid conflict of interest, and said that a leader needs emotional maturity to be able to stand up and say "We made a $2 billion mistake." In response to a question, Hagedorn noted that a model like ASTRA "never really worked in the Navy."

Richard Obermann described how Congress views risk. He pointed out different kinds of risk, including safety risk (a dominant focus in the space world after the Columbia accident), cost and schedule risk, performance risk, and political risk. He noted that Congress understands risk, although not in a rigorous way, and often has to make decisions with little information (which, he observed, is one type of risk management). Congress is looking at whether the President's new plan is safe enough. However, the perception of risk and safety can vary over time, with perception immediately after an accident quite different from at other times. The questions Congress must address are wide ranging. One is the cost estimate. Is it right? Too low? Another is performance risk—what has to work right for the program to succeed? Is a miracle involved? What if performance falls short of the goal? Is the initiative resilient? What is political risk? It can mean risk to a member of Congress, but more broadly, it is the vulnerability of a mission to the external political environment, such as a new administration, a new economic climate, or a new geopolitical environment. The lack of clear information on risk will make Congress less likely to commit to a new vision.

Obermann also noted that members of Congress perceive risk based on their past experience with NASA, and previous problems with the agency's cost estimates make them more likely to view costs as high risk. Members also want milestones or tracking points to make sure a program proceeds on target. Obermann mentioned that on a number of occasions Congress has questioned the rigor and realism of some of NASA's planning efforts.

On the subject of probabilistic risk, Obermann asked how confident one could be that a risk is low probability. He pointed out that the risk of losing a shuttle was originally set at about 1 in 100,000. After the Challenger accident, it was set at 1 in 100. He asked whether that risk is one of losing just a single space shuttle or if it is the risk of losing the entire human spaceflight program. The risk and reward calculation depends on what is at stake, and different members of Congress have different opinions. It is a matter not only of how confident we can be that a risk is low probability but also of whether we can achieve consensus on what the cost or consequence is.

Obermann said that risk planning tools (such as were used for ASTRA) are useful for internal planning but will not convince Congress that risk has been eliminated. More useful is a clear delineation of high risks and what the NASA strategy is to alleviate them.

In response to questions, Obermann said that while members of Congress understand statistics they also know that statistics can be used in different ways and are skeptical of a number in isolation. They also tend to cite the statistics that buttress their arguments. Once burned by a statistic, they are very wary of similar statistics. Asked about the extent to which his comments pertained also to agencies like the Government Accounting Office, the Congressional Research Service, and the Congressional Budget Office, Obermann pointed out that support agencies respond to questions from members and the analysts from these agencies present the desired information paired with the assumptions they use in their analyses. He also noted that with the demise of the Congressional Office of Technology Assessment, there is no entity to provide real risk analysis for members of Congress.

In response to a comment about the small statistical sampling that often constrains the modeling of low-probability events, Obermann noted that now and then members are interested in risks from near-Earth asteroids, but it becomes hard to understand the meaning of such probabilities. If the risk models were better for such low-probability events, perhaps there would be more interest in the issue.

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Michael Stamatelatos began his comments by noting that risk is a combination of likelihood and severity of consequence, and that types of mission risk include technical (safety, performance) and programmatic (cost, schedule). He asserted that there is no such thing as qualitative risk assessment, because any meaningful qualitative statement about risk has, either explicitly or implicitly, some quantitative basis. Terms like "high", "medium," and "low" risk can be interpreted differently by different people in the absence of a quantitative reference. Qualitative risk assessment has value mainly as a simple way of communicating risk results that are obtained quantitatively. He also noted that perceived risk changes with exposure to consequences, even though quantitative risk may not have changed.

Stamatelatos described the use of probabilistic risk assessment at NASA, pointing out that it is done for shuttle upgrades, construction in space (e.g., the ISS), safety compliance issues (e.g., those associated with Prometheus or Mars sample return), and design (e.g., Prometheus). He agreed that there is a need to improve risk awareness within NASA and to develop in-house expertise to understand probabilistic risk requirements, because risk assessment is a decision support tool and, as such, it cannot be effectively used if decision makers do not understand its methods and findings. He also commented on the need for risk awareness and for management decisions to be informed by risk but not be risk-based—that is, they should not rely solely on risk assessment.

In response to a question, Stamatelatos said that his office was involved with the President's initiative only at a conceptual level, but that once the vision is more concrete, more rigorous risk assessment can be conducted. In response to a question about how important it is to start risk assessment early in program planning, Stamatelatos said that it should start sooner rather than later; however, if you wait until you have all the information, you will not need a risk assessment. Quantitative risk assessment can inform decisions about where to put money and can identify where the largest risks are. Operational risk can also be reduced once a system has been designed and built, since specific components and technologies can be evaluated.

Donna Shirley asked how, for a broad vision such as ASTRA, does losing one technology (or not achieving maturity for it) affect the risk for the entire system? She contended that if a specific amount of risk is decreed at the highest level, program managers would be inspired to suppress information to try to achieve that decreed risk. This is not productive. Barry commented that since as far back as the Apollo program NASA has never adopted a probabilistic risk assessment culture. The CAIB thought that NASA should use probabilistic risk assessment as a tool to inform decisions, but did not think that the agency should be a slave to the process. Barry went on to say that repeated untoward occurrences (e.g., foam falling off the booster rocket, the erosion of the O-rings) should have signaled potential problems. Although some disagree that probabilistic risk assessment would have correctly identified the foam as a risk, the point is that repeated loss of foam should have been a sign to engineers of a potential problem. Panelists and audience members agreed that the management culture and institutional barriers at NASA still need to be addressed.

7

International Cooperation and Competition—Why, How, When?

The final topic of discussion at the workshop was international cooperation and competition. Eric Rice, president and CEO of Orbital Technologies Corporation (ORBITEC), was the panel moderator. Four panelists participated in the discussion: Ian Pryke, Center for Aerospace Policy Research at George Mason University (formerly with the European Space Agency); Joan Johnson-Freese, Naval War College; Joanne Gabrynowicz, National Remote Sensing and Space Law Center at the University of Mississippi; and Marcia Smith, Congressional Research Service. Each was asked to direct their discussion to a set of focusing questions to be answered with respect to their areas of expertise and experience:

- What are the real goals and interests of the nations of the world with respect to their involvement in space tourism, space exploration, space bases, space commercialization, space settlements, and planetary terraforming?
- What are the specific short- and long-term goals and objectives of the United States, the European Space Agency (ESA), China, Japan, and Russia in terms of their national and international space activities?
- Should future manned lunar surface and Mars surface activity be national (U.S.) or international? What are the economic, social, political, or other benefits to be gained by nations doing it alone vs. doing it together with all or several partners?
- Discuss implications of the ASTRA paradigm in terms of international cooperation and competition. When government agreements on ISS are complete, what should happen in the future? How will China's new space capability enter into U.S. decisions?
- What are the commercial and political issues related to mining and use of insitu resources on planetary surfaces by one nation, several nations, or the whole space community? What should be done from the international perspective?

Ian Pryke began the discussion with a basic overview of international cooperation. He stated that international cooperation is not intrinsically good; it is done because there is some net benefit or some advantage to the partners. It is not a universal panacea, and an international project is most likely to face increased management complexity and cost. Pryke also mentioned that because countries cooperate in some areas does not mean they cannot compete in others.

International cooperation can be used as a tool of foreign policy. The International Space Station is one example. Pryke believes that had it not been used as such a tool, it would not have survived the administration of President William Clinton. Using a technology project in this way can be a double-edged sword. The project can become a hostage to foreign policy—policy that can and does change. The rationale for cooperation varies from partner to partner. However, as long as the end goal is the same, partners can still work together. Pryke observed that if you can get a country to cooperate with you on your space program and spend its money to do so, it will have less money to pursue other objectives that you may not like.

Pryke mentioned that space is no longer a cold war competition between two superpowers. Many countries have active, mature space programs. This maturing capability makes them prime candidates for partnership or competition. International cooperation tends to make the project more affordable for each party involved, although the overall cost of implementation increases. Moreover, when more countries are involved, the expertise base for the project is broader and robustness and redundancy are added (e.g., backup launch capacity such as that provided by Russian Soyuz for access to the ISS while the shuttle is grounded). International cooperation can also add legitimacy to a program and assist in its advocacy within national government debate.

Pryke then moved on to answer the question of why we should have international cooperation for the President's vision. He said the answer is "because the President said so," meaning that the decision—that there should be an international component—had been debated and decided at the highest levels. Such debate has yet to take place within the governments of potential partners. However, since the January speech, the White House has been silent on its vision. If it is serious about involving other nations, the administration should be discussing this with them at high levels. Other countries will need to determine why it would be in their best interests to cooperate. In the President's policy document outlining the new exploration vision, there is only discussion of furthering U.S. goals.[1] In remarks made following the President's speech, NASA Administrator Sean O'Keefe also confirmed that it would be a U.S.-led initiative aimed at achieving U.S. objectives.[2]

Three classes of cooperating countries were suggested by Pryke: (1) Current members of the ISS cooperative agreement (Canada, Europe, Japan, and Russia), (2) China, now a major space power by virtue of being the third nation that has put an astronaut into space, and (3) other nations such as India, Brazil, and Israel, which have smaller space programs and that can perhaps be involved in robotics. Europe has its own program, Aurora, which is developing a plan for solar system exploration. A number of missions are in the preliminary planning stage. There are some good overlaps between the plans of Aurora and NASA. Pryke mentioned that there are various models of cooperation that can be considered, ranging from program coordination through programmatic interdependence to dedicated international institutions.

Pryke suggested that the United States should engage the international community sooner rather than later. Before the ISS was announced by President Ronald Reagan, the United States had already approached all the partners some months in advance. In contrast, for this new vision, the ISS implementing agencies were called the day of the vision announcement. Steidle said that the Aldridge commission has asked NASA to produce plan for potential international partners.

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[1]National Aeronautics and Space Administration, *The Vision for Space Exploration*, February 2004.

[2]Transcript from the NASA Press Conference on the Future Vision for Exploration, January 14, 2004. Available online at <http://www.nasa.gov/missions/solarsystem/explore_main.html>, accessed March 23, 2004.

The panel moderator, Eric Rice, began the discussion period by asking if Pryke felt a need for an international space authority to control the Moon or space. Pryke believed that events do not yet warrant that. There are other treaties that have been ratified that will help resolve any space cooperation issues. John Cullen, staff member for the Senate Commerce committee, asked, How high a hurdle is ISS completion to future cooperation? Pryke stated that discontinuing the ISS effort now would create barriers to any new cooperation effort. However, the new vision does include completing the ISS, and at this time there is no clearly defined end date for U.S. participation in the program.

Steering committee member Dava Newman asked about the attitude of other countries (including the public and media) toward further space exploration. Pryke mentioned that Great Britain is not very interested in human exploration. They are not participating in European human endeavors or in the ISS but are interested in robotic exploration. The British are debating the extent to which they want to be involved in the Aurora program. As for the rest of Europe, when European astronauts fly on U.S. shuttles, they return as real heroes. So there is strong public interest. Whether that can be nurtured to the point of a major human initiative remains to be seen, Pryke said.

Joan Johnson-Freese, an expert on the Chinese space program, began her presentation via teleconference by discussing the autumn 2003 Chinese launch of a human into space. With this launch, China became the third country with manned launch capabilities. The launch had been preceded by four unmanned precursor launches. There were no technical surprises, but there were two political surprises: (1) Chinese leader Jiang Zemin was not in attendance even though he was a proponent of the manned space program and (2) the government was very open about its launch and there was none of the secrecy usually surrounding Chinese military operations. Johnson-Freese suggested that the reasons for the openness were not unlike those of the Apollo era: domestic pride, credibility, international prestige, economic development, jobs, science and engineering education support, and hero development. Technology for such a spaceflight will transfer between military and civil space, providing dual-use capability. There are 150,000 aerospace workers in 130 organizations—their aerospace program is a huge jobs program. China has also been a leader in supporting a treaty banning space weapons and is pursuing asymmetric responses to space weapons (e.g., antisatellite weapons (ASATs)).

China understands that the United States is the only space superpower and is not trying to seek parity. However, it does recognize that space is a strategic asset. China desires its own strategic assets and does not want to rely on other nations. It does not want the technology gap between the United States and China to widen. It also seeks inclusion in what is sometimes referred to as the international family of spacefaring nations, which often cooperate with one another.

China’s capsule design was based on the Russian Soyuz, but with Chinese updates. The next step is to develop and launch a laboratory in space (i.e., an orbital module) and a small space station (smaller than the Russian Mir). The space program will probably launch two or three astronauts at its next launch, in 2005. Its lunar program, called *Chang’e*, includes an unmanned lunar orbiter, a lander by 2010, and eventually a sample return. The government has not yet officially announced a manned lunar mission, but such a mission is eventually expected. Ultimately, what the Chinese do in space will be determined by (1) economics and (2) space posturing (i.e., Space Wei Qi [3]). The government is spending scarce currency to make this program work. Future work will be based on spending at an economically feasible rate. The program is also based on posturing for the future and avoiding enlargement of the technology gap.

Johnson-Freese mentioned that the United States was rather reticent in its discussion of the Chinese success. Other nations were congratulatory and welcomed China to the space community. She also commented on the details of the new U.S. space vision, asking whether it was a "vision for the millennium or a $12 billion set of PowerPoint slides." Johnson-Freese believes that there are several conditions for success of the vision, including (1) high-level, sustained commitment, (2) relative affordability, and (3) a clear goal. She thinks the vision should be inclusive and international. The strategic vision for space differs from country to country. The United States has established itself as international power but now needs to be an international leader. There are many different reasons for international cooperation in space. For example, Japan desires research under microgravity conditions. Johnson-Freese mentioned that pulling such research from the future ISS plans would be bad for the Japanese. Europe looks to form a European identity. China looks for legitimacy. Johnson-Freese believes that the United States should not pursue the vision alone because it would be too expensive. She warned that other countries might form partnerships without us. It is better to be part of the international community.

Johnson-Freese went on to discuss the ASTRA paradigm. She believes that there is strength in the recognition of infrastructure, but it appears to be somewhat linear in nature—that is, it assumes an equal-increment progression from Step 1 to Step 2 to Step 3. She suggested that this incremental progression was improbable and that it is possible to emphasize process over product. She stressed that NASA should not become mired in process and organization rather than product. John Mankins, NASA Headquarters, asked if any of the panelists knew of industrial models for international cooperation that might help in the development of ASTRA. Pryke said there were a few examples of industry consolidation in Europe that crosses borders (e.g., the Concorde). Johnson-Freese mentioned that China is working with a number of industry partners for viability. However, the chances of getting China involved are slim.

Joanne Gabrynowicz began her presentation by mentioning that international cooperation and competition occur in legal and political as well as technical forums. Events surrounding space technologies and cases have catalyzed the setting of precedents in the law. Sputnik led to the formation of the United Nations Committee on Peaceful Uses of Outer Space (COPUOS) and four different treaties. The Cosmos 954 nuclear-powered satellite that hit Canada resulted in a set of principles on Nuclear Power Sources (NPS Principles).[4] Landsat led to the United Nations Principles on Remote Sensing. In general, previous technologies have set the bar for the legal uses of space. There is also a trend for social conditions to catalyze political and legal responses—for

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[3] Joan Johnson-Freese, Space Wei Qi, The Launch of Shenzhou V, Naval War College Review, Spring 2004, LVII (2): 121-145.

[4] A Soviet nuclear-powered spy satellite, Cosmos 954, crashed in northern Canada in 1978. This event led to the emergence of issues related to the use of nuclear power in space and the United Nations Principles Relevant to the Use of Nuclear Power Sources in Outer Space. Text is available online at <http://www.oosa.unvienna.org/SpaceLaw/nps.html>; accessed March 15, 2004.

example, the Declaration on International Cooperation in the Exploration and Use of Outer Space for the Benefit and in the Interest of All States, Taking into Particular Account the Needs of Developing Countries.[5]

Gabrynowicz mentioned that every component of the new U.S. space vision raises legal questions:

- The space shuttle termination raises contracts and procurement issues.
- Termination of the ISS raises similar concerns, including the fact that all agreements were premised on evolution of the station. Some rights and obligations extend beyond termination. The ISS cooperative agreement is essentially a treaty of sorts.
- Permanent lunar base activity will raise issues such as property rights, territory rights versus rights to resources, and military uses.
- A human Mars mission raises environmental legal issues, informed consent for astronauts issues, and a variety of treaty issues, including whether or not there needs to be a Mars treaty.

Gabrynowicz identified potential legal issues that arose from discussions in this workshop. For example, depending on the circumstances, “space mission denial” and “space-based engagement” can be potential treaty violations. The Outer Space Treaty[6] provides that nonexclusive access to space is a right of all signatories. Project Prometheus could raise additional legal issues. The Nuclear Test Ban Treaty prohibits nuclear explosions in space. Will Prometheus technology involve explosions regardless of size? The NPS Principles distinguish between reactors and radioisotope generators and specify design requirements. Will Prometheus technology meet these? Other nuclear uses may violate United Nations principles on nuclear power sources. Using the Moon is also extremely controversial. The Outer Space Treaty is silent on property rights. Gabrynowicz believes legally that there is nothing that prohibits commercial use of the Moon under government supervision.

Modes of international interaction range from competition (e.g., Apollo, Sputnik) to cooperation (e.g., ISS) to integration (e.g., Earth observations such as NPOESS/Initial Joint Polar-Orbiting Operational Satellite System, Global Monitoring for Environment and Security, Disaster Charter/Group on Earth Observations). The CUPUOS has a legal subcommittee. The Russians have indicated in this forum that they want to eliminate the existing treaties and start over with a comprehensive treaty. Gabrynowicz also mentioned that space activities are increasingly blurring the line between military use and civil use, increasing the technology divide. She also noted that a new generation of space law is emerging as new spacefarers like China and Nigeria become active. Gabrynowicz said international law tends to be unenforceable, but the court of public opinion is becoming more influential. She cautioned that the space community should be very

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[5]Text of the declaration is available online at <http://www.oosa.unvienna.org/SpaceLaw/spbentxt.htm>; accessed April 14, 2004.

[6]The United Nations Declaration of Legal Principles Governing the Activities of States in the Exploration and Use of Outer Space was entered into force in October 1967. Text is available online at < http://www.oosa.unvienna.org/SpaceLaw/outerspt.html>; accessed March 15, 2004.

careful with the words it uses. For example, she said there is a legal distinction between "colonization" and "settlement."

Marcia Smith of the Congressional Research Service completed the panel's remarks with an overview of international issues in outer space. Whether there should be international cooperation for the new exploration vision is really a nonissue, she said, because President Bush had decreed in his policy directive that it would happen. Instead, the question becomes, Who will take us up on the offer? The President's initiative includes robotic as well as human exploration, opening the initiative to a wide range of countries. The participation of any nation is subject to the availability of funds, which is a complicating factor for its partners. For example, NASA never knows what its future budget will be, making it difficult for potential partners to evaluate the likelihood of a particular project succeeding. Smith stated that the U.S. space program itself was born from both cooperation and competition, starting with the 1957-1958 International Geophysical Year. NASA's 1958 charter includes language directing the agency to cooperate with other nations. Among other things, NASA needed worldwide tracking sites, which was one motivating factor for international cooperation.. Cooperation was born of practicality more than altruism. She noted that many think of the Apollo program as the centerpiece of the U.S.-Soviet space race. However, one month before he was assassinated, President Kennedy spoke before the United Nations and invited the Soviet Union to join in that endeavor. After Kennedy died, President Johnson chose to pursue Apollo as a national effort. (The Soviet Union never responded to the invitation in any case.). Thirty years later, participation in ISS was a carrot offered by the United States to the new Russia in exchange for Russia agreeing to abide by rules to stem the proliferation of ballistic missile technology. Smith commented that, in the future, the United States will need to be viewed as a reliable partner for space cooperation.

A period of general discussion followed Smith's presentation. Committee chair Branscome asked which cooperative models are the most successful (one such model is industry multinational cooperation). Gabrynowicz mentioned that collaborative private law agreements are a new initiative. These agreements are multinational in nature but are executed by private parties. The UNIDROIT Convention, for example, is being negotiated now on financing space assets (i.e., creditor-debtor relationships, banking). Smith said that cooperation usually assumes each partner brings its own money to the table. Pryke mentioned another commercial model involving Arianespace, International Launch Services, and the Japanese, which are agreeing to back up each other's launch systems.

John Mimikakis, staffer from the House Science Committee, asked if this cooperation was something the administration will take seriously. He also asked the panelists what options the administration has for getting out of its space agreements. Pryke mentioned that quitting the ISS would create so much anti-U.S. feeling that further cooperation might not be possible. Gabrynowicz mentioned the superconducting supercollider as an example of a project that was terminated because the partners failed to fund their share of the project. In the case of the ISS, however, the partners have already provided substantial amounts of money. Smith mentioned the example of Ulysses in the 1980s, where the U.S. unilaterally pulled out from the project and did not deliver the promised spacecraft.[7] Europe has not forgotten. Major changes in ISS were also problematic. In the future, countries may decide to partner with countries other than the United States.

Donna Shirley asked if the planned shift of focus of the ISS to physiological research would have any impact on the other nations involved. Pryke stated that each nation still has its own utilization rights. Europe and other nations do not have to modify their utilization plans even if the U.S. experiments shift focus. Gabrynowicz also said that there is no legal obstacle, because utilization is considered evolutionary under the ISS agreement. Molly Macaulay also mentioned it is not only the United States that can be considered an unreliable partner. Pryke noted that ESA does not operate on the basis of annual appropriations. Because it can obtain multiyear funding, there is more certainty in what it agrees to do. Smith mentioned that other countries also fail to meet their commitments sometimes. An option is to coordinate programs (e.g., Mars explorers) to limit duplication of effort, rather than jointly building spacecraft, which adds complexity.

[7]Ulysses was a joint NASA and European Space Agency (ESA) mission to map the Sun from a polar orbit. The original mission plan included two spacecraft, one provided by NASA, the other by ESA. NASA canceled its spacecraft in 1981. NASA did continue to partner with ESA by providing launch via the space shuttle, several instruments for the ESA spacecraft, and operational assets.

Appendixes

Appendix A

Statement of Task

The Aeronautics and Space Engineering Board of the National Research Council will plan and host a series of workshops on technology policy issues related to the interrelationship between government, industry and other stakeholders in advancing human and robotic space exploration and development. To accomplish this task the NRC will establish a steering committee of approximately six members to plan workshop agendas and solicit input from appropriate participants. The steering committee will have expertise and specific knowledge regarding space exploration and/or modes of interaction between the government and industry concerning technology development and demonstration. The series of workshops will be focused primarily on the development and demonstration of space technologies based on optimal modes of interaction between government agencies, industry, and other stakeholders.

One workshop will focus on policy issues concerning the development and demonstration of space technologies. The rationale, from the perspective of different stakeholders, for the long-term cultivation of advanced space systems will be a major topic to be discussed by senior level government and industry officials. A second workshop will focus on the interrelationship between government and industry in the development of advanced space systems. The discussion will center around the question: "What is the best mode of interaction between NASA, industry, and other stakeholders when developing and demonstrating advanced space systems?" Information and ideas obtained by NASA at the workshops will be used in future planning of programs and activities sponsored by the Office of Space Flight.

Stepping Stones to the Future of Space Exploration: A Workshop Report

Appendix B

Committee Member Biographies

DARRELL R. BRANSCOME, *Chair*, is a senior systems engineer in the Applied Technology Group at Science Applications International Corporation. He retired from NASA following a career in space access, exploration, and atmospheric sciences. His last position at NASA was as director of the Space Access and Exploration Programs Office at NASA Langley Research Center. In this position he was responsible for formulating and implementing Langley's space access and exploration programs, including efforts supporting the second generation program, Advanced Space Transportation, shuttle evolution, and the Hyper-X flight demonstration program. Mr. Branscome also served as staff director for the U.S. House of Representatives Subcommittee on Space Science and Applications, bringing the perspective of Congress to the steering committee. He was awarded both B.S. and M.S. degrees in mechanical engineering from Virginia Polytechnic and State University. Honors include AIAA Fellow and the NASA Exceptional Service and Outstanding Leadership Medals.

STEVEN GOREVAN is chairman of engineering management, design, and systems engineering at Honeybee Robotics, a small company involved in both space and terrestrial robotics. He is project manager on the development and implementation of advanced automated systems for use in surface-based planetary exploration. He serves as coinvestigator and project manager for the Mars Exploration Rover 2003 rock abrasion tool design and development and has served as project manager of several NASA small business grants and other robotic mining and telerobotic operations for NASA. He was the robotic drill project manager for NASA's Mars Surveyor rover. Mr. Gorevan has also served as a member of several government councils and committees on space exploration, including the NASA Solar System Roadmap Committee of 1998.

MOLLY K. MACAULEY is a senior fellow with Resources for the Future (RFF), Washington, D.C. She has been director of academic programs at RFF since 1996. Since 1983 Dr. Macauley's research at RFF has included several diverse areas: public finance, energy economics, the value of information, and economics and policy issues of outer space. Recent projects include: assessing the value of technology transfer and satellite remote sensing, the cost-effectiveness of a faster, better, cheaper space program, and the development of public policy and performance measures for NASA's New Millennium Program. Dr. Macauley has been a visiting professor at Johns Hopkins University, Department of Economics. She has testified before Congress on the Commercial Space Act of 1997, the Omnibus Space Commercialization Act of 1996, the Space Business Incentives Act of 1996, and space commercialization. Dr. Macauley has served on many national committees and panels, including the congressionally mandated Economic Study of Space Solar Power (chair), the National Research Council's Helium Reserve Committee, the Steering Group on Space Applications and Commercialization, and the Committee on Space Solar Power, among others. She has served on the board of directors of Women in Aerospace and as president of the board of advisors of the Thomas Jefferson Public Policy Program at the College of William and Mary. She has recently completed a new report on the government's role in research and development, with emphasis on science and technology.

DAVA J. NEWMAN is professor of aeronautics and astronautics and engineering systems at the Massachusetts Institute of Technology (MIT) and a MacVicar Faculty Fellow. In addition to these responsibilities, she was recently named director of the Technology and Policy Program at MIT. Her expertise is in multidisciplinary research that combines aerospace biomedical engineering, human-in-the-loop modeling, biomechanics, human interface technology, life sciences, systems analysis, design, and policy. Dr. Newman's research studies are carried out through spaceflight experiments, ground-based simulations, and mathematical modeling. Current research efforts include advanced space suit design, dynamics and control of astronaut motion, mission analysis, and engineering systems design and policy analysis. She also has ongoing efforts in assistive technologies to augment human locomotion here on Earth. Dr. Newman is the author of *Interactive Aerospace Engineering and Design*, an introductory engineering textbook with accompanying CD-ROM, published by McGraw-Hill, Inc., in 2002. She has also published more than 100 papers in journals and refereed conferences. Dr. Newman received her B.S. degree from the University of Notre Dame and S.M. degrees from MIT's Technology and Policy Program and the department of Aeronautics and Astronautics. She serves as a member of the Aeronautics and Space Engineering Board and has also served as a member of the NRC Committee on Advanced Technology for Human Support in Space, the Committee for the Assessment of NASA's Space Solar Power Investment and the Committee on Engineering Challenges to the Long-Term Operation of the International Space Station.

ERIC E. RICE president, CEO, and chairman of Orbital Technologies Inc. (ORBITEC), is currently leading the development of revolutionary microgravity research systems for spaceflight; advanced high-energy-density propellant-based propulsion engines for future space transport systems and space platforms; in situ propellant processing on the Moon and Mars; an innovative cryogenic fluid management technology; and advanced combustors for rocket engines. ORBITEC is a small aerospace business very involved in the government's Small Business Innovative Research Awards. Dr. Rice holds a Ph.D. in aeronautical and astronautical engineering from the Ohio State University and a B.S. in chemistry and physics from the University of Wisconsin. Dr. Rice is a fellow of the American Institute for Aeronautics and Astronautics (AIAA); founder and 2002-2004 chairman of the AIAA Space Colonization Technical Committee; 1992 chairman and current member, AIAA Space Transportation Technical Committee; 1996-1997 chairman and past member, AIAA Microgravity and Space Processes Technical Committee; past member AIAA Space Systems Technical Committee; past member, AIAA Nuclear and Future Flight Propulsion Technical Committee; member, National Space Society; member, American Astronautical Society; named a Distinguished Alumnus of the Ohio State University; chairman, Wisconsin Space Institute; and associate director, Industry Programs Wisconsin Space Grant Consortium.

Stepping Stones to the Future of Space Exploration: A Workshop Report

CHARLES R. TRIMBLE is one of the founders and was president and CEO of Trimble Navigation, guiding it to its dominant role in the Global Positioning System information technology market. Before founding Trimble, Mr. Trimble was manager of integrated circuit research and development at Hewlett-Packard's Santa Clara Division. During his tenure at HP, he was recognized for developing commercial advances in efficient signal processing, high-speed analog-to-digital converters, and digital time measurement techniques to the picosecond level. Mr. Trimble received his B.S. degree in engineering physics, with honors, in 1963, and his M.S. degree in electrical engineering, in 1964, from the California Institute of Technology. He was a member of the Vice President's Space Advisory Board's task group on the future of U.S. space industrial base as a representative of the National Space Council. In September 1994, Mr. Trimble was honored with the Piper General Aviation award from the AIAA for pioneering the manufacture and application of affordable GPS. He recently served on the NRC Committee on Government-Industry Partnerships for the Development of New Technologies and currently serves on the NRC Committee on Capitalizing on Science, Technology, and Innovation: An Assessment of the Small Business Innovation Research Program. Mr. Trimble is a member of the NAE, the Council on Foreign Robotics, and the California Institute of Technology board of trustees.

CHARLES D. WALKER was the first noncareer, industry-sponsored astronaut, serving as payload specialist on three space shuttle missions. On these flights, Mr. Walker operated equipment designed by McDonnell Douglas Astronautics Company for its electrophoresis biotechnology commercialization program (EOS) device. As chief test engineer of the EOS program, Mr. Walker was extensively involved with the laboratory development and spaceflight test of the EOS device. He currently serves in government relations and was previously the senior specialist for Advanced Space Programs Development at the Boeing Company (McDonnell Douglas was acquired by Boeing in 1997). His initial assignment was that of test engineer on the aft propulsion subsystem for the space shuttle orbiters. Mr. Walker has been a member of an independent national space policy review project and served on the former National Research Council Space Applications Board. He has also served on several government and university research center panels. Mr. Walker is currently a board director of the Challenger Center for Space Science Education. Mr. Walker received his undergraduate degree in aeronautical and astronautical engineering from Purdue University in 1971. Prior to joining McDonnell Douglas, he was a project engineer with the Naval Sea Systems Command working on computer-controlled manufacturing systems, a design engineer for Bendix Aerospace and, before that, an engineering technician and a firefighter with the U.S. Forest Service.

Appendix C

Workshop Agenda

February 23-24, 2004

Washington, D.C.

Monday, February 23

OPEN SESSION

8:15 am Welcome and Introduction — Darrell Branscome, Chair

8:30 Focus Topic 1: "The Rationale for Human and Robotic Space Exploration"
Moderator: Charles Walker
Panel Discussion

Neil Armstrong, EDO Corporation (retired)
David J. Goldston, Chief of Staff, House Committee on Science
Wesley Huntress, Geophysical Laboratory, Carnegie Institution of Washington
David Logsdon, U.S. Chamber of Commerce, Space Enterprise Council
Donna Shirley, Director, Experience Science Fiction, Seattle

Focusing Questions:

- What are the compelling reasons for human or robotic presence in space?
- What are the appropriate roles for robotic exploration and human exploration and development of space?
- What technological barriers must be overcome?
- What role should federal government, industry, academia, and the private citizen have in this exploration and development of space?
- How best do we establish and sustain public support for such endeavors?

10:00 Break

10:15 Overview of Office of Exploration Systems (Code T) and Context of FY2005 Budget — Adm. Craig Steidle, NASA

10:45 Presentation of Advanced Systems, Technologies, — John C. Mankins

	Research, and Analysis for Future Spaceflight Capabilities	Director of Human and Robotics Technology, Code T
11:45	Question and Answer Period	
12:15 pm	Lunch	
1:15	Recent Architecture Studies and Technology Drivers	James Geffre Johnson Space Flight Center
1:45	Focus Topic 2: "Technology as a Driver for Capability Transformation" Moderator: Darrell Branscome	
1:50	DARPA Space Activities: Genesis, Legacy, and Vision	Joe Guerci, DARPA
2:15	Panel Discussion Moderator: Charles Trimble David Hardy, DOD Space Experiments Review Board Brad Parkinson, Stanford University, GPS Model Christine Sloane, General Motors (PNGV/FreedomCAR)	
3:15	Break	
3:30	Panel Discussion Moderator: Dava Newman Jacqueline Haynes, Intelligent Automation, Inc.- small business perspective Stanley Schneider, National Polar-orbiting Operational Environmental Satellite System (NPOESS) Project Chris Stevens, NASA New Millennium Program Manager, JPL	

Focusing Questions:

- What, briefly, is the role of technology as an agent for organization and capability transformation, specifically as related to your organization?
- What other factors must be present to facilitate technology as an agent for transformation?
- What are the obstacles that are in the path of using technology to accomplish capability transformation?
- What are the important barriers that must be overcome in using technology to facilitate capability transformation?
- What are the challenges to achieving technology insertion into capability development?

- What are the appropriate time templates to use for technology-driven innovation?

4:30	Final Thoughts/Discussion	Dava Newman
5:00-6:00	Reception	

Tuesday, February 24

OPEN SESSION

8:15 am	Welcome Back	Darrell Branscome

8:20 Focus Topic 3: "Risk Aversion—Flying in the Face of Uncertainty"
Moderator: Molly Macauley
Panel Discussion

Gen. John Barry, CAIB viewpoint
Joseph Fuller, Futron Corporation
Gregg Hagedorn, NAVSEA
Allan Mazur, Syracuse University
Richard Obermann, Staff Member, House Science Committee
Michael G. Stamatelatos, NASA Director for Safety & Assurance Requirements

Focusing Questions:

- What lessons might be shared about differences in risk perception by the public, the Congress, and the agency (NASA)? How are perceptions influenced by risks that are low probability but high cost?
- The NASA model under discussion (ASTRA) omits explicit treatment of risk. Risk can be defined in many ways—it can, for example; include economic, technological, and political uncertainty—but no matter how it is defined, the model does not explicitly include it. Specifically, the model does not (1) incorporate the consequences of failure to meet milestones, (2) identify decision points at which technology development might be terminated because of cost, engineering problems, or obsolescence, (3) illustrate the cost impacts of failure or redirection of technology development, or (4) include fallback strategies. What modeling techniques might you suggest that would enable the model to incorporate probabilistic treatment yet remain tractable?
- Among the arguments against including probabilistic treatment in the model are that it renders the model more difficult for decision makers to comprehend and can undermine the political ability to sell the technologies. How significant are these concerns and how can they be

addressed? Lessons learned from the development of other technologies (for instance, nuclear power generation, the superconducting supercollider, synthetic fuels) might be useful if you can share them.

10:00 Break

10:15 am Focus Topic 4: "International Cooperation/Competition–Why, How, When?"
Moderator: Eric Rice
Panel Discussion

Joanne Gabrynowicz, National Remote Sensing and Space Law Center
Joan Johnson-Freese, Naval War College *(by telephone)*
Ian Pryke, George Mason University
Marcia Smith, Congressional Research Service

Focusing Questions:

- What are the real goals and interests of the nations of the world with respect to their involvement in space tourism, space exploration, space bases, space commercialization, space settlements, and planetary terraforming?
- What are the specific short- and long-term goals and objectives of the United States, the European Space Agency (ESA), China, Japan, and Russia in terms of their national and international space activities?
- Should future manned lunar surface and Mars surface activity be national (U.S.) or international? What are the economic, social, political, or other benefits to be gained by nations doing it alone vs. doing it together with all or several partners?
- Discuss implications of the ASTRA paradigm in terms of international cooperation and competition. When government agreements on ISS are complete, what should happen in the future? How will China's new space capability enter into U.S. decisions?
- What are the commercial and political issues related to mining and use of in situ resources on planetary surfaces by one nation, several nations, or the whole space community? What should be done from the international perspective?

11:30 Wrap-Up Discussion/Where We Go Now — Darrell Branscome

12:00 noon Adjourn

Appendix D

Workshop Attendees

Steering Committee	
Darrell Branscome	Science Applications International Corporation
Molly Macauley	Resources for the Future
Dava Newman	Massachusetts Institute of Technology
Eric Rice	ORBITEC
Charles Trimble	U.S. Global Positioning System Industry Council
Charles Walker	Boeing
Speakers and Panelists	
Neil Armstrong	EDO Corporation (retired)
Gen. John Barry	Air Force (retired)
Joseph Fuller	Futron Corporation
Joanne Gabrynowicz	National Remote Sensing and Space Law Center, University of Mississippi
James Geffre	NASA Johnson Space Center
David Goldston	House Committee on Science
Joe Guerci	DARPA
Greg Hagedorn	NAVSEA
David Hardy	Air Force Research Laboratory
Jacqueline Haynes	Intelligent Automation, Inc.
Wesley Huntress	Carnegie Institute of Washington
Joan Johnson-Freese	Naval War College (by phone)
David Logsdon	U.S. Chamber of Commerce, Space Enterprise Council
John Mankins	NASA Headquarters
Gary Martin	NASA Headquarters
Allan Mazur	Syracuse University
Dick Oberman	House of Representatives Subcommittee on Space
Brad Parkinson	Stanford University
Ian Pryke	Center for Aerospace Policy Research, George Mason University
Stanley Schneider	NOAA-NPOESS
Donna Shirley	University of Oklahoma
Christine Sloane	General Motors
Marcia Smith	Congressional Research Service
Michael Stamatelatos	NASA Headquarters
Craig Steidle	NASA Headquarters
Christopher Stevens	Jet Propulsion Laboratory

Other Attendees

Andrew Aldrin	Boeing
Terry Allard	NASA Headquarters
Iwan Alexander	Case Western Reserve University
Christian Beckner	Center for Strategic and International Studies
Norm Brown	NASA Marshall Space Flight Center
John Cullen	Senate Commerce Committee
Barry Epstein	NASA Headquarters
Lea Gifford	Roger Williams School of Law
Naite′ Jaureguy-Naudin	Center for Strategic and International Studies
Jitendra Joshi	Universities Space Research Association
Jonathan Krezel	NASA Headquarters
Evan Michelson	NRC Intern
John Mimikakis	House Science Committee
Chris Moore	NASA Headquarters
Ronald Mutzelberg	Boeing
Patrice Pages	National Academies
Jamila Rockette	Lewis Burke Associates
Robert Smylie	NASA
Mary Snitch	Lockheed Martin
John Stocky	JPL
Nantel Suzuki	NASA Headquarters
Gui Trotti	Trotti and Associates, Inc.
Lisa Vandemark	Institute of Medicine
Sharon Welch	NASA Langley Research Center

Staff

Karen Harwell	National Academies
George Levin	National Academies
Maureen Mellody	National Academies
Bridget Edmonds	National Academies

Appendix E

Acronyms and Abbreviations

AIAA	American Institute for Aeronautics and Astronautics
ASAT	antisatellite weapon
ASEB	Aeronautics and Space Engineering Board
ASTRA	Advanced Systems, Technologies, Research, and Analysis
ATLAS	Advanced Technology Life-cycle Analysis System
CAIB	Columbia Accident Investigation Board
CEV	crew exploration vehicle
Code R	Aerospace Technology Enterprise
Code S	Space Science Enterprise
Code T	Office of Exploration Systems
Code Y	Earth Science Enterprise
COPUOS	Committee on the Peaceful Uses of Outer Space
DARPA	Defense Advanced Research Projects Agency
DOD	Department of Defense
ESA	European Space Agency
EVA	extravehicular activity
FreedomCAR	Freedom Cooperative Automotive Research
GPS	global positioning system
HEDS	Human Exploration and Development of Space
ISS	International Space Station
JPL	Jet Propulsion Laboratory
LEO	low Earth orbit
MIT	Massachusetts Institute of Technology
NASA	National Aeronautics and Space Administration
NAVSEA	Naval Sea Systems Command
NMP	New Millennium Program
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-orbiting Operational Environmental Satellite System

NRC	National Research Council
ORBITEC	Orbital Technologies, Inc.
RFF	Resources for the Future
SBIR	Small Business Innovative Research
STTR	Small Business Technology Transfer
THREADS	Technology for Human/Robotic Exploration and Development of Space
TRL	technology readiness level
TTB	technology tool box