A Constrained Space Exploration Technology Program: A Review of NASA's Exploration Technology Development Program

The National Academies Press

A Constrained Space Exploration Technology Program

A Review of NASA's Exploration Technology Development Program

Committee to Review NASA's Exploration Technology Development Program

Aeronautics and Space Engineering Board

Division on Engineering and Physical Sciences

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

THE NATIONAL ACADEMIES PRESS 500 Fifth Street, N.W. Washington, DC 20001

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This study was supported by Contract No. NNH05CC16C between the National Academy of Sciences and the National Aeronautics and Space Administration.

Cover: Design by Timothy Warchocki.

International Standard Book Number 13: 978-0-309-12583-3
International Standard Book Number 10: 0-309-12583-9

Available in limited supply from Aeronautics and Space Engineering Board, 500 Fifth Street, N.W., Washington, DC 20001, (202) 334-2858.

Additional copies of this report are available from the National Academies Press, 500 Fifth Street, N.W., Lockbox 285, Washington, DC 20055; (800) 624-6242 or (202) 334-3313 (in the Washington metropolitan area); Internet, http://www.nap.edu.

Printed in the United States of America

THE NATIONAL ACADEMIES

Advisers to the Nation on Science, Engineering, and Medicine

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Ralph J. Cicerone is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. Charles M. Vest is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institute of Medicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Ralph J. Cicerone and Dr. Charles M. Vest are chair and vice chair, respectively, of the National Research Council.

www.national-academies.org

COMMITTEE TO REVIEW NASA'S EXPLORATION TECHNOLOGY DEVELOPMENT PROGRAM

EDWARD CRAWLEY, Massachusetts Institute of Technology, *Co-Chair*
BONNIE J. DUNBAR, Museum of Flight, *Co-Chair*
GARY L. BENNETT, Metaspace Enterprises
ELIZABETH CANTWELL, Los Alamos National Laboratory
SHYAMA P. CHAKROBORTY, Northrop Grumman Integrated Systems
RAMON L. CHASE, Analytic Services, Inc.
GARY S. GEYER, Consultant, Las Cruces, New Mexico
KENNETH GWINN, Sandia National Laboratories
AYANNA HOWARD, Georgia Institute of Technology
STEVEN D. HOWE, Universities Space Research Association
JOHN R. HOWELL, University of Texas at Austin
JOHN E. HURTADO, Texas A&M University
RAMKUMAR KRISHNAN, Fluidic Energy, Inc.
IVETT A. LEYVA, Air Force Research Laboratory
RAYMOND MARIELLA, Lawrence Livermore National Laboratory
DANIEL MASYS, Vanderbilt University
EDWARD McCULLOUGH, Boeing Company
DOUGLAS MEHOKE, Johns Hopkins University Applied Physics Laboratory
JAMES F. MILLER, Argonne National Laboratory
TODD J. MOSHER, MicroSat Systems, Inc.
GUILLERMO TROTTI, Trotti and Associates, Inc.
GERALD D. WALBERG, Walberg Aerospace
IAN WALKER, Clemson University
WILLIAM W. WANG, The Aerospace Corporation
MARILEE J. WHEATON, The Aerospace Corporation

Staff

JOHN WENDT, Study Director
BRIAN DEWHURST, Study Director (from January 2008)
KERRIE SMITH, Study Director (through December 2007)
SARAH CAPOTE, Program Associate
HEATHER LOZOWSKI, Financial Associate (through March 2008)

AERONAUTICS AND SPACE ENGINEERING BOARD

RAYMOND S. COLLADAY, Lockheed Martin Astronautics (retired), *Chair*
CHARLES F. BOLDEN, JR., Jack and Panther, LLC
ANTHONY J. BRODERICK, Aviation Safety Consultant, Catlett, Virginia
AMY L. BUHRIG, Boeing Commercial Airplane Group
PIERRE CHAO, Center for Strategic and International Studies
INDERJIT CHOPRA, University of Maryland, College Park
ROBERT L. CRIPPEN, Thiokol Propulsion (retired)
DAVID GOLDSTON, Harvard University
R. JOHN HANSMAN, Massachusetts Institute of Technology
PRESTON A. HENNE, Gulfstream Aerospace Corporation
JOHN M. KLINEBERG, Space Systems/Loral (retired)
RICHARD H. KOHRS, Independent Consultant, Dickinson, Texas
IVETT A. LEYVA, Air Force Research Laboratory
EDMOND L. SOLIDAY, United Airlines (retired)

Staff

MARCIA S. SMITH, Director

Preface

In January 2004, President George W. Bush announced new elements of the national space policy by issuing the Vision for Space Exploration (VSE).[1] The new policy set out goals for NASA, including that of exploring the "solar system and beyond" with human and robotic missions—specifically, to "extend human presence across the solar system, starting with a human return to the Moon by the year 2020." In the year that followed, NASA created the Exploration Systems Mission Directorate (ESMD) as the primary agent for the development of the exploration program. NASA assigned ESMD the primary responsibility for the development of space technology to support the exploration program. ESMD in turn created and charged the Exploration Technology Development Program (ETDP) to execute this development.

In the report[2] that accompanied the Science, State, Justice, and Commerce fiscal year 2007 appropriations bill passed by the U.S. House of Representatives,[3] NASA was directed to "enter into an arrangement with the National Research Council (NRC) for an independent assessment of NASA's restructured Exploration Technology Development Program (ETDP) to determine how well the program is aligned with the stated objectives of the Vision for Space Exploration (VSE), identify any gaps, and assess the quality of the research." Although that bill did not become law, NASA nonetheless asked the NRC to make this assessment.

A statement of task was developed by NASA and the NRC (see Appendix A), and a committee was formed by the NRC's Aeronautics and Space Engineering Board to carry out this task.

The Committee to Review NASA's Exploration Technology Development Program was assembled and approved by the NRC Governing Board on September 28, 2007. The committee consists of 25 members (see Appendix B) and includes a cross section of senior executives, engineers, researchers, and other aerospace professionals drawn from industry, universities, and government agencies, with expertise in all of the fields comprised by the ETDP.

---

[1] National Aeronautics and Space Administration (NASA), *The Vision for Space Exploration,* NP-2004-01-334-HQ, NASA, Washington, D.C., 2004, p. iii.

[2] U.S. House of Representatives, *Science, State, Justice, Commerce, and Related Agencies Appropriations Bill, Fiscal Year 2007*, H. Rept. 109-520, Committee on Appropriations, House of Representatives, 109th Congress, 2nd Session, U.S. Government Printing Office, Washington, D.C., 2006.

[3] U.S. House of Representatives, H.R. 5672, *Departments of Commerce and Justice, Science, and Related Agencies Appropriations Act, 2007*, available at http://thomas.loc.gov/.

The committee held its first meeting on October 10-11, 2007, in Washington, D.C. The meeting included a series of presentations by NASA personnel that provided an overview of the administrative and technical background for the ETDP. A set of questions to be used in the assessment process was agreed on by the committee and was sent to NASA for distribution to the centers. This was done in order to provide the centers with a clear and concise idea of the issues that the committee was charged to assess. (See Appendix C for a list of these questions.)

A subset of the committee met at the Jet Propulsion Laboratory in Pasadena, California, on November 8-9, 2007, for specialized presentations and a tour of the laboratory. A second subset met at the NASA Johnson Space Center in Houston, Texas, on November 27-30, 2007, and a third subset visited the NASA Glenn Research Center in Cleveland, Ohio, on December 11-12, 2007. At each site visit, specialized presentations of the projects that constitute the ETDP were made and a tour of relevant facilities was given. A lead specialist and at least two other committee members were selected to perform a concentrated review of each project. Their reports and preliminary ratings were discussed by all other members of the committee using e-mail and in teleconferences organized on January 8, 11, and 16, 2008, to ensure consistency in the ratings given to each project. These reviews formed the basis of the committee's interim report, described below.

The full committee met for a second time on February 5-6, 2008, in Irvine, California, to continue its data-gathering activity, obtain clarification on selected areas of ETDP technologies, and examine in detail crosscutting issues that emerged as a result of the overall study process.

Following the second meeting, the interim report prepared by the committee was transmitted to NASA, on March 28, 2008.[4] The interim report contained the committee's assessments of each of the 22 ETDP projects, as well as a brief discussion of the crosscutting issues that the committee planned to discuss in the final report. The reviews of the 22 ETDP projects are presented in Chapter 2 of this final report and are largely unchanged from those delivered in the interim report. It is important to emphasize that the committee's assessments were of the projects as they stood in November/December 2007. Thus the committee did not attempt to account for any technical progress made by the projects in early 2008.

The committee co-chairs briefed ETDP management and project leaders on the interim report on April 15, 2008. At that time, the committee solicited written comments from the program in response to the interim report. The resulting input was considered during the drafting of the final report.

The full committee met for a third and final time on April 21-22, 2008, in Woods Hole, Massachusetts, to come to consensus on its findings and recommendations and to begin drafting the final report. A number of teleconferences were held later to finish preparing the report for the NRC review process.

---

[4] National Research Council, *Review of NASA's Exploration Technology Development Program: An Interim Report*, The National Academies Press, Washington, D.C., 2008.

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 Report Review Committee of the National Research Council (NRC). 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:

Steven Battel, Battel Engineering,
Jesse Beauchamp, California Institute of Technology,
Robert L. Crippen, Thiokol Propulsion (retired),
John C. Mankins, ARTEMIS Innovation Management Solutions, LLC,
E. Phillip Muntz, University of Southern California,
Simon Ostrach, Case Western Reserve University (retired),
David Van Wie, Johns Hopkins University Applied Physics Laboratory, and
Dianne Wiley, The Boeing Company.

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 Maxine Savitz, Honeywell Incorporated (retired). Appointed by the NRC, she 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.

Contents

APPENDIXES

Summary

In January 2004, President George W. Bush announced new elements of the nation's space policy by issuing the Vision for Space Exploration (VSE),[1] which instructed NASA to "extend human presence across the solar system, starting with a human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations." NASA was also directed to "develop the innovative technologies, knowledge, and infrastructures both to explore and to support decisions about the destinations for human exploration," among other objectives. As acknowledged in the VSE, significant technology development will be necessary to accomplish the goals that it articulates.

In the past 4 years, NASA has mobilized and focused its resources on the critical new tasks assigned, including the maturing of the technologies necessary for exploration. NASA's Exploration Technology Development Program (ETDP) is designed to support, develop, and ultimately provide the necessary technologies for the agency's new Constellation flight program.

The Committee to Review NASA's Exploration Technology Development Program is broadly supportive of the intent and goals of the VSE and finds that the ETDP is making progress toward the stated goals of technology development, but that it is operating within significant constraints that limit its ability to successfully accomplish those goals. The constraints include the still-dynamic nature of the Constellation Program requirements, the constraints imposed by a limited budget, the aggressive timescale of early technology deliverables, and the desire within NASA to fully employ the NASA workforce.

The ETDP is composed of 22 technical projects; each was assessed by the committee in terms of the quality of the research, the effectiveness of transitioning research findings into the flight program, and the degree of alignment of the project with the VSE. The committee found that in 20 of the 22 ETDP projects, corrective action leading to project improvement was either warranted or required. However, the committee believes that the ETDP contains a range of technologies that will, in principle, enable the realization of many of the early endeavors currently imagined in the *Exploration Systems Architecture Study*.[2] The committee concluded that the ETDP, if adequately and stably funded and executed in a manner consistent with the planning process, would likely make available the required technology on schedule to its customers in the Constellation Program.

---

[1] National Aeronautics and Space Administration (NASA), *The Vision for Space Exploration,* NP-2004-01-334-HQ, NASA, Washington, D.C., 2004, p. iii.

[2] National Aeronautics and Space Administration, *Exploration Systems Architecture Study—Final Report,* NASA-TM-2005-214062, NASA, Washington, D.C., November 2005.

Because of the constraints cited above, the ETDP as created by NASA is a supporting technology program very closely coupled to the near-term needs of the Constellation Program. The ETDP is focused on only incremental gains in capability, and it has two programmatic gaps (integration of the human system, and nuclear thermal propulsion). NASA has in effect suspended research in a number of technology areas traditionally within the agency's scope and has in many areas essentially ended support for longer-term technology research traditionally carried out within NASA and with strong university collaboration. These actions could have important consequences for aspects of the VSE beyond the initial, short-duration lunar missions—including an extended human presence on the Moon and human exploration of Mars and beyond.

With respect to the management of the ETDP, the program incorporates good processes for tracking Constellation Program requirements, for dealing with the mechanics of formal technology transfer, and for managing the programmatic risk of its own technology developments. However, there is a lack of clarity and completeness in the Constellation Program requirements as perceived by ETDP project personnel, as well as a need to improve the human side of the technology transfer process and to clarify how technology developments can contribute to a reduction in exploration (i.e., Constellation) programmatic risk.

Also, in general, the ETDP has not taken advantage of many external resources that could potentially reduce cost or schedule pressure, aid in the development of the NASA proposed technology, and/or provide alternative and backup technologies. Nor, in many cases, has the ETDP taken advantage of external peer reviews.

Finally, the present ETDP lacks an integrated, systematic test program. Of particular importance is that several ETDP projects, as currently formulated, do not include mission-critical tests—that is, system or subsystem model or prototype demonstrations in an operational environment—that are needed to advance the technology to technology readiness level (TRL) 6.

ASSESSMENT OF THE PROJECTS OF THE EXPLORATION TECHNOLOGY DEVELOPMENT PROGRAM

The 22 research projects of the ETDP are on subjects ranging from thermal protection systems to research on the International Space Station (ISS). The committee evaluated each of the 22 ETDP projects on the basis of the following:

1. The quality of the research effort, taking into account the research team, contacts with appropriate non-NASA entities, and the plan for achieving the objectives;
2. The effectiveness with which the research is carried out and transitioned to the exploration program, including progress to date, facilities, apparent gaps in the program, and the likelihood that the required TRL will be reached[3] (the committee decided that simply noting gaps, as requested in the study statement of task, was too narrow an objective and that gauging "effectiveness" as defined here was more appropriate); and
3. The degree to which the research is aligned with the Vision for Space Exploration (since the VSE includes the wording "in preparation for human exploration of Mars," the committee chose to highlight any project that did not appear to have considered plans that included this aspect).[4]

---

[3] See Appendix D for definitions of technology readiness levels.

[4] The committee notes that after the completion of its assessments of the 22 individual projects in late 2007, the Congress passed the fiscal year 2008 Omnibus Appropriations Bill, which contained a provision prohibiting NASA from funding any activities devoted *solely to preparing for the human exploration of Mars*. The committee chose not to modify its findings on alignment with the VSE based on this language for several reasons. First, the committee interpreted as dominant its statement of task, which includes reference to the entire Vision for Space Exploration, explicitly including the human exploration of Mars. Second, by and large, on this alignment criterion the committee was critical of technology projects that did not consider *extensibility* of their technology to Mars. An example of potentially extensible technology is the Orion thermal protection system for Earth reentry. The committee did not criticize in the assessment of the 22 projects the absence of a Mars-unique technology, an example of which is a martian aerodynamic entry descent and landing system.

The committee's rating of each ETDP project is indicated by its assignment of a flag whose color represents the committee's consensus view, as follows:

- *Gold star.* Quality unmatched in the world; on track to deliver or exceed expectations.
- *Green flag.* Appropriate capabilities and quality, accomplishment, and plan. No significant issues identified.
- *Yellow flag.* Contains risks to a project/program. Close attention or remedial action is warranted.
- *Red flag.* Threatens the success of the project/program. Remedial action is required. (This level was not used in assessing a project's degree of alignment with the VSE.)

The ratings are summarized in Table S.1 and are discussed more fully in Chapter 2 in the committee's observations on the individual projects. A few projects were given two ratings because of major distinctions between elements within a given project.

TABLE S.1 Summary of the Committee's Ratings for Each ETDP Project with Regard to Quality, Effectiveness in Developing and Transitioning Technology, and Alignment with the Vision for Space Exploration

Project Name	Quality	Effectiveness	Alignment
1 Structures, Materials, and Mechanisms	🟨	🟨	🟨
2 Ablative Thermal Protection System	🟨	🟨	🟨
3 Lunar Dust Mitigation	🟩	🟥	🟨
4 Propulsion and Cryogenics	🟩	🟩	🟩
5 Cryogenic Fluid Management	🟨	🟨	🟨
6 Energy Storage	🟩 🟨	🟩 🟨	🟩
7 Thermal Control Systems	🟨	🟩	🟨
8 High-Performance and Radiation-Hardened Electronics	🟨	🟨	🟩
9 Integrated Systems Health Management	🟩	🟨	🟩
10 Autonomy for Operations	🟨	🟨	🟩
11 Intelligent Software Design	🟩	🟨	🟩
12 Autonomous Landing and Hazard Avoidance	★	🟩	🟩
13 Automated Rendezvous and Docking Sensors	🟨	🟨	🟨
14 Exploration Life Support	🟨	🟨	🟨
15 Advanced Environmental Monitoring and Control	🟩 🟥	🟩 🟥	🟩
16 Fire Prevention, Detection, and Suppression	🟩	🟨	🟩
17 Extravehicular Activity Technologies	🟨	🟨	🟨
18 International Space Station Research	🟩	🟨	🟨
19 In Situ Resource Utilization	🟩	🟥	🟩
20 Fission Surface Power	🟩	🟨	★
21 Supportability	🟩	🟨	🟩
22 Human Robotic Systems/Analogs	🟩	🟨	🟩
Totals			
Gold star	1	0	1
Green flag	12	5	12
Yellow flag	10	16	9
Red flag	1	3	0

Key:

★ Gold star: Quality unmatched in the world; on track to deliver or exceed expectations.
🟩 Green flag: Appropriate capabilities and quality, accomplishment, and plan. No significant issues identified.
🟨 Yellow flag: May contain risks to project/program. Close attention or remedial action may be warranted.
🟥 Red flag: This area threatens the success of the project/program. Remedial action is required.

NOTE: A few projects were given two ratings because of major distinctions between elements within a given project.

Finding: The committee evaluated the 22 individual ETDP projects and rated the quality of the research, the effectiveness with which the research is carried out and transitioned to the exploration program, and the degree to which the research is aligned with the VSE. The committee found that, with two exceptions, each project has areas that could be improved.

Recommendation: Managers in the Exploration Systems Mission Directorate and Exploration Technology Development Program should review and carefully consider the committee's ratings of the individual ETDP projects and should develop and implement a plan to improve each project to a level that would be rated by a subsequent review as demonstrating "appropriate capabilities and quality, accomplishment, and plan" (green flag).

Finding: The range of technologies covered in the 22 ETDP projects will, in principle, enable many of the early endeavors currently imagined in NASA's *Exploration Systems Architecture Study* architecture,[5] but not the entire VSE.

In examining the projects and the scope of the ETDP, the committee found two significant technology gaps and also identified several crosscutting issues that are characteristic of many of the 22 ETDP projects or of the overall management of the ETDP. A fundamental concern that reflects all of these issues is that the ETDP is currently focused on the short-term challenges of the VSE and is addressing the near-term technologies needed to meet these challenges. Although it is clear that much of this focus results from the constraints on the program, the committee is concerned that the short-term approach characteristic of the current ETDP will have long-term consequences and result in compromised long-term decisions. Extensibility to longer lunar missions and to human exploration of Mars is at risk in the current research portfolio.

GAPS IN THE SCOPE OF THE EXPLORATION TECHNOLOGY DEVELOPMENT PROGRAM

In evaluating the 22 ETDP technology research thrusts, the committee identified two areas requiring greater emphasis: (1) integration of the human system and (2) nuclear thermal propulsion.

Integration of the Human System

Finding: The committee did not find a high degree of awareness of the interdependencies between the ETDP technology projects and associated human health risks and human-factor design considerations.

The integration of human-related requirements and engineering is essential for ensuring mission success and safety. However, none of the presentations given to the committee called out as design drivers the detailed human health/human factor risks or requirements identified in what NASA regards as controlling documents (such as the *Human Research Program Requirements Document*[6] or the *NASA Space Flight Human Systems Standards*[7]). Some presenters were unaware of the existence of human system risk and requirements documents.

Recommendation: Exploration Technology Development Program (ETDP) project managers should clearly identify the interrelationships between human health and human factor risks and requirements[8] on the one hand

---

[5] National Aeronautics and Space Administration, *Exploration Systems Architecture Study—Final Report,* NASA-TM-2005-214062, NASA, Washington, D.C., November 2005.

[6] National Aeronautics and Space Administration, *Human Research Program Requirements Document, Human Research Program,* HRP-47052, Revision A, NASA Johnson Space Center, Houston, Tex., July 2007.

[7] National Aeronautics and Space Administration, *NASA Space Flight Human Systems Standards,* Volumes I and II, NASA-STD-3001, NASA, Washington, D.C., 2007.

[8] As identified in such documents, as appropriate, as NASA, *Human Research Program Requirements Document, Human Research Program,* HRP-47052, Revision A, NASA Johnson Space Center, Houston, Tex., July 2007; NASA, *NASA Space Flight Human Systems Standards,* Volumes I and II, NP-2006-11-448-HQ, Washington, D.C.; and the Risk Mitigation Analysis Tool developed under the direction of Jeffrey R. Davis.

and technology development on the other and should ensure that those risks and requirements are addressed in their project plans. Each ETDP project manager should be able to show clearly where that project fits within the integrated Exploration Systems Mission Directorate Advanced Capabilities Program (which includes the ETDP, the Lunar Precursor Robotic Program, and the Human Research Program), and this integrated program plan should include all elements necessary to achieve the Vision for Space Exploration.

Recommendation: Exploration Technology Development Program (ETDP) project managers should systematically include representatives of the Human Research Program on the ETDP technology development teams.

Nuclear Thermal Propulsion

Finding: NASA has no project for examining the fundamental issues involved in recovering the nuclear thermal rocket (NTR) technology even though the utility and the technical feasibility of the NTR have been established.

Recommendation: The Exploration Technology Development Program should initiate a technology project to evaluate experimentally candidate nuclear thermal rocket (NTR) fuels for materials and thermal characteristics. Using these data, the Exploration Systems Mission Directorate should assess the potential benefit of using an NTR for lunar missions and should continue to assess the impact on Mars missions.

MANAGEMENT AND EXECUTION OF THE EXPLORATION TECHNOLOGY DEVELOPMENT PROGRAM

Context of the Program

On the basis of its examination of the context in which the ETDP operates, the committee presents three findings:

Finding: In general, the *ETDP is making progress toward its stated goals.* It has a technology development planning process responsive to the needs of the Constellation Program, and if adequately and stably funded and executed in a manner consistent with the planning process, the ETDP would probably make the required technology available on schedule to its customers in the Constellation Program.

Finding: The *ETDP is operating within significant constraints.* These constraints include the still-dynamic nature of the requirements handed over from the Constellation Program; the constraints imposed by a limited budget, both from a historical perspective and relative to the larger exploration goals; the aggressive timescale of early technology deliverables; and the desire within NASA to fully employ the NASA workforce at its “ten healthy centers.” These constraints have posed many management and programmatic challenges, which in some cases have impeded the efficiency and effectiveness of the ETDP.

Finding: The *ETDP has become NASA’s principal space technology program. It is highly focused and is structured as a supporting technology program to the Constellation Program*, designed to advance technologies at TRL 3 and above toward TRL 6. Because of this shift toward the relatively mature end of the technology investment spectrum, which is very closely coupled to the near-term needs of the Constellation Program, NASA has also in effect suspended research in a number of technology areas traditionally within the agency’s scope, and it has in many areas essentially ended support for longer-term (TRL 1-2) technology research.

Program Management and Implementation Methodology

The ETDP spans the full spectrum of elements that are part of large-systems design, planning, and engineering—from requirements and risk mitigation to systems testing. It is thus imperative that systems engineering principles be applied and integrated across the ETDP. The three main areas in which the committee identified issues related to effective systems engineering application were risk reduction, requirements roadmaps and management, and effective technology transfer.

Finding: Although the ETDP has a well-conceived process for managing the programmatic risk of its own technology development, the committee found a lack of clarity in the way that the ETDP accounts for the contributions of its technology developments to reducing exploration (i.e., Constellation) program risk, to reducing operational and human health risks, and to considering human-design-factor issues in operations.

Finding: Recognizing the well-established annual process of reviewing and revising the requirements levied on the ETDP by the Constellation Program, the committee nevertheless found a lack of clarity and completeness in the requirements as perceived by ETDP project personnel and a lack of integration of technology requirements (as would be expressed, for example, in a technology roadmap).

Finding: While the ETDP has a good administrative process for determining the formal mechanics of technology transfer, it could improve the effectiveness of the human side of the process by reviewing and adopting effective practice in this area, with the objective of developing a methodology of technology transfer from the development project to the flight project that ensures the successful infusion of the technology.

Recommendation: The Exploration Systems Mission Directorate (EMSD) should review its process for the management of technology development to ensure the timely delivery of technologies for seamless integration into its flight programs. In particular, the ESMD should (1) review and incorporate the considerable expertise in the management and transfer of technology in the larger aerospace, government, and industrial communities; (2) strengthen its management approach by, for instance, appointing a program-level system engineer to ensure that requirements are developed, maintained, and validated in a consistent and complete manner across the entire program; and (3) address the following three issues in particular: (a) the need for a careful assessment of the impact of its technologies on human and operational risk, (b) the need for definition and management of technology requirements, and (c) the importance of recognizing the human elements in the eventual effective transfer and infusion of technology.

Balance Between Near-Term and Far-Term Technology Investments in the ETDP Portfolio

A challenge to the ETDP is to strike the proper balance between near-term investments that serve a specific mission, often resulting in incremental advances, and long-term investments that may lead to innovations with a potential to be enabling at some time in the distant future.

Finding: The ETDP is currently focused on technologies at or above TRL 3, a focus driven by the need to bring together all of the available resources of NASA to reduce nearer-term Constellation mission risk and at the same time reduce potential Constellation Program schedule slippages within the assigned budget profile.

Finding: Most ETDP projects represent incremental gains in capability, which is not inconsistent with the focus on projects at TRL 3 and above. NASA has largely ended investments in longer-term space technologies that will enable later phases of the VSE, allow technology to “support decisions about . . . destinations,” in the words of the VSE, and in general preserve the technology leadership of the United States. In assessing the balance between near-term and far-term technology investments, the committee found that the current balance of the ETDP is too heavily weighted toward near-term investments.

Recommendation: The Exploration Systems Mission Directorate should identify longer-term technology needs for the wider Vision for Space Exploration (VSE) that cannot be met by the existing projects in the Exploration Technology Development Program (ETDP) portfolio, which are currently at technology readiness level (TRL) 3 or above. To meet longer-term technology needs, the committee recommends that the ETDP seed lower-TRL concepts that target sustainability and extensibility to long-term lunar and Mars missions, thus opening the TRL pipeline, re-engaging the academic community, and beginning to incorporate the innovation in technology development that will be necessary to complete the VSE.

Involvement of the Broader Community

One of the ESMD's requirements for the ETDP is that projects "engage national, international, commercial, scientific, and public participation in exploration to further U.S. scientific, security, and economic interests."[9] Interaction with external peers can take a number of forms and should occur throughout the research life cycle. Because of limited budgets and the pressure to fully employ the NASA workforce at "ten healthy centers," the ETDP has emphasized internal endeavors. Although in many cases technology development internal to NASA is most appropriate because of NASA's unique capabilities, infrastructure, and superior skills, there are other cases in which academia, research laboratories, or industry may be better suited to performing the research. However, even when research is performed outside NASA, it is critical that NASA develop and maintain subject-matter expertise so that it can effectively direct and interact with these external research efforts.

Finding: Some ETDP projects have made alliances with others in the broader community that will add to the effectiveness or efficiency of the project. However, the committee observes that in general, the ETDP has not taken advantage of many external resources that could potentially reduce cost or schedule pressure, aid in the development of NASA's proposed technology, and/or provide alternative and backup technologies.

Finding: In many cases, ETDP projects do not take advantage of external technical peer review.

Finding: While many ETDP projects are technically or programmatically led by distinguished NASA personnel, certain other projects would benefit significantly from having a nationally recognized technical expert on the leadership team.

Finding: In the transition to the ETDP's current structure, NASA has terminated support for hundreds of graduate students. The development of human resources for future space activities may be significantly curtailed by reductions in NASA support for university faculty, researchers, and students.

Recommendation: The Exploration Technology Development Program should institute external advisory teams for each project that (1) undertake a serious examination of potential external collaborations and identify those that could enhance project efficiency, (2) conduct peer review of existing internal activities, and (3) participate in a number of significant design reviews for the project.

Recommendation: The Exploration Systems Mission Directorate should implement cooperative research programs that support the Exploration Technology Development Program (ETDP) mission with qualified university, industry, or national laboratory researchers, particularly in low-technology-readiness-level projects. These programs should both support the ETDP mission and develop a pipeline of qualified and inspired future NASA personnel to ensure the long-term sustainability of U.S. leadership in space exploration.

Testing

Testing is needed to address specifically the risks inherent with any new technology. The lack of testing in the current ETDP poses the threat that the technologies will not ultimately be available to be integrated into the Constellation Program, which increases the overall programmatic risk.

---

[9] National Aeronautics and Space Administration, *Exploration Systems Mission Directorate Implementation Plan*, p. 5. Available at www1.nasa.gov/pdf/187112main_eip_web.pdf.

Finding: The present ETDP lacks an integrated, systematic test program. Of particular importance is that several ETDP projects, as currently formulated, do not include mission-critical tests—that is, system or subsystem model or prototype demonstrations in an operational environment—that are needed to advance the technology to TRL 6.

Recommendation: The Exploration Systems Mission Directorate should evaluate its test capabilities and develop a comprehensive overall integrated test and validation plan for all Exploration Technology Development Program (ETDP) projects. All ETDP projects should be reviewed for the absence of key tests (ground and/or flight), especially those that are required to advance key technologies to technology readiness level (TRL) 6. Where new facilities or flight tests are required, conceptual designs for the facilities or flight tests should be developed in order to establish plans and resource requirements needed to include the necessary testing in all ETDP projects.

CONCLUSION

At the conclusion of its study, the committee had developed an appreciation of the enormity of the task faced by the NASA workforce engaged in the ETDP, especially in light of the significant constraints under which the ETDP operates. These include the following:

- The constraints imposed by a limited budget relative to the exploration goals,
- The still-dynamic nature of the requirements handed over from the Constellation Program,
- The timescale laid out to meet the requirements of the VSE, and
- The desire within NASA to fully employ the NASA workforce at all of its centers.

In spite of these constraints, the committee was impressed with the intensity of the effort and with the dedication and enthusiasm that personnel showed for playing a part in contributing to the VSE. The committee was particularly impressed with the degree to which cooperation between NASA's field centers has developed and the fact that all 10 NASA centers are engaged in the program.

The committee hopes that the observations, findings, and recommendations offered in this report will contribute to the ultimate success of the ETDP and to eventual success in a program to explore the solar system and beyond.

1

Introduction

In January 2004, President George W. Bush announced new elements of the nation's space policy by issuing the Vision for Space Exploration (VSE).[1] Extracted from the document are the following key statements:

> The fundamental goal of [the VSE] is to advance U.S. scientific, security, and economic interests through a robust space exploration program. In support of this goal, the United States will:
>
> - Implement a sustained and affordable human and robotic program to explore the solar system and beyond;
> - Extend human presence across the solar system, starting with a human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations;
> - Develop the innovative technologies, knowledge, and infrastructures both to explore and to support decisions about the destinations for human exploration; and
> - Promote international and commercial participation in exploration to further U.S. scientific, security, and economic interests.

The National Research Council's (NRC's) Committee to Review NASA's Exploration Technology Development Program was asked to perform an independent assessment of NASA's restructured Exploration Technology Development Program (ETDP) and to offer findings and recommendations related to "*the relevance of ETDP research to the objectives of the Vision for Space Exploration*, to any gaps in the ETDP research portfolio, and to the quality of ETDP research [emphasis added]" (see Appendix A). Because of the pointed reference to the VSE in the statement of task, the committee carefully reviewed the text of the VSE quoted above, consulted with NASA officials and other individuals who participated in the drafting of the statement of task, and interpreted the VSE introductory text and four bulleted points quoted above in the following way:

- The committee takes literally the implication of the VSE's introductory text, which states that "a robust space exploration policy" is the *means* to "advance the U.S. scientific, security, and economic interests," and not an *end* in itself.

---

[1] National Aeronautics and Space Administration (NASA), *The Vision for Space Exploration,* NP-2004-01-334-HQ, NASA, Washington, D.C., 2004, p. iii.

- The committee interpreted a “sustained” program in the first bulleted point of the VSE as one that will deliver value to its stakeholders now, and in such a way that it will not fail to deliver value in the future (this interpretation is consistent with the language of the hallmark Brundtland report on sustainability).[2] In the context of space exploration, this implies that the program should deliver benefits to its stakeholders (enumerated as the nation’s “scientific, security and economic interests” in the VSE, and by reference others cited in the National Aeronautics and Space Act of 1958, P.L. 85-568, as amended). In addition, a sustainable program of exploration must be affordable, must be robustly supportable in the political community, must seek the lowest practical level of risk to human life, and must clearly communicate the residual risk to key stakeholders.
- The committee interprets the challenge of “a human return to the Moon” in the second bulleted point as being integral with “preparation for human exploration of Mars.” One of the stated objectives of the policy and of NASA for a return to the Moon is to develop the technology, systems, and workforce capable of succeeding at the far more difficult challenge of Mars exploration.
- In considering the third bulleted point, the committee believes that in this study it is particularly responsible for critiquing the critical role chartered for technology not only to explore but also “to *support decisions* [emphasis added] about the destinations for human exploration.” This phrasing implies to the committee that the technology program should be a thought-leading element of the exploration program, enabling new approaches to a sustainable campaign of exploration.
- The fourth bulleted point touches on the need for the ETDP to engage the external community in technology development both commercially and internationally in order to further its interests. Thus the committee examined how the ETDP is engaging the external community.

Because exploratory voyages lead to an understanding of the unknown, the benefits of exploration cannot be defined precisely in advance. The committee believes, however, that the development of technology for those exploratory missions can independently contribute value to the nation’s stakeholders, in particular, given the following:

- Preparing for exploration accelerates the development of technologies important for U.S. scientific, security, and economic interests;
- Inspiring young people to seek careers in science and engineering is critical to U.S. future competitiveness; and
- Discovering new knowledge about the universe will stimulate human thought and creativity in the sciences and the humanities.

Specifically, the committee was asked to review the technology program supporting NASA’s exploration endeavor. Under the current NASA organization, the human exploration aspect of the VSE is entrusted to the Exploration Systems Mission Directorate (ESMD). To meet its objectives, the ESMD must develop the enabling technologies for its missions of exploration. NASA’s ETDP is part of the Advanced Capabilities theme of ESMD, which also includes the Human Research Program (HRP) and the Lunar Precursor Robotic Program (Figure 1.1). As is emphasized in the committee’s findings and recommendations in Chapter 3, the interface between the ETDP (assigned the engineering portion of Advanced Capabilities) and the HRP (assigned the human portion of Advanced Capabilities) is vital and should be carefully maintained. In addition, the Lunar Precursor Robotic Program could offer a possible opportunity for technology demonstration that has not yet been realized.

The ETDP develops new technologies that will enable NASA to conduct future human and robotic exploration missions, while reducing mission risk and cost. At present, the primary customers of the ETDP are the designers of flight systems in the Constellation Program, which is developing the Orion Crew Vehicle, Altair Lunar Lander, and Ares Launch Vehicles. As discussed in Chapter 4, the committee is concerned about the ETDP’s focus on near-term technologies to support these vehicles, which are all designed to operate in a relatively short duration

---

[2] World Commission on Environment and Development, *Our Common Future: Report of the World Commission on Environment and Development,* Oxford University Press, New York, N.Y., 1987.

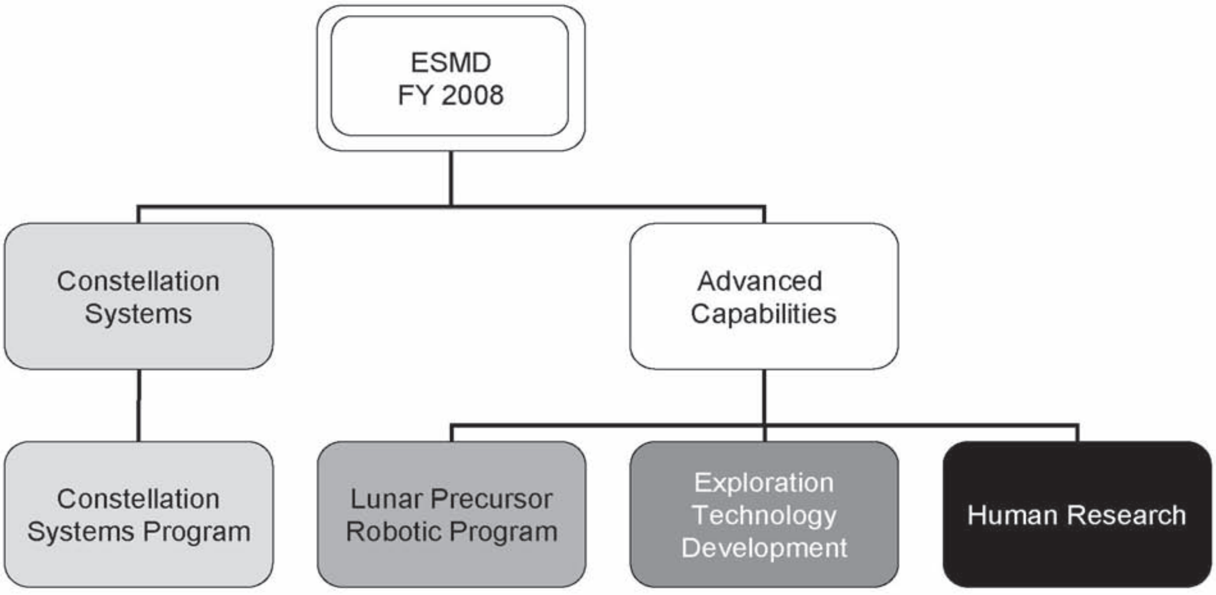


FIGURE 1.1 An FY 2008 organization chart of NASA's Exploration Systems Mission Directorate (ESMD). The Exploration Technology Development Program is a part of the Advanced Capabilities theme. SOURCE: NASA.

paradigm in which resupply from Earth is possible. It should be borne in mind in the ESMD that, by proxy, the developers of systems for which a project office has not yet been established (such as lunar surface systems and Mars exploration systems) are also customers of the ETDP.

The ETDP has initiated 22 technology projects to meet the requirements that flow from the Constellation Program (the ETDP's primary customer). Their assessment as individual projects is the first objective of this report. The projects are these:

01 Structures, Materials, and Mechanisms
02 Ablative Thermal Protection System for the Crew Exploration Vehicle
03 Lunar Dust Mitigation
04 Propulsion and Cryogenics Advanced Development
05 Cryogenic Fluid Management
06 Energy Storage
07 Thermal Control Systems
08 High-Performance and Radiation-Hardened Electronics
09 Integrated Systems Health Management
10 Autonomy for Operations
11 Intelligent Software Design
12 Autonomous Landing and Hazard Avoidance Technology
13 Automated Rendezvous and Docking Sensor Technology
14 Exploration Life Support
15 Advanced Environmental Monitoring and Control
16 Fire Prevention, Detection, and Suppression
17 Extravehicular Activity Technologies
18 International Space Station Research

19 In Situ Resource Utilization
20 Fission Surface Power
21 Supportability
22 Human-Robotic Systems/Analogs

Chapter 2 of this report presents an assessment of each of these 22 individual projects. The objectives and status of each project are summarized. Ratings are assigned by the committee for the quality of the research, the effectiveness with which the research is carried out and transitioned to the exploration program, and the degree to which the research is aligned with the VSE. Gaps in the individual projects are discussed within these assessments. The committee's findings on the 22 individual projects are indicated by the ratings in the text of the descriptions of the individual projects and are summarized in Table 2.1 in the next chapter. Chapter 2 also contains a general recommendation for improvement. Specific recommendations on the 22 projects are not made explicitly, but the commentary for each project contains observations that suggest courses of action that will strengthen the projects.

The content of Chapter 2 is only slightly revised from that in the interim report of the committee issued in April 2008.[3] The evaluation represents a snapshot in time as of late November and early December 2007. The dynamic nature of the ETDP and the Constellation Program may cause certain observations and recommendations to be overtaken by events, but within the scope of the NRC's task, one comprehensive review of the projects was all that could be performed.

At the conclusion of its study, the committee had developed an appreciation of the enormity of the task faced by the NASA workforce engaged in the Exploration Technology Development Program, especially in light of the significant constraints under which the ETDP operates. These include the following:

- The constraints imposed by a limited budget relative to the exploration goals,
- The still-dynamic nature of the requirements handed over from the Constellation Program,
- The timescale laid out to meet the requirements of the VSE, and
- The desire to fully employ the NASA workforce at all of its centers.

In spite of these constraints, the committee was impressed with the intensity of the effort and with the dedication and enthusiasm that personnel showed for playing a part in contributing to the VSE. The committee was particularly impressed with the degree to which cooperation has developed between NASA's field centers and with the fact that all 10 NASA centers are engaged in the program. This was quite evident in many of the briefings to the committee and in all of the program plans. NASA is to be complimented on this level of engagement.

Reflecting on the overall ETDP, its interfaces with the other elements of the Advanced Capabilities office, and its interactions with the Constellation Program, the committee identified a number of crosscutting issues, discussed in Chapters 3 and 4. These two chapters attempt to consider the ETDP in a more holistic sense, taking a top-down approach to the whole program, compared to the more bottom-up approach of Chapter 2 and the interim report. Chapter 3 discusses findings and recommendations pertaining to gaps in the ETDP as a whole, including the interface with the Human Research Program.

The committee's statement of task asks for additional comments in certain areas (see Appendix A). Chapter 4, with a focus more on a programmatic level, provides findings and recommendations for increasing the effectiveness of the ETDP through its management, balancing near-term and far-term technology investments, engaging the external community, and making potentially greater use of testing in technology development.

Indexing the contents of this report to the statement of task indicates the following alignment:

- The specific criteria for the committee to use are these:
  — Alignment with the stated objectives of the VSE (for the individual projects: Chapter 2);

---

[3] National Research Council, *Review of NASA's Exploration Technology Development Program: An Interim Report,* The National Academies Press, Washington, D.C., 2008.

  - — The presence of gaps in research (for the individual projects: Chapter 2; for the ETDP as a whole: Chapter 3); and
  - — The quality of research (for the individual projects: Chapter 2).

- NASA believes that it will be beneficial for the NRC to make additional comments and recommendations in the following areas:

  - —The effectiveness of the program in developing technology products and transitioning them to its customers (for the individual projects: Chapter 3; overall: Chapter 4);
  - —The balance between near-term and far-term technology investments (Chapter 4);
  - —The metrics used for assessing progress in technology development (commented on where appropriate: Chapter 2);
  - —The involvement of the broader community (commented on where appropriate: Chapter 2; overall: Chapter 4);
  - —The program management and implementation methodology (Chapter 4); and
  - —The overall capabilities of the research team (commented on where appropriate: Chapter 2).

2

Assessments of the Projects of the Exploration Technology Development Program

This chapter contains the committee's findings and recommendations on the 22 projects constituting NASA's Exploration Technology Development Program (ETDP). Following a summary of each project's objectives and status is the committee's review of the quality of each project, the effectiveness with which the project is being developed and transitioned to the Constellation Program, and the degree to which the project is aligned with the Vision for Space Exploration (VSE).

Each of the 22 ETDP projects was evaluated on the basis of the following criteria:

1. The quality of the research effort, taking into account the research team, contacts with appropriate non-NASA entities, and the plan for achieving the objectives;
2. The effectiveness with which the research is carried out and transitioned to the exploration program, including progress to date, facilities, apparent gaps in the program, and the likelihood that the required technology readiness level (TRL) will be reached[1] (the committee decided that simply noting gaps, as stated in the study task, was too narrow an objective and that gauging "effectiveness" as defined here was more appropriate); and
3. The degree to which the research is aligned with the Vision for Space Exploration (since the VSE includes the wording "in preparation for human exploration of Mars," the committee chose to highlight any project that did not appear to have considered plans that included this aspect).[2]

In each of these three areas, the committee rated the projects using a flag whose color represents the committee's findings on the project. A summary of the ratings scheme is provided in Table 2.1. A few projects were given two flag colors stemming from major distinctions between elements in the project. In the sections below, detailed observations on each project are presented, and gaps within a given project are identified. As is noted at

---

[1] See Appendix D for definitions of technology readiness levels.

[2] The committee notes that after the completion of its assessments of the 22 individual projects in late 2007, the Congress passed the fiscal year 2008 Omnibus Appropriations Bill, which contained a provision prohibiting NASA from funding any activities devoted *solely to preparing for the human exploration of Mars*. The committee chose not to modify its findings on alignment with the VSE based on this language for several reasons. First, the committee interpreted as dominant its statement of task, which includes reference to the entire Vision for Space Exploration, explicitly including the human exploration of Mars. Second, by and large, on this alignment criterion the committee was critical of technology projects that did not consider *extensibility* of their technology to Mars. An example of potentially extensible technology is the Orion thermal protection system for Earth reentry. The committee did not criticize in the assessment of the 22 projects the absence of a Mars-unique technology, an example of which is a martian aerodynamic entry descent and landing system.

TABLE 2.1 Summary of the Committee's Assessment Ratings Scheme

Criterion	Description of Criterion	Gold Star	Green Flag	Yellow Flag	Red Flag
1. Quality of research	• Research plan • Capability of team • Non-NASA contacts	All criteria under Green Flag were highly rated.	Technical approach and tasks described. Success criteria defined. Resources adequate for tasks; personnel competent. Good contacts made with appropriate non-NASA entities.	Project plan not clear. Technical approach is marginal, activity duplicates existing capability, plan does not address TRL 6. Team not balanced. Not making use of knowledgeable non-NASA entities.	Little evidence of a plan. Team not up to the task. Resources not adequate to accomplish tasks.
2. Effectiveness with which project is being developed and transitioned	• Transition to exploration program • Appropriate facilities • Progress • Gaps • Likelihood of achieving desired TRL	All criteria under Green Flag were highly rated.	Transition plan defined. No gaps. Progress being made and milestones being met. TRL 6 achievable by transition date.	Gaps identified. Important scheduling or funding or performance risks. Milestones are slipping significantly. Likelihood of TRL 6 is at risk.	No viable plan to achieve TRL 6 by the needed date. No transition plan. Status threatens success of overall program.
3. Alignment with VSE	• Project supports VSE objectives. • Project supports Constellation objectives.	Project is investigating enabling technologies for lunar and Mars exploration	Clear linkage to all VSE goals.	No linkage to post-lunar exploration.	Not employed for this criterion.

NOTE: TRL, technology readiness level; VSE, Vision for Space Exploration.
The flag colors can be summarized as follows:

- *Gold star.* Quality unmatched in the world; on track to deliver or exceed expectations.
- *Green flag.* Appropriate capabilities and quality, accomplishments, and plan. No significant issues identified.
- *Yellow flag.* Contains risks to project/program. Close attention or remedial action is warranted.
- *Red flag.* Threatens the success of the project/program. Remedial action is required. (This level was not used in assessing a project's degree of alignment with the Vision for Space Exploration.)

the end of the chapter, the ratings constitute the committee's findings on the 22 projects. The committee's general recommendation is that those projects should be improved whose ratings indicate the need for positive change.

The 22 projects assessed, with a short description of each, are as follows:

01 *Structures, Materials, and Mechanisms:* Technologies for lightweight vehicle and habitat structures and low-temperature mechanisms.

02 *Ablative Thermal Protection System for the Crew Exploration Vehicle:* Prototype, human-rated, ablative heat shield for Orion (the crew vehicle) and advanced thermal protection system materials.

03 *Lunar Dust Mitigation:* Technologies for protecting lunar surface systems from the adverse effects of lunar dust.

04 *Propulsion and Cryogenics Advanced Development:* Non-toxic propulsion systems for Orion and the Lunar Lander.

05 *Cryogenic Fluid Management:* Technologies for long-term storage of cryogenic propellants.

06 *Energy Storage:* Advanced lithium-ion batteries and regenerative fuel cells for energy storage.

07 *Thermal Control Systems:* Heat pumps, evaporators, and radiators for thermal control of Orion, and lunar surface systems such as habitats, power systems, and extravehicular activity (EVA) suits.

08 *High-Performance and Radiation-Hardened Electronics:* Radiation-hardened and reconfigurable, high-performance processors and electronics.

09 *Integrated Systems Health Management:* Design, development, operation, and life-cycle management of components, subsystems, vehicles, and other operational systems.

10 *Autonomy for Operations:* Software tools to maximize productivity and minimize workload for mission operations by automating procedures, schedules, and plans.

11 *Intelligent Software Design:* Software tools to produce reliable software.

12 *Autonomous Landing and Hazard Avoidance Technology:* Autonomous, precision-landing and hazard avoidance systems.

13 *Automated Rendezvous and Docking Sensor Technology:* Development of sensors and software to rendezvous and dock spacecraft.

14 *Exploration Life Support:* Technologies for atmospheric management, advanced air and water recovery systems, and waste disposal.

15 *Advanced Environmental Monitoring and Control:* Technologies for monitoring and controlling spacecraft and habitat environment.

16 *Fire Prevention, Detection, and Suppression:* Technologies to ensure crew health and safety on exploration missions.

17 *Extravehicular Activity Technologies:* Component technologies for an advanced EVA suit.

18 *International Space Station Research:* Fundamental microgravity research in biology, materials, fluid physics, and combustion using facilities on the International Space Station.

19 *In Situ Resource Utilization:* Technologies for regolith (loose rock layer on the Moon's surface) excavation and handling, for producing oxygen from regolith, and for collecting and processing lunar ice and other volatiles.

20 *Fission Surface Power:* Concepts and technologies for affordable nuclear fission surface power systems for long-duration stays on the Moon and the future exploration of Mars.

21 *Supportability:* Technologies for spacecraft and lunar surface system repair.

22 *Human-Robotic Systems/Analogs:* Technologies for surface mobility and equipment handling, human-system interaction, and lunar surface system repair.

Descriptions of the ETDP and its technology infusion plans can also be found in two public documents.[3,4]

01 STRUCTURES, MATERIALS, AND MECHANISMS

Objective

The Structures, Materials, and Mechanisms project has two goals: (1) to develop lightweight structures for lunar landers and surface habitats, which may be used in future modes of the Crew Exploration Vehicle (CEV) and crew launch vehicle to save weight and/or cost, and (2) to develop low-temperature mechanisms for rovers, robotics, and mechanized operations that may need to operate in shadowed regions of the Moon.

Status

The structures element of the Structures, Materials, and Mechanisms project consists of inflatable (expandable) structures for buildings on the surface of the Moon and very large single-segment propellant tank bulkheads made

---

[3] C. Moore and F. Peri, "The Exploration Technology Development Program," AIAA Paper 2007-136 in *45th Aerospace Sciences Meeting Conference Proceedings*, American Institute of Aeronautics and Astronautics, Reston, Va., 2007.

[4] D.C. Beals, "Technology Infusion Planning Within the Exploration Technology Program," IEEEAC Paper #1108, available at http://ieeexplore.ieee.org/iel5/4161231/4144550/04161576.pdf.

of aluminum-lithium (Al-Li). The materials element consists of parachute material, radiation shielding kit materials, and Al-Li for very large propellant tank domes. Little in the way of advanced materials for lightweight vehicles, landers, rovers, and habitats was presented to the committee. The mechanisms element consists of gear boxes, electric motor sensors, and motor controls for robotic systems that would operate in continuous darkness at the poles.

Most elements of this project use system engineering principles to provide minimum risk and to ensure on-time delivery. Designing, fabricating, and testing a piece of demonstration hardware are aspects of all three elements. This project is staffed and conducted primarily at NASA, with a few industry and academic partnerships.

The potential application of lean manufacturing and rapid prototyping technologies needs to be fully explored in the current ETDP. Experience has shown that these technologies can have a significant impact on cost and schedule.

Ratings

Quality: Yellow Flag

Some team members appear to have little or no expertise in their project area. A lack of experience combined with limited interaction with industry can have a serious adverse impact on the quality of work. The lack of interaction with industry has resulted in situations in which NASA work has not yet reached the TRL level of similar projects in industry that are currently at TRLs of 6 or 7. An example of industry capability is Al-Li structures and welding. In addition, industry has demonstrated large friction stir weld-spun domes that are very close to the Ares I requirements. The alloy Ti Al Beta 21 S is currently being used by industry and is not being considered by NASA in the VSE program. The project group itself identified some existing manufacturing techniques not being used by NASA owing to licensing issues rather than technology development issues. It also appears that a lack of specific requirements in some cases has allowed in-house projects to float goals and produce simplistic measures of success.

Effectiveness in Developing and Transitioning: Yellow Flag

This set of activities seem to lack direct tie-in to an integrated, overarching plan. The objectives for most of the tasks are not rooted directly in supporting the VSE or Constellation Program requirements, which limits their ability to be transitioned to the customer. While this limits the risk to the customer, it also limits the overall effectiveness of the work. It is not clear why some specific elements of this project were selected; nevertheless, overall, the project is proceeding in a timely manner and the results are expected to be available to meet VSE and Constellation Program schedules.

Following are comments of the committee on specific project issues:

- *Aluminum-lithium manufacturing: friction stir weld-spun domes.* The metals industry has been crafting friction stir weld and spun domes for a long time. The main reason for pushing this technology is the required size—that is, the 5.5-meter diameter. However, other non-NASA organizations have achieved this technology in sizes very close (5.2 m) to what NASA is trying to achieve. The benefit to the Constellation configuration from incorporating this technology with a small delta in dimension from the state of the art is not clear.
- *Low-temperature mechanisms.* This project element has selected a few components and tested them under the cold temperature extremes present on the Moon. However, when asked about its specific application, the project team was unsure. Some components may work individually under the specified environment but may not function as part of higher-level subsystems or systems.
- *Advanced material for parachutes.* This project element lacks a useful figure of merit. Material is being evaluated for potential application as the CEV parachute material. Team members stated that this material has a strength-to-weight ratio approximately twice that of other currently available fibers, and consequently, that it will yield more than 40 kg in mass savings for the three CEV parachutes. Unanswered is the question of the cost per kilogram to achieve this reduction in mass and the resulting overall gain in system performance.

- *Expandable structures.* This project element uses lunar regolith as part of a pressurized architecture, which is somewhat cumbersome. It is not clear that this is the best design solution because, for example, the abrasive dust in a low-gravity situation could be a menace to equipment and personnel.
- *Advanced composite structures.* Exotic materials, such as lightweight composites, often promise great advantages on paper and sometimes in practice. It was not clear from the presentation of the team responsible for this element how and where these composite materials were going to be applied throughout the Constellation Program. The performance benefit or the figure of merit was not clearly identified. Composite materials may potentially provide significant advantages in weight reduction, but system trade-offs are needed in order to identify and quantify those gains.
- *Facilities.* No new facilities were identified by the committee as needed to validate performance capabilities.
- *Radiation shielding kit*. This technology, which proposes a type of blanket or sleeping bag approach as a portable shield, is a good fundamental research area. However, unless its specific application to various program elements is identified, it is very difficult to see its impact. The use of this kit was not traded against other competing options, and it requires figures of merit.

Alignment with the Objectives of the Vision for Space Exploration: Yellow Flag

The performance benefit to the VSE and Constellation programs from the Structures, Materials, and Mechanisms project may not be fully achieved because of an apparent lack of specific requirements coming from the Constellation Program office. There appears to be little in the way of enabling technology in this project. Therefore, a strong push for these technologies by the customer is not apparent.

02 ABLATIVE THERMAL PROTECTION SYSTEM FOR THE CREW EXPLORATION VEHICLE

Objective

Extremely large heat fluxes are experienced by the Crew Exploration Vehicle (CEV) during reentry from the Moon or Mars. An ablative heat shield is required for thermal protection. The heat shield design and thermal protection system (TPS) material qualification represent major technological challenges. The NASA team for this project stated that the present TRL is 4. The TRL needs to be advanced to 6 to support the CEV project.

Status

The project team is composed of NASA, the companies producing the materials, and the CEV contractor. The work is being carried out in a coordinated manner and, overall, is of good quality. The currently used metrics are appropriate. It appears that an upgrade to the arc-jet facility at NASA's Ames Research Center (ARC) will take place that will improve its flow simulation capabilities.

Material test specimens and TPS materials for the primary and backup CEV heat shields are being produced by aerospace companies. The CEV contractor has built a full-scale heat shield test article and will build the flight heat shield. These developments are being directed and reviewed by NASA to ensure the coordinated consideration of reentry mechanical and thermal loads. There is no possibility of alternate technologies being developed within the ETDP. The plan is to have an acceptable TPS design by CEV Preliminary Design Review (PDR) and to have the technology matured by CEV Final Design Review (FDR).

Ratings

Quality: Yellow Flag

The heat shield is being designed using heating rate predictions from an uncoupled analysis; that is, the char surface temperatures are assumed to be radiation equilibrium temperatures rather than being calculated from a heat balance for the ablating heat shield. The injection of the pyrolysis gases and char oxidation products (which may significantly change the prediction of the heating rate) is ignored. This approach does not represent the current state of the art and could lead to either an over- or underprediction of the bond-line temperatures late in the entry.

While industry has been involved in producing candidate TPS material, there is no significant involvement of the national laboratories. However, organizations such as Sandia National Laboratories as well as other Department of Energy (DOE) and Department of Defense (DOD) laboratories could contribute to this effort.

Effectiveness in Developing and Transitioning: Yellow Flag

Even though 40 years have elapsed since the Apollo 4 flight test and the state of the art in heat shield design has advanced significantly during that time, the ability to simulate a lunar-return Earth entry in ground-based facilities still does not exist. The planned ground-test arc-jet facility improvements are desirable, but they will not provide an adequate approximation of all flight conditions and cannot be scaled to the full heat shield dimensions. Within the present state of the art, it is not possible to build ground test facilities that will duplicate (or even adequately approximate) flight conditions. Only a reentry flight test at lunar-return velocity and at a scale sufficient to assess the effects of joints and gaps between the heat shield panels will qualify the heat shield for use on a crewed lunar-return mission. Because NASA had not made a decision at the time that the committee was carrying out its data gathering, the committee was not clear as to whether an uncrewed flight test is planned; if not, the effectiveness with which this project is being developed and transitioned would be labeled with a red flag.

Alignment with the Vision for Space Exploration: Yellow Flag

Planetary-return heating rates are much higher than lunar-return heating rates. A CEV-like vehicle entering at 13 km/s from Mars will experience peak stagnation-point heating rates (convective and radiative) three times greater than the lunar-return values. Furthermore, at 13 km/s the stagnation-point heat load is approximately 70 percent radiative, whereas for lunar-return entries it is less than 25 percent. Therefore, an entirely different heat shield design may be required for reentry from Mars; hence the present technology does not fully support the entire VSE.

03 LUNAR DUST MITIGATION

Objective

Dust was an issue for the Apollo astronauts, and it continues to be an issue for the Mars Exploration Rovers (MERs). Dust presents both a health risk (e.g., from inhalation and damage to spacesuits) and a mission risk (e.g., for its obscuring of landing sites, causing equipment to overheat, and covering solar arrays). In response to these dust issues, NASA established the Lunar Dust Mitigation project, with the goal of providing the "knowledge and technologies (to TRL 6) required to address adverse dust effects to humans and to exploration systems and equipment, which will reduce life cycle cost and risk, and will increase the probability of sustainable and successful lunar missions."[5]

Status

The Lunar Dust Mitigation project has clearly defined requirements that have been delineated into well-stated project plans to bring the TRL to 5. The development objectives of each of these plans were understood by the team members as clearly stated deliverables. Interaction within the NASA organizations involved in the project seems appropriate. The expertise of dealing with regolith resides within NASA, but outside sources are being sought in appropriate areas where industrial cooperation can benefit the program. The extensibility to Mars appears to be assumed, as the Moon is the current focus. The team seems to be motivated and enthusiastic about achieving its

---

[5] National Aeronautics and Space Administration, *Exploration Technology Development Program. Technology Development Project Plan. Dust Management Project Plan,* Document No. DUST-PLN-0001, NASA Glenn Research Center, Cleveland, Ohio, November 2007.

goals. The team has test plans within the scope of available resources—that is, test facilities—but the need for full-scale testing is not reflected in the current project plan or the Constellation plan. Individual experiences within the Apollo program are being folded in to the development of the projects, except for the overall experience of equipment being crippled by dust contamination on the surface.

Ratings

Quality: Green Flag

The Lunar Dust Mitigation project plan has well-developed requirements and an appropriate layout of program elements to achieve a TRL of 5. Requirements from many sources are driving the correct program development to satisfy the goals. Outside sources have been sought for expertise in dust mitigation within the mining industry—more interaction with hard-rock mining would enhance this effort. Small Business Innovation Research (SBIR) projects are also being used to solicit outside expertise and advance the TRL in some areas. Apollo experiences with dust effects are being folded in to the technology plans. Component-level testing of various mechanisms in a vacuum environment is a good element of this program.

Effectiveness in Developing and Transitioning: Red Flag

Low-TRL ideas that would be matured later than 2013 are not being considered currently in SBIR or other programs; this will limit the continuity of new ideas being inserted into this project's long-term goals. The production of regolith simulant in the time necessary to allow for testing also poses a risk to this effort. Currently, the risks are very high owing to the lack of full-scale, long-term testing to prove the effectiveness of the developed products. A full-scale test facility and the testing of equipment (e.g., bearings and seals, robots, EVA suits, crawlers) under long-term exposure are necessary for the ETDP to develop and prove the criticality of these vital resources on the Moon and Mars. The lack of plans to include a full-scale test facility negatively impacts the effectiveness of the effort in a major way and if left unresolved virtually guarantees failure to reach project goals expressed as TRL 6.

Alignment with the Vision for Space Exploration: Yellow Flag

The impact of the Lunar Dust Mitigation project on the VSE is clearly enabling, and this is understood by the Constellation Program. Without control of the effects of dust, exploration on the surface would be seriously compromised. Even robotic precursors could be less effective without this control. This is recognized by the NASA team and included in its project plans. The yellow flag rating reflects the lack of any development for the Mars environment—which may have its own problems with dust as shown by the MERs—as the lunar environment appears to be the sole focus of this project.

04 PROPULSION AND CRYOGENICS ADVANCED DEVELOPMENT

Objective

The Propulsion and Cryogenics Advanced Development (PCAD) project is focused on the development of the ascent and descent propulsion systems for the Lunar Lander. The team is working on three main areas: the descent main engine, the ascent main engine, and reaction control system (RCS) thrusters for the ascent propulsion system. According to NASA, the ascent liquid oxygen/methane (LOX/CH_4) main engine is currently at TRL 3, the RCS thrusters are at TRL 4, and the descent main engine is at TRL 5.

Status

The PCAD team is composed of NASA employees and several contractors for the main engines and the RCS. The contractors include major aerospace companies and smaller companies. The PCAD project is well focused around the established risk areas for each of the three main project elements that are being worked on. The main customers of PCAD are the Lunar Lander Projects Office (LLPO) and the Orion Crew Module Project Office.

For the descent main engine, the current choice of propellants is liquid oxygen/liquid hydrogen (LOX/LH_2). This choice was made to meet the lander weight budget because the performance of LOX/LH_2 is better than that of storable propellants. Meeting the throttle requirement for this engine (currently about 30 percent, but for some versions it could be lower) is mission enabling for the Lunar Lander. The main risks with this engine are stable throttling, performance, and reliable ignition.

For the ascent propulsion system, nitrogen tetroxide/monomethyl hydrazine (NTO/MMH) and LOX/CH_4 are under consideration. However, the current technology project is focused only on LOX/CH_4, since this is a new propellant combination to be used for this application. The projected benefits of using LOX/CH_4 versus hypergolic fuels are higher performance, which translates into mass savings of approximately 180 kg to 360 kg; lower costs; and a comparable development schedule and achievable reliability. The main challenges that need to be resolved for the LOX/CH_4 engine to be chosen over the storable propellants are reliable ignition (especially after long-term missions on the order of 6 months), performance, and fast start. RCS thrusters using LOX/CH_4 are also being developed that are intended to have higher performance and maneuverability than those using storable propellants. In this case, the major risks are reliable ignition, performance, storability, and repeatable pulse width.

Although Russia, Korea, Pratt & Whitney Rocketdyne, and others are designing or have designed liquid oxygen/methane (LOX/CH_4) engines, they are not designed for a similar application and therefore are not being used as a baseline for comparison with the current ascent engine being developed.

Both main engines and the proposed RCS described above minimize the contamination of the vehicle and landing area and improve ground procedures on the launch pad.

Ratings

Quality: Green Flag

The work of the PCAD project seems to be well coordinated among the primary customers, namely, the Lunar Lander Projects Office and the Orion Crew Module Project Office, the NASA technology development teams from the NASA Glenn Research Center (GRC), the NASA Johnson Space Center (JSC), and the NASA Marshall Space Flight Center (MSFC), and the contractors. The existing test facilities seem to be sufficient for this project.

For the descent engine, the team is pursuing a LOX/LH_2 engine based on the RL-10 and is working with Pratt & Whitney Rocketdyne to develop the new engine. The team is tackling critical design issues, such as the injector design. Its metrics are well defined and relevant to the development program. The team is aware of the risks that it faces. However, there are gaps in the project that the team is aware of but could not address owing to insufficient resources: controls, turbomachinery, and high-heat-transfer chambers.

For the ascent module, the team is focusing on LOX/CH_4 for the reasons mentioned above. The team plans to mature this technology before the LLPO has to choose between this new technology and hypergolic fuels. The team is very aware of the key parameters that it must demonstrate: reliable ignition, performance, and fast start. Its program is well tailored to these objectives. The team is simultaneously carrying out a development project for LOX/CH_4 RCS thrusters that would go hand in hand with the main engine.

Effectiveness in Developing and Transitioning: Green Flag

The LLPO is considering two choices for the main ascent engine: LOX/CH_4 and storables. Because the risks associated with developing an LOX/CH_4 engine are greater than those associated with developing a storable propellant engine for this application, the decision has been made to focus only on the LOX/CH_4 engine in the technology project. As a result of a first set of vehicle studies carrying out both options, the LLPO found that an LOX/CH_4 engine could result in a mass savings of 180 kg to 360 kg. As of this writing, the decision about which type of engine to procure was slated for 2011 or so, after the PCAD team has had a chance to investigate in detail the prospect of using LOX/CH_4 and has given its results to the LLPO and others to support an informed decision.

Within PCAD, preliminary tests carried out by the two contractors working on the LOX/CH_4 engine are underway. Alternative designs are also being considered. The PCAD team and the LLPO are working closely to feed each other the results from their studies.

For the descent engine, the team is carrying only one contractor, Pratt & Whitney Rocketdyne, owing to cost constraints, which means that only one design is being considered. However, in terms of transition, the team is well positioned because the contractor has been involved from the beginning and has the experience to complete the full cycle of design, development, testing, and production.

Alignment with the Vision for Space Exploration: Green Flag

An LOX/CH_4 main ascent engine would be a great benefit for Mars exploration because it is amenable to in situ resource utilization. The team has also tried to foresee what requirement changes the LLPO might present to it and has tried to develop flexible designs. For example, its LOX/CH_4 engine project is expected to be flexible with respect to thrust changes and the number of the starts required.

The PCAD technology development team is pursuing “green” propellants such as LOX, LH_2, and CH_4, as opposed to hypergolic fuels, for both the descent and the ascent engines. One can only assume that such “green” propellants will continue to be the preferred choice for other exploration-class missions.

05 CRYOGENIC FLUID MANAGEMENT

Objective

The objective of the Cryogenic Fluid Management (CFM) project is to develop the technologies for the long-duration storage and distribution of cryogenic propellants in support of all Exploration missions. The development of these enabling technologies is crucial for various NASA customers in the Constellation Program including the Lunar Lander, Earth Departure Stage, and Lunar Surface Operations projects as well as for the Mars program.

Status

The scope of the Cryogenic Fluid Management project includes a number of interrelated elements: Long-Duration Propellant Storage, Cryogenic Propellant Distribution System, and Propellant Management Under Low-Gravity Environment. A number of design and test qualification tasks under each of these elements have been defined and are being executed according to the plan in place. The tasks are being performed primarily at various NASA centers—specifically, GRC, MSFC, JSC, ARC, Goddard Space Flight Center (GSFC), and Kennedy Space Center (KSC). The project includes a relatively smaller involvement from external agencies, including universities and small companies. The current TRLs were stated by the NASA team as follows: Propellant Storage—TRL 4, Propellant Distribution—TRL 5, Liquid Acquisition—TRL 4, Mass Gauging—TRL 3. However, based on the current technical maturity, a TRL of 4 for the Propellant Distribution System would be more appropriate.

The plans to achieve the desired TRL of 6 by the PDR of various Constellation elements include a combination of analytical modeling with component and integrated system tests under specified nonspace and simulated space environments. In some cases, such as Mass Gauging systems, a number of competing systems such as the Pressure-Volume-Temperature system, Radiofrequency Gauge, and Optical Mass Gauge are in the process of being evaluated.

Ratings

Quality: Yellow Flag

The CFM project is spearheaded by a very competent group. The involvement of industries and universities appears to be minimal compared with the direct NASA involvement. The analytical modeling work or the subscale-level testing under a nonspace environment cannot be extrapolated to determine the performance and functions of the full-scale systems under zero- or low-gravity applications.

Effectiveness in Developing and Transitioning: Yellow Flag

A number of technology gaps may have serious consequences for the overall exploration program. Testing subscale or full-scale systems under low gravity is essential in order to demonstrate the applicability of the selected technologies or systems. The achievement of a TRL of 6 or higher before the PDR of various exploration elements may not be realized owing to the lack of these essential tests, mostly caused by funding or scheduling limitations. In some cases, the lack of a fully integrated system test before the flight may lead to undesirable risks. It was mentioned that the Constellation Program Office is evaluating the risks associated with bypassing some of these tests or the eventuality of not achieving the desired TRL 6 by the PDR. This position is in direct conflict with the “Enabling Technologies” designation assigned to the CFM project by the Exploration Program Office. (An “enabling technology” is understood to mean one that must be achieved to enable the success of the mission or an important component of the mission.) However, the committee did not see the absence of achieving a TRL of 6 as a major deficiency if an analysis of the program-level risks, underway at the time of writing, concludes that a TRL of 6 is not required.

Alignment with the Vision for Space Exploration: Yellow Flag

The architectural benefit of using cryogenic propellants in the exploration program is well understood and identified. The selection of LOX/LH_2 for the Earth Departure Stage and the Lander Descent Module provides a significant performance benefit compared with other competing propellant systems. However, a number of technical risks associated with the long-duration-in-space storage, propellant distribution, and acquisition remain unresolved. Similarly, the same issues exist for the LOX/CH_4 propulsion system that is currently being evaluated for application in the Lander Ascent Module. The lunar surface operations for later and longer missions covering up to 210 days require well-proven technologies for long-term cryogenic storage and fluid transfer between surface assets. However, the relationship and dependencies of the CFM systems and the lunar surface concepts of operations (CONOPS) were not described or presented to the committee. The applicability of the technologies and the design solutions identified for lunar missions to long-duration missions to Mars and beyond were not addressed.

06 ENERGY STORAGE

Objective

The objective of the Energy Storage project is to reduce risks associated with the use of lithium batteries, fuel cells, and regenerative fuel cells for the Lunar Lander, lunar surface systems, EVA, and both Ares I and Ares V. Major deliverables are rechargeable batteries for lander ascent, EVA, and lunar surface mobility; primary fuel cells for lander descent; and regenerative fuel cells for lunar surface power and lunar mobility. Rechargeable batteries and regenerative fuel cells are energy storage devices and cannot by themselves provide all the power needed for long-duration missions; a power source (solar or nuclear) is also needed. The objective is to deliver TRL 5 technologies to Constellation System Requirements Reviews and TRL 6 hardware for their PDRs.

Status

The battery and fuel cell research for the Energy Storage project is being carried out at GRC, the Jet Propulsion Laboratory (JPL), JSC, KSC, and a few university and industrial collaborators and contractors. NASA has very good facilities for both battery and fuel cell research and testing. The project is well coordinated among the NASA centers.

It is not clear if the current performance targets for the Energy Storage project will meet the future mission requirements. Customer requirements are not yet well established but presumably will be much better defined in the future. The present metrics are based on a bottom-up approach and, in lieu of established customer requirements, are appropriate as a temporary measure.

The NASA research effort is quite small compared with that of other agencies and of the battery and fuel cell companies. Consequently, by focusing on issues that are specific to its needs rather than trying to make fundamental advances in the technology, the project will reach its goals more effectively and at lower cost. Some NASA-focused issues include low-temperature operation and lightweight packaging for batteries, and fuel cell technologies that achieve high performance and long-term reliability without the cost constraints of the commercial market.

Ratings

Quality: Fuel Cells: Green Flag; Batteries: Yellow Flag

NASA's needs for fuel cell development will not be met solely by the commercial market in that NASA's focus is on mass reduction and the commercial market is focused on cost reduction. Furthermore, NASA fuel cells will operate on H_2/O_2, whereas commercial products operate on H_2/air or gas mixtures (H_2, CO_2, and so on) derived from the reforming of conventional fossil fuels (e.g., natural gas, propane). The NASA fuel cell team is conducting high-quality research with modest resources. The project is fully cognizant of ongoing work in industry and other agencies and makes good use of related research underway in the broader fuel cell community. The team has benefited from a good investment in research and testing facilities.

Although GRC has a long history in electrochemical technology, the current battery team is in a state of transition, with a new project manager and a new principal investigator. Little evidence was presented to the committee to indicate that the battery work is well coordinated with non-NASA efforts. There appears to be only limited collaboration with DOE and DOD efforts. The battery team's characterization of the current performance of space-rated batteries as a specific energy of 130 Wh/kg at 30°C at the cell level significantly underestimates the current state of the technology: space-rated cells with specific energies of greater than 165 Wh/kg are currently available from ABSL Space Products, SAFT S.A., and Quallion, although these cells are not yet qualified for human-rated applications. The team has good facilities for research and testing but does not have a capability for fabricating 18650-size cells (18 mm diameter by 65 mm length, a size commonly used in laptops) or larger cells. This indicates a lack of a well-developed plan and/or capability for transitioning NASA's electrode and electrolyte materials development into full-scale hardware and its subsequent technology insertion into the Constellation Program. However, GRC is conducting a testing program on large cells procured from industrial battery developers, and other NASA centers are conducting a materials development effort in which new materials are tested in very small cells.

Effectiveness in Developing and Transitioning: Fuel Cells: Green Flag; Batteries: Yellow Flag

The current battery and fuel cell technologies used on EVA and the space shuttle are old technologies, and even technologies available today would provide significant performance benefits. The NASA development plan offers the potential for significant improvements over the state of the art, and it is on track to deliver the hardware at the needed TRL at the appropriate time for advanced lithium-ion batteries. However, lithium-sulfur and lithium-metal batteries will probably not reach the required TRLs to meet the Constellation Program's schedule for the Lander Ascent Vehicle, EVA, and lunar surface mobility. The time line requires TRL 5 hardware for the Lander system requirement review by March 2012 and TRL 6 hardware for the EVA PDR by September 2012. This is due to the combination of the present state of development of lithium-sulfur and lithium-metal batteries and the very low level of planned future resources allocated to their development, particularly in the areas of safety and cycle life. Similarly, while the work on primary fuel cells is nearly on track to meet schedule requirements, that on regenerative fuel cells needs to be accelerated to meet the Constellation Program's schedule requirements for the lunar surface systems.

NASA's battery development efforts will have comparatively little impact on advancing the technology except in those areas where NASA's requirements are unique (e.g., operations at very low temperatures). The multibillion dollar commercial market for lithium batteries will drive advances by industry, and other federal agencies such as DOE and DOD have much larger programs in lithium battery research and development (R&D). A unique feature of the NASA applications is that life requirements are lower, and thus some trade-offs in packaging can be implemented to reduce weight. Extending the operating temperature range of the batteries to extremely low temperatures would also benefit NASA. NASA's fuel cell development efforts are less dependent on non-NASA research, as the objectives of the commercial fuel cell research are quite different, with its focus on reducing cost and its operation on air rather than oxygen. The regenerative fuel cell being developed by NASA could readily find application as an energy storage medium for terrestrial markets in intermittent renewable energy systems such as wind and solar.

Alignment with the Vision for Space Exploration: Green Flag

The research on battery and fuel cell technologies is well aligned with the VSE, and these technologies are critical to the Constellation requirements. Batteries have been identified as critical for the Lunar Lander and as enabling for EVA and lunar mobility. Primary fuel cells are critical for Lunar Lander power. Regenerative fuel cells have been identified as critical storage systems for Lunar Surface Systems. These technologies are also enabling for the Mars mission. Long-term durability and reliability under extreme conditions (particularly for fuel cells) may be critical for the Mars mission, and accelerated tests to understand durability and reliability issues should be included in the planning.

07 THERMAL CONTROL SYSTEMS

Objective

Nearly all Constellation hardware will require systems to mitigate the extreme temperature conditions encountered in space and on lunar and planetary surfaces. The objective of the Thermal Control Systems (TCS) project is to advance the technology readiness level for critical lunar thermal control system technologies and to mitigate thermal-control-specific Orion risks.

Status

The TCS technologies include a number of different projects underway at several NASA centers. The effort is focused on active thermal control technologies. Passive technologies are not viewed to be part of this project's area of responsibility. Project elements include fluids, heat acquisition, evaporative heat sinks, radiators, system design and testing, and two-phase systems. To date, the technology efforts have focused almost exclusively on Orion. Over the next 3 years, NASA's schedule shows that the efforts move more toward the Lunar Lander. Although it was noted that the lunar exploration goal is to land anywhere at any time, the specific efforts are wholly aimed at the initial landing, planned for not more than 7 days at one of the poles. Much of the team that was working in the thermal technology area has transitioned to roles on the Orion program. The current projects include the Orion efforts, which are now moving toward the integrated system test phase and toward early work on the planned Lander tasks.

Ratings

Quality: Yellow Flag

The emphasis of the Thermal Control Systems project is to re-engineer and optimize the existing Apollo systems to reduce their resource requirements (mass and power). Another aim of the effort is to transfer the technical knowledge from the older to the younger generation of engineers through the redesign of the old systems. While these projects will probably be useful to the Constellation Program in reducing mass and complexity, the focus on incremental technology developments may miss alternative approaches. No overall vision is pushing new directions or looking far into the future. Furthermore, the movement of people off the technology projects and onto the Constellation hardware programs fosters the idea that the ETDP effort is not a technology development program but only an additional engineering resource for the Constellation thermal effort. There is little outside university or national laboratory involvement. Industry support seems to be focused on those companies with existing ties to specific NASA centers. Some supporting examples are given below.

To date, the technology focus of this project has been on active thermal control systems for Orion. One effort is aimed at replacing the old two-fluid (inside and outside) system with a common fluid used in both places. The benefit of this effort is aimed at reducing complexity, allowing common parts and interfaces between systems. The one stated goal of this effort was to generate long-term stability data for potential fluids. This result seems to be more of a supporting engineering role than a developmental one. Also, there is no metric to define whether this approach is actually beneficial to the Constellation Program's efforts. Suggested metrics to determine if a single-fluid operation is superior to the two-fluid system are long-term fluid stability, system mass, heat rejection rate, power requirements, and cost.

Another goal was to develop a radiator system with at least a 25 percent mass reduction over the present orbiter radiator design. The issue with fluid-loop-coupled radiators is the connection between the metal fluid loop and the low-mass composite radiator. A significant amount of work has been done on composite radiators from a variety of organizations. The effort presented did not seem to build on any of that existing work. It was reported that the Constellation Program had not decided to go ahead with this technology.

It was noted that the thermal technology project is supporting the In Situ Resource Utilization (ISRU) and Robotics efforts because they do not have thermal expertise. Again, while this effort is useful, it is at some level draining resources from one area to support another. The result may be better systems in those areas that appear to need them, but the cost is the lack of development of new thermal technologies.

Finally, the technology effort is focused only on active systems. Passive systems are not part of this area of responsibility. Any longer-term lunar landing effort will need to combine both active and passive systems. The separation of these two fields means that any synergy that could be achieved by combining active and passive systems will be harder to find.

Effectiveness in Developing and Transitioning: Green Flag

The overall technology development effort of the TCS project seems to be well tied in to the Constellation Program. The project has defined objectives that were driven by Constellation's needs and perceived risks. Customer service agreements (a form of contract between Constellation, which is the customer, and the ETDP, which is the supplier) are in place and being used. The efforts in the technology areas are reviewed frequently by the Constellation team. The detailed schedule for the technology development activities is in line with the Constellation Program's reviews. Budgets are tracked and funds can be moved from one area to another on a quarterly basis. However, it is difficult to quickly add new organizations into the effort from a contractual perspective, which limits the project's ability to include new suppliers.

It is difficult to assess how the project will fit into the overall Constellation effort. Most of the technology items discussed are in the early design stage. Milestones for early in 2008 include design and requirements reviews. Design and analysis reports are due later in the year. Project success will eventually be determined on the basis of how those technology items develop. Since the technology efforts tend to be incremental, there is a low risk of the technologies not achieving their objectives—the existing approach is the backup technology. Probably the most important goal is the change from a consumable-based cooling system to a closed system.

From a technology point of view, the project needs to be careful that the technology efforts are not just performing as the feeder team for the hardware programs. Much of the original Orion technology group has moved to hardware roles on the program. This transition of people is good for transferring ownership of the technology to the Constellation Program, but at the cost of losing experience in the technology team. Part of the technology effort needs to look forward at technologies that will change how things can be done. The present effort is almost entirely focused on improving the existing approach.

Alignment with the Vision for Space Exploration: Yellow Flag

The technology development plan of the TCS project is aimed at performance rather than at architectural benefits. A main goal for the elements of the projects is to reduce resources (mass, power, complexity) used by the active thermal control elements on the Orion and Lunar Lander systems.

The technology efforts are hampered by the fact that little work is being done on exploration technologies outside the Constellation Program. The project approaches presented to the committee focus on the Apollo architecture for getting to the Moon and staying there for a short period. The technologies will be of help in updating the Apollo designs for future use, but this inward focus may keep other ideas from surfacing that would support different architectural approaches.

The technologies discussed are specific to the Apollo architecture. Technologies for the lunar outpost and rovers are left to future years. The approach for any long-term habitats, in regions other than the poles, assumes that electrical power will be there to support large-scale heat pumps and cooling systems. Operation in the martian atmosphere and mitigation of long-term dust effects are gaps.

08 HIGH-PERFORMANCE AND RADIATION-HARDENED ELECTRONICS

Objective

The intent of the High-Performance and Radiation-Hardened Electronics (RHESE) project is to advance the current state of the art for radiation-hardened electronics. This is and will always be an issue of significant importance across all elements—with or without a crew—of U.S. space assets.

Status

The RHESE project includes close partnerships between NASA and academia. The project maintains some relationships with the DOD. The RHESE project includes five subprojects: modeling of radiation effects on electronics, single-event-effects-immune reconfigurable field-programmable gate arrays, high-performance processors, reconfigurable computing, and silicon-germanium (SiGe) electronics for extreme environments. The SiGe project has successfully demonstrated technology advances. This project will wrap up in 2009; the high-performance processor and reconfigurable computing projects are expected to ramp up around the same time.

Ratings

Quality: Yellow Flag

Although this work has elements that are quite interesting, and JPL is credibly among the best civilian agencies in the world in this arena, there are significant gaps in the RHESE project team’s knowledge of the state of the art across the panorama of U.S. agencies that conduct work in this area. A number of DOD activities are making significant progress in this field, and NASA will find it useful to make contact with them. The fact that NASA is currently collaborating with the Defense Advanced Research Projects Agency (DARPA) and the Defense Threat Reduction Agency on high-performance processor development was not elaborated on in the presentation to the committee but is hinted at in the project’s documentation. The extent of NASA’s collaboration is unclear with respect to tasking, funding split, and status, and it is uncertain that the project has the best approach to move forward. There is a pressing need for RHESE in NASA’s future missions, both human and robotic; however the roadmap, roles, and responsibilities between DOD and NASA need to be clarified and properly funded.

NASA has world-class researchers in this area, but management does not appear to have a sufficiently strong technical background to appreciate the opportunities for significant advancements in this field. This is an area in which the management of the project should be drawn from field expertise. Failure to resolve this issue is likely to limit NASA’s ability to truly understand the advances being made across all researchers in the United States and abroad in this key area. When these management issues are resolved, NASA will be in a position to determine how to integrate its knowledge with input from external agencies. In this way, a complete understanding of the combined effects of radiation, thermal, volatile, and particulate environments that will be likely on the Moon can be brought to bear on the design of reliable electronic components.

Effectiveness in Developing and Transitioning: Yellow Flag

Those with experience in the long-term life of critical electronic components and systems in uncrewed systems (NASA has plenty of expertise, especially at JPL as well as at GSFC) know how much likelihood of failure should be allocated to these systems. It does not appear that the highest management levels for the Constellation/Orion missions understand these risks, nor is it even clear that appropriate industrial firms have been involved in risk allocations associated with the long-term functioning of space electronics for these missions. This concern is derived from the lack of concrete requirements, the apparent lack of any reasonable priority (by virtue of extremely low funding levels of some of the subtasks), and the apparent lack of upper management's incorporation of electronics issues into mission architectures and planning.

An example of the lack of concern is that currently funded R&D teams in this area, as presented to the committee, are not deeply informed about the radiation or volatile environment on the lunar surface—an absolutely necessary prerequisite to the proper modeling of radiation effects on electronics. Radiation-hardened electronics can be an extremely expensive endeavor in terms of both cost and risk—improper design (ill-informed by physical realities) could deeply jeopardize deliverables such as electronics-based systems fabricated with these components, launch schedules, and even missions.

Finally, the work that was presented to the committee would apparently not be closed-loop system tested in a relevant environment, owing in large part to limited buy-in from mission elements. This fact limits the likelihood that these technologies can be validated for flight in time for insertion into mission architectures. Thus the incorporation of novel electronics concepts, such as redundancy and maintainability strategies, into mission architectures is effectively precluded, virtually eliminating any efficiencies that could be built in through more robust electronics.

Alignment with the Vision for Space Exploration: Green Flag

Clearly the work of the RHESE project has enormous applicability to lunar outpost and Mars missions. All of the work being done in its project elements is highly extensible to longer-term missions and to long-duration spaceflight and missions to the surface of Mars.

09 INTEGRATED SYSTEMS HEALTH MANAGEMENT

Objective

Integrated Systems Health Management (ISHM) is a system engineering discipline that addresses the design, development, operation, and life-cycle management of components, subsystems, vehicles, and other operational systems. The primary objectives of ISHM are to maintain nominal system behavior and function and to ensure mission safety and effectiveness under off-nominal conditions. ISHM is an enabling capability for risk mitigation, mission safety, and mission assurance for space exploration. Specifically, ISHM is to provide a systematic methodology to increase ground system availability for Constellation. The project elements presented were as follows:

- Solid-rocket motor health management, with an add-on proof-of-concept test for NASA that will be accommodated in a flight demonstration on a DOD microsatellite called Tactical Satellite-3;
- Integrated ground system diagnostics, with infusion into ground support and analyses infrastructure; and
- In-space, closed-loop, long-duration validation of a complete ISHM system.

Status

The ISHM project plan contains a good analysis of the state of the art outside NASA and has a well-characterized and specific set of objectives. Integration of the objectives into operational missions a still a somewhat ambiguous matter to the committee.

Ratings

Quality: Green Flag

In the ISHM project, mid-TRL historical developments are used, with limited flight demonstrations, to develop flight heritage technologies that can be inserted into the Constellation Program. The technical approaches are solid, if somewhat limited. A good assessment has been made of what is required for the maturation of ISHM technologies such that actual mission program insertion can occur.

Effectiveness in Developing and Transitioning: Yellow Flag

There was no clear visibility for the roadmap and risks associated with the ISHM effort to expand and enhance the limited scope of developments underway to include the addition of new systems and subsystems. This seems, in part, a result of what appears to the committee to be limited buy-in from the customer, despite significant performance parameters assigned to this project for risk reduction in Constellation. For example, a full assessment of failure modes for a complete validation of models was described as needing 20 or so more hot-fire tests of an Ares I that were not included in either the project budgets or time lines.

A roadmap for building the end-to-end ISHM and its integration into the end-to-end flight controls would be a critical element in moving this rating from a yellow to green flag. Also important to effective transitioning would be a more detailed roadmap for flight qualification for the eventual end-to-end model.

Alignment with the Vision for Space Exploration: Green Flag

If effectively developed, integrated, and validated through lunar experience, ISHM technologies will provide critical risk management tools for future missions. Automated system health monitoring and management technologies are well aligned with the VSE, and they are critical to the Constellation requirements. These technologies are also clearly enabling for the Mars mission.

However, if the critical risk management tools are to evolve between now and a Mars mission, NASA is encouraged to look at ways to increase safety (reliability) margins in vehicle design, not simply to improve the control and monitoring software. While this project is clearly aligned with the VSE, the approach may not be complete enough to allow a transition to future elements of the VSE without a great deal more work.

10 AUTONOMY FOR OPERATIONS

Objective

The primary objective of the Autonomy for Operations (A4O) project is to provide software tools to maximize productivity and minimize workload for mission operations by automating procedures, schedules of activities, and plans. The primary customer for the technology is Constellation. The technology will provide mission operations software capabilities for Constellation mission operations, onboard control, crew assistance, and robotics. The key technologies are reusable building blocks, the automation of mission operations functions, and support for human interaction. Current testing opportunities have primarily focused on using data from the International Space Station (ISS).

Status

Non-NASA technology development efforts for procedure automation, software validation, and verification (V&V) currently exist. A4O technology has primarily focused on ISS-based applications, in which the state of the practice is primarily manual (for the construction of command sequences). The current team is composed of ARC, JSC, Langley Research Center (LaRC), and JPL personnel. There are some university and industry partnerships. Deliverables include (1) procedure development environment and procedure automation, with success criteria equating to reduction by a factor of 2 to 10 in the time to create procedures, time to validate procedures, and number of errors; and (2) mission control center, training management, and flight product production automation, with success criteria equating to reduction by a factor of 2 in the time to validate the plan. Software validation is primarily through customer feedback, testing on relevant examples, and shadow-operations—that is, running the software in the background and testing to determine if the outputs match with what the humans did.

Ratings

Quality: Yellow Flag

The A4O technology development is focused on specific NASA objectives (in particular, ISS), yet the project does not provide a coherent picture of how individual software technologies under the A4O project address Constellation Program needs. Although advanced technologies in automation and software V&V currently exist, the project does not seem to build on a requirements or human factors perspective, which has been shown to be a standard practice in this area. It was also not fully shown how key performance metrics used to assess quality of effort will be analytically evaluated or compared to the state of the art in industry.

Effectiveness in Developing and Transitioning: Yellow Flag

The Constellation Program requirements that A4O technology seeks to address include five elements that focus on (1) control of automated functions, (2) fault detection and recovery, (3) integrated mission planning and analysis, (4) concurrent monitoring and control of three active space vehicles, and (5) the capability to return crew to Earth without ground communication. Although the goals of the project are properly outlined, a roadmap to project success is not obvious. In particular, it is unclear how these requirements directly map to the technology products (or stated achievements) that are being developed in the A4O project, or in deriving the key performance metrics for this project.

Infusion points into Orion and Lunar Lander operations are highlighted as milestones, but there is not a clear roadmap for transitioning development from ISS-specific examples to Constellation-specific examples. There seems to be a strong disconnect, or at least a lack of good communications, between the ETDP team and the customer, Constellation.

Alignment with the Vision for Space Exploration: Green Flag

The primary objective of providing software tools to maximize productivity and minimize the workload for mission operations, if achieved, could provide significant benefit toward achieving the VSE. The technology concepts would extend to other exploration missions as well as providing significant performance benefits. To achieve these benefits though, the A4O project needs to focus on getting direct buy-in from the mission operators/astronauts/technology user base.

11 INTELLIGENT SOFTWARE DESIGN

Objective

The Intelligent Software Design (ISD) project is intended to provide the Constellation Program with capabilities to analyze the behavior and support the certification of software-intensive, mission-critical systems over a wide range of nominal and off-nominal scenarios, in a highly automated fashion.

Status

Despite problem areas discussed below, the committee found that, overall, this is a well-conceived and well-planned project to develop model-based software validation and automatic code generation capabilities to decrease the costs of software development and the risks it faces in the Constellation Program. The criticality of autonomous and reconfigurable software design appears to be well understood by the ISD project implementers. It is unclear that flight project managers share this assessment, and this fact is reflected in unclear approaches for validation and testing. All elements—validation testing, autocode verification, model-based analysis, and reliable systems—have top-notch personnel and clearly articulated goals. This project is primarily conducted at NASA, however, with very little involvement of communities outside NASA.

In terms of technology infusion, a lack of clarity is inherent in many of the elements regarding the degree of autonomy needed by the customer versus the cost involved for mitigating risks identified in the Constellation Program and documented in the ISD project plan. This appears to be a function of unclear priorities provided by the Constellation Program for the infusion of these technical advances into the flight program.

Ratings

Quality: Green Flag

The ISD project team has made well-thought-out critical choices for addressing the project objectives and risks within the limitations of the unclear customer requirements. In this case, the team is pursuing a set of tools for reducing cost and risks in the complex mission-critical software systems required for Constellation. The team is aware of the risks that is faces. There are gaps in the program that the team is aware of but cannot address owing to cost issues. This is a well-balanced and appropriately focused program. The members of the team were very seasoned and experienced.

To a reasonable extent, the project takes advantage of commercial (non-NASA) work that is open source or what can credibly be called commercial off-the-shelf technology. The project could benefit from the additional involvement of universities and others in investigating the application of commercial concepts that would be considered low TRL because they have not been fully applied to a crewed space endeavor.

Effectiveness in Developing and Transitioning: Yellow Flag

The ISD project is subject to an aggressive schedule, and although the schedule is feasible, funding limits the probability of this project achieving its full goals in the time frame presented to the committee. Exacerbating the scheduling problem is the fact that no credible plans to fully test and verify the advances were presented to the committee. Currently, no subproject technologies are yet human-qualified. In general, although this would not be impossible to achieve, it is unclear how transition to TRL 6 will be successfully accomplished. Nevertheless, the present status does not threaten the success of the overall program.

Alignment with the Vision for Space Exploration: Green Flag

The benefit of this project to both lunar and Mars exploration is well aligned with the goals of the VSE. These technological advances, given the virtual guarantee that mission software will increase in complexity and requirements for reliability, will all be enabling for a Mars mission as well as the lunar mission.

12 AUTONOMOUS LANDING AND HAZARD AVOIDANCE TECHNOLOGY

Objective

The primary objective of the Autonomous Landing and Hazard Avoidance Technology (ALHAT) project is to develop and mature various hardware and software components that will aid lunar descent vehicles. Overall, the goal is for the system to enable safe, accurate, and precise landing near selected landing sites anywhere on the lunar surface unaided by humans. The primary customer for the technology is the Lunar Lander Projects Office.

Status

The technology that the ALHAT project develops includes hardware and software components. Some of the hardware components are locally developed sensors such as flash lidar (Light Detection and Ranging), scanning lidar, optical Doppler lidar, and cameras, whereas other components are commercially available sensors (inertial motion units, star trackers, and altimeters). The software components include algorithms to convert sensor data to vehicle-state information, algorithms that aid vehicle flight, and guidance and navigation algorithms. The TRL for the overall system varies. Some sensors can be considered to be at TRL 3 or 4 (flash lidar), whereas others have flown in space but have not been employed for lunar landing scenarios (scanning lidar). The algorithms range from TRL 3 to TRL 5. The current team is composed of personnel from JSC, LaRC, JPL, the Charles Stark Draper Laboratory, and Johns Hopkins University Applied Physics Laboratory. Moreover, there is some university and industry involvement (by the University of Texas at Austin, Utah State University, Jacobs Engineering Group, Inc., and Fastmetrix, Inc.).

Ratings

Quality: Gold Star

The quality of the NASA development effort on the ALHAT project is high. The team has the experience and expertise to carry out the technology development. Moreover, the team is working in a tightly coordinated manner. It has reported several major accomplishments and significant findings, ranging in scope from technical achievements, to vendor site visits, to written operation concept reports, to independent reviews of the ALHAT project.

The team has recognized several technology areas that had not previously been identified. These include a need for sensors that can provide real-time elevation maps of terrain during descent; a need to increase and improve the operational range, accuracy, and resolution of flash lidar; and a need for a velocimeter that can provide accurate and precise horizontal velocity measurements. It is noteworthy that the team has identified these gaps and plans to address each one by the Lunar Lander PDR in the year 2011.

The broader community is involved in this project; however, there is room for additional involvement. Facilities at LaRC, JPL, and JSC are being used and are adequate to advance to TRL 5. Achieving TRL 6 will require free-flier tests.

Effectiveness in Developing and Transitioning: Green Flag

The technology roadmap for the ALHAT project shows a systems engineering approach to problem solving. Continued development of hardware and software technology is planned, with significant milestones set for June and September 2008. Technology testing and integration are ongoing, and will become the primary activity of the project in 2009 and beyond. The schedule shows ALHAT validation (TRL 5) in 2010. The technology transition plan shows that the ALHAT project will be infused into the Lunar Lander Projects Office by 2011. Moreover, tests on a free-flying test vehicle could provide TRL 6 prior to Lunar Lander FDR. The committee voiced some concern as to whether adequate consideration has been given to testing requirements that will take this technology to an integration stage such that TRL 6 is actually achievable within the time frame specified.

The schedule risks appear to be acceptable, and there appear to be no high-risk technology obstacles to the project.

Alignment with the Vision for Space Exploration: Green Flag

Overall, the ALHAT project is well aligned with the needs of the Lunar Lander Projects Office. The technology benefits the Constellation architecture and several elements of the VSE beyond the Constellation Program. The technologies and techniques appear to have an architectural benefit in that the methods will be applicable to any spacecraft landing on planetary surfaces. The approaches are aimed at having a high likelihood of success while minimizing risks and costs.

13 AUTOMATED RENDEZVOUS AND DOCKING SENSOR TECHNOLOGY

Objective

The primary objective of the Automated Rendezvous and Docking Sensor Technology (AR&DST) project is to reduce risk associated with relative navigation sensors for proximity operations and docking through development, testing, and simulation. The primary customer for the technology is the Orion project, but it is important to the Altair Lunar Lander as well as to future Exploration activities.

Status

The technology developed in this project will provide a vision navigation sensor (or suite of sensors) to aid rendezvous, proximity operations, and docking. The sensor(s) shall have an operational range that spans from 5 km to dock. The current effort is focused on the Natural Feature Image Recognition (NFIR) technique, the Next Generation Advanced Video Guidance Sensor (NGAVGS), and simulation and testing. The Orion program is in the process of a contractor-led AR&D sensor procurement, Vision Navigation Sensor (VNS), of its own that did not include NFIR or NGAVGS by definition, so the transition of this technology to the primary customer is unclear. It appears that the development status of both the NFIR and the NGAVGS is near TRL 5. It is important to mention that the predecessor to the NGAVGS, the Advanced Video Guidance Sensor (AVGS), was operational in some space flight testing on Orbital Express and the Demonstration of Autonomous Rendezvous Technology mission (TRL 7 to 8 was achieved), and therefore some elements of the NGAVGS may claim a higher TRL.

It is known that non-NASA technology development efforts for AR&D sensors are underway, but it appears that these techniques are not being strongly considered within the AR&DST project. Some of this is due to International Traffic in Arms Regulations concerns since this is a significant area of work outside the United States. The current team is composed of JSC, MSFC, and JPL personnel. There are no university or industry partnerships except for two recently selected SBIR projects.

Ratings

Quality: Yellow Flag

Critically, other non-NASA efforts may be extremely relevant to the Automated Rendezvous and Docking Sensor Technology project. The absence of university or industry partnerships suggests that these non-NASA potential solutions may be being overlooked.

It is unclear how the team plans to objectively and directly benchmark the NGAVGS and NFIR techniques and how the VNS, the Orion-procured sensor, will fit into the mix. Alternatives being developed outside NASA also may have a role in this objective comparison.

A mix of testing facilities exists within NASA (JSC and MSFC), at contractors, and within the DOD (Naval Research Laboratory). The plan by which all of these capabilities will be fully utilized is unclear since the focus by the NASA presenters addressing the committee was on JSC. The team did mention that it plans to revisit the testing plan to look at this wider set of facilities. Also, in the simulation area it does not appear that previous work both within and outside NASA was being fully utilized, since it was stated that the team is largely developing its own simulations at JSC.

Effectiveness in Developing and Transitioning: Yellow Flag

The project's technology roadmap shows the continued development of NFIR and NGAVGS on parallel paths to 2010, with technology enhancements to support Orion from 2009 to 2012. Simulation and testing end after 2008, which appears to be a disconnect with continued NFIR and NGAVGS development unless it is assumed that Orion picks up this work. In 2011 Lunar Optical Navigation and technology enhancements begin funding to support the Altair Lunar Lander.

Since this project is only focused on the AR&D sensors rather than on the whole AR&D problem, it lacks a systems engineering approach to solving the problem and largely appears to be responding only to Orion requirements, many of which focus solely on the ISS mission. The sensor technology transition is scheduled for the summer of 2008 and will occur before the Orion PDR, which was moved from May 2008 to September 2008.

Many of the technology risks are associated with meeting the minimum range, maximum range, and frequency requirements. It is noteworthy that four of the five top project risks are ranked as high-likelihood, high-consequence risks. Risk management approaches are mentioned, but the technology development will need to be closely monitored and scrutinized.

Alignment with the Vision for Space Exploration: Yellow Flag

AR&D is often cited as a critical technology needed to support the VSE in the near term for Orion's mission to the ISS, in the mid-term for the Altair Lunar Lander, and in the long term for future Mars architectures. That is why it is especially important that a holistic, systematic approach be taken to this technology. This project appears to the committee to suffer from a somewhat myopic focus on solely near-term needs for the Orion-to-ISS mission and on the sensors alone. This approach is likely to result in technologies that do not support the VSE as a whole and that penalize future elements.

14 EXPLORATION LIFE SUPPORT

Objective

The objective of the Exploration Life Support (ELS) project is to develop and mature life support system technologies that meet mission requirements approximately 6 years before flight or occupancy of the various elements of the Constellation Program such as the Crew Exploration Vehicle (Orion), Lunar Lander, Lunar Habitat, and the pressurized rovers. The technologies selected cover Air Revitalization Systems, Waste Management Systems, Water Recovery Systems, and Habitation Engineering.

Status

In the ELS project, critical technologies have been defined, responsibilities have been assigned to a large number of NASA centers, and grants and cooperative agreements have been established with non-NASA and non-U.S. organizations. In general, a great deal of this work is being developed and executed in-house, with little explicit reference to knowledge outside NASA. The committee was advised that at one time there had been considerable collaboration with universities and other cooperative agreements but that these collaborations had all been terminated recently, primarily because of budget reductions. The research scope has also been impacted with the elimination of biological research related to plant and microbe growth, which had been part of the "closed loop life support" strategy followed for several decades previously (e.g., Controlled Ecological Life Support System, or CELSS). Without the fractional gravity research into plant growth and without the quantification of other variables, it is not clear how the life support loop will be closed. It was also unclear whether or not the research plan had been coordinated with the design reference missions for resupply to either lunar or Mars bases. The design reference missions assumed a reduction in costs due to resupply requirements by utilizing CELSS technologies.

In terms of requirements and risk mitigations, this project plan is less definitive than many others in the ETDP portfolio, and there is no clear roadmap for transition from technology development to infusion into final flight hardware.

Ratings

Quality: Yellow Flag

The ELS team is very capable. In general, the selected technologies (Air Revitalization Systems, Waste Management Systems, Water Recovery Systems, and Habitation Engineering) appear to provide good approaches to significant performance and architectural benefits, but very few data based on comprehensive system engineering were presented to the committee to quantify these benefits. This is a very NASA-centric set of efforts that may benefit from broader involvement with communities outside NASA, interactions that had existed at one time but which were terminated because of budget reductions in recent years. Although the project elements are reasonable across the board, there appears to be no substantial innovation here. No early-stage research will be done to bring in innovation. The lack of understanding of the lunar dust environment is a major concern. This area, along with particulate mitigation, causes concern because it is unclear that the technology being developed will be flexible enough to accommodate the needs for the lunar environment once those needs are better understood. The impact of failure to achieve the required technology readiness level by the Constellation Program target dates was not assessed or quantified. The dependencies of the ELS on other subsystems have been identified, but the impact of these dependencies on the overall system-level architecture has not been quantified.

Effectiveness in Developing and Transitioning: Yellow Flag

The risks associated with the potential inability of the ELS project to achieve TRL 6 by the dates needed for the Constellation Program were not articulated. In some areas, funding limitations are highly likely to lead to a level of maturity lower than that required for successful infusion into the vehicles. The required maturity level needs to be established on the basis of Constellation requirements rather than of "available funding" or "customer negotiations," as stated in the project's technology transition plan.

The overriding issue is the timely maturation and qualification of the technologies for infusion into the various vehicles with an acceptable level of adverse impact on the vehicle configuration in terms of mass, power, consumables, or CONOPS in terms of heat rejection requirements, reduced resupply, hygiene and housekeeping, and crew time.

Alignment with the Vision for Space Exploration: Yellow Flag

ELS technologies will clearly have major impacts on risk mitigation for long-duration missions such as the lunar outpost missions and Mars missions. The extensibility of the ELS project to Mars missions, CONOPS on the surface of the Moon or Mars, and specific planetary protocols regarding matters such as atmospheric pollution were not explained or presented to the committee even though "Moon as a Test Bed for Mars" and "Planetary Protection" were listed as benefits of the ELS project. Consequently, the alignment of the ELS project with the

VSE is tenuous at best, and little information was provided relative to the additional risks associated with longer-term missions.

15 ADVANCED ENVIRONMENTAL MONITORING AND CONTROL

Objective

The goal of the Advanced Environmental Monitoring and Control project is to develop and provide environmental monitoring and control systems for future crewed NASA vehicles and lunar habitats. As part of that development, the project will take advantage of testbed opportunities such as the ISS to gain knowledge and experience with respect to the operation of monitoring and control in space and to use that knowledge and experience to reduce risk. Four specific project elements were reviewed: the Vehicle Cabin Atmosphere Monitor (VCAM), Electronic Nose (ENose), Colorimetric Solid Phase Extraction (CSPE), and Lab-on-a-Chip Application Development (LOCAD).

Status

JPL is developing and will qualify and deliver in late 2008 the VCAM, an air-quality monitoring analytical instrument capable of measuring both targeted and unknown trace gases at parts-per-million to parts-per-billion levels. The Laboratory Standard version of the VCAM is being tested on the ground, detecting simulated mixtures of what would be seen in flight, and it is currently at TRL 5. The VCAM will be operated autonomously once a day, and its measurements of species identities and concentrations will be telemetered to the ground. The project team has been implementing a modular, staged approach, starting with the mass spectrometer for the CEV, then adding the gas chromatograph for the CEV/Lunar Lander Vehicle, then, finally, a full system for lunar outpost and Mars missions.

The ENose uses an array of semiselective chemical sensors. The response of the array can be considered a “fingerprint,” which is deconvolved for both identification and quantification. The device, which NASA stated is at TRL 6 regarding its application to the ISS, runs continuously and autonomously.

The CSPE instrument is currently designed to monitor trace analytes in drinking water; its goals address the needs of the space program for analytical instruments and methodologies that (1) meet the monitoring requirements of ISS and space shuttle missions, (2) acquire the analytical data necessary for further defining the critical monitoring requirements for crew health and safety in future missions, and (3) serve as a platform for the development of the analytical methods and ancillary hardware for the projected monitoring requirements for the lunar, Mars, and other VSE missions. The status of the CSPE instrument, according to NASA, is TRL 4+, and it has already been used in microgravity testing.

The LOCAD integrates microfluidics and microarray technology to assess microorganisms, initially on ISS surfaces and later on future crewed missions. The LOCAD team and its partners are developing chips and a handheld unit to perform the analyses. The LOCAD Portable Test System will be used by the crew to perform rapid (within minutes) assessments, and the results will be compared with those of the commonly employed method of plate culturing (~3 days for analysis). Cartridges for gram-negative bacteria are already onboard ISS, and work is currently being done to send up cartridges for the detection of yeast and mold and for gram-positive bacteria. This will allow for a complete characterization of the ISS microbial environment. Work is also underway to develop more advanced readers and swabbing tools to better meet future Constellation needs. At the same time, the LOCAD team is having discussions with the exploration medical research community and other Constellation projects to further define requirements for technology development.

Ratings

Quality: Green Flag for All Project Elements Except LOCAD; Red Flag for LOCAD

No new science is being proposed or discovered on the VCAM; it is an instrumentation effort. The work at the JPL is based on previous flight-qualified instrumentation. The VCAM team is well qualified and understands how to tailor the instrument to meet NASA's deliverables. The ENose team is experienced and qualified, but external experts and field trials would very likely strengthen the team and provide confidence in its performance. The CSPE project element has a sufficiently broad, non-NASA-based team, with all the capabilities that are needed. It uses a conceptually straightforward approach to monitoring trace chemicals in drinking water. It is largely an instrumentation engineering problem, and the team has implemented an approach that has produced prototypes that are physically robust, including testing in short-duration microgravity use aboard a C-9 aircraft.

Regarding the LOCAD, application of microfluidics to microbial assays is not a new concept. NASA would have done much better investing in existing industry-developed microbial detection and identification technologies rather than spending so many of its resources internally. As a general remark, the committee believes that the entire LOCAD element would benefit from external peer review, both for the process of rewarding R&D funds and for reviews of ongoing projects. While the definition of a red flag does not apply, strictly speaking, to this case in that the success of the mission has not been threatened, the committee believes that the project as presented was far behind the state of the art.

Effectiveness in Developing and Transitioning: Green Flag for All Projects Except LOCAD; Red Flag for LOCAD

The VCAM project element is staged, as described above, and can fall back to a lower-performance version with fewer modules if full integration of all three modules proves to be intractable for a flight-qualified system. JPL has delivered flight-qualified instruments to NASA in the past, but this system is more complicated. Previous generations of the ENose have been flown, and performance continues to improve. No particular risks were noted by the committee, but non-NASA research in this field should be evaluated for possible improvements to the NASA instrument. The CSPE project element is expected to be at TRL 6 by August 2009. Prototypes that have been designed and operated have performed well.

Because the LOCAD team did not involve external members who were working at the state of the art, insufficient time remains for incorporating state-of-the-art assays and technologies. The implementation path, thus far, is deficient. While strictly speaking the definition of a red flag does not apply to this case in that the success of the mission has not been threatened, the committee believed that the project element could have been significantly better accomplished and at lower cost if industry expertise had been incorporated at an early stage.

Alignment with the Vision for Space Exploration: Green Flag

If integration of the VCAM modules is successful and able to distinguish methanol from atmospheric oxygen, it could possibly replace the volatile organic monitor and the Analyzing Interferometer for Ambient Air. Certain lifetime issues will have to be addressed if use on a Mars mission is considered. The ENose, if it were coupled well to the VCAM, could replace larger, heavier units. Any crewed mission would in principle benefit from such a continuously operating, sensitive event detector. The CSPE project element has value and usefulness for maintaining astronaut health, independent of flight architecture for crewed missions. The LOCAD is a valid concept, and its development will be beneficial to the VSE.

16 FIRE PREVENTION, DETECTION, AND SUPPRESSION

Objective

In support of the VSE, NASA has launched a Fire Prevention, Detection, and Suppression (FPDS) project with the objective of developing "technologies that will ensure crew health and safety on exploration missions by (1) reducing the likelihood of a fire, or (2) if one does occur, minimizing the risk to the crew, mission, or system."[6]

---

[6] National Aeronautics and Space Administration, *Fire Prevention, Detection, and Suppression Project Plan*, Exploration Technology Development Program, Advanced Capabilities Division, Exploration Systems Mission Directorate, Document No. FPDS-PLN-001, Version 2.0, NASA Langley Research Center, November 26, 2007, p. 10.

The FPDS project is aimed at determining the flammability of proposed materials in exploration-type environments, developing advanced fire detection systems capable of making measurements of low-gravity fire signatures (e.g., Smoke Aerosol Measurement Experiment, SAME), developing models of smoke dispersion in an exploration-type environment, and developing fire extinguishers (e.g., the portable, fine-water mist fire extinguisher).

Status

NASA has long had requirements and conducted research relating to the prevention, detection, and suppression of fires. The Apollo 1 fire was a dramatic reminder of the dangers of fire around spacecraft. More recently, the Russians had a potentially catastrophic fire aboard their Mir Space Station.

NASA's plan is focused on the three major elements: prevention, detection, and suppression. A multi-organizational team (including universities) is involved in this project. SBIR grants are being leveraged in the development of technologies such as the portable, fine-water mist fire extinguisher.

Regarding fire prevention, NASA has a flammability test that materials must pass. If a material does not pass "Test 1" (upward flame spread test), the material must undergo additional testing or be reviewed by materials and processes personnel. Moreover, NASA strives to minimize ignition sources.

The current fire detection system on the ISS employs smoke detectors based on photoelectric technology, positioned near air return vents. To extinguish fires, the ISS has carbon dioxide fire extinguishers. For the Constellation Program, the requirement is that exploration vehicles (e.g., Crew Exploration Vehicle, Lunar Lander, and Outpost) have fire detection and suppression capability. NASA has identified gaps in knowledge about fire propagation, detection, and suppression in low-gravity environments.

This project performs applied research on reducing the risk of fire in a zero-gravity or less than 1-gravity environment. Most of the work is to determine the flammability of materials in these environments and to detect fire.

Some activity was dedicated to suppression. Most of the activity was directed at the space transportation element of the exploration program, microgravity, with a minor amount focused on the Moon or Mars environments.

This project includes substantial cooperation with non-NASA organizations, including the Naval Research Laboratory, the National Institute of Standards and Technology, the Colorado School of Mines, Ohio State University, Case Western Reserve, and several contractors. Contacts with the U.S. Nuclear Regulatory Commission and the U.S. Air Force might prove useful. There is not a competitive industry for this research outside NASA. However, the certification of materials to characterize their ability to fly in space is conducted at MSFC and at the White Sands Missile Range. It was stated that neither MSFC nor the White Sands Missile Range performs the technology development tasks that the FPDS project at GRC does.

Ratings

Quality: Green Flag

The FPDS project is a reasonably well balanced and appropriately funded program at present, but the proposed future funding profile does not bode well for its continuance. The members of the team are very seasoned and experienced.

While, like every effort, the project is fiscally restrained from doing all that the project team would like to do, the team is making significant contributions and the facilities available seem adequate for the task.

Effectiveness in Developing and Transitioning: Yellow Flag

The GRC team identified potential problems in having sufficient personnel to properly infuse the technology developed if skilled machinists continue to be focused on other activities (e.g., Ares I project). While progress on the research is being made, declining budgets will eventually diminish overall results and lead to a loss of experienced personnel. In particular, there will be a loss of funding in 2013, just when some Exploration systems will be coming online. Moreover, it was reported that no fire suppression research is currently being funded.

Alignment with the Vision for Space Exploration: Green Flag

The FPDS project is well connected to its customers because fire prevention, detection, and suppression will remain important subjects in all missions envisioned in the VSE. However, the technology is not highly rated on the needs scale because it has already been pursued for several years on the space shuttle and the ISS, and the knowledge is advanced. This work seems to entail an ongoing process that incrementally adds to the knowledge base with no critical point at which it must be completed.

Due to the emphasis on the zero- and low-gravity nature of the application, this is a "NASA-only" technology with no outside effort, except for NASA contracts, to sustain it. It is a pay-as-you-go activity that primarily serves only one mission: human spaceflight.

17 EXTRAVEHICULAR ACTIVITY TECHNOLOGIES

Objective

The capability for humans to work on the lunar surface is a required component of the lunar mission architecture. EVA technologies, including life support systems, suit materials, anthropometric optimization, power systems, and data systems, are critical technologies that will enable humans to walk and work on the surface of the Moon and Mars. The Constellation Program EVA Systems project, in conjunction with the ETDP, will develop these required technologies, which will be grouped by the following suit systems: Pressure Garment; Life Support; and Power, Communications, Avionics, and Informatics (PCAI) systems.

Status

Presentations to the committee on the EVA suit technology deferred critical systems, such as the Pressure Garment, to the Constellation Program with no clear identification of the developers, the state of research, the responsible party for final oversight of the system, the TRL of the integrated system, risk assessment, and so on. There did not appear to be an adequate transfer of decades of knowledge and operational-technical experience into the new suit development with respect to the relationship between anthropometric design and scaling of systems. For example, without the periodic exchange of this information, it is possible that the independent design of the subsystems could drive the anthropometric design of the suit, rather than the human operational requirements, or that there could be other incompatibilities, thereby significantly degrading both lunar and Mars surface operations. Additionally, the involvement of low-TRL research from universities seemed largely absent.

Ratings

Quality: Yellow Flag

All the elements of the EVA Technologies project have appropriate utility, and the objectives are well understood. The project team has a good mix of experience and energy, and the enthusiasm for the effort points to good execution. Very few breakthrough technologies or innovations were considered or presented to the committee. The following comments are made with regard to various subprojects:

- The packaging effort for the Portable Life Support System (PLSS) should seek expertise in penetration and shock protection that exists outside NASA—a physical test-based program by itself will not achieve the packaging and weight-reduction goals. Collaboration with ergonomic and human factors experts would sharpen the weight reduction goals.
- Suit Water Membrane Evaporator technology is developed from previous NASA research and is sound, but it offers no breakthroughs.
- Rapid Cycle Amine: there is a need for better understanding of toxicity issues.

- Metabolic Temperature Swing Absorption was identified through a competitive procurement process. Company independent research and development funds have taken this technology to a TRL of 3. It is questionable whether this project element can be developed mainly through SBIR funding.
- The utility of the variable-pressure regulator is very novel and useful for the VSE, a great innovation. The current plan seems achievable, but this was one of the lowest TRL elements shown.
- The communications radiation-hardening effort would benefit from increased contacts with industry and the DOD laboratories to achieve its goals.
- The PCAI team has developed useful contacts with the DOD in the areas of audio communications, batteries, displays, and speech recognition that should prove beneficial.

Effectiveness in Developing and Transitioning: Yellow Flag

Resource limitations and disparate development organizations (not identified on a single project element chart) negatively impact the EVA Technologies project. An integrated EVA team (PLSS and suit) would focus goals and result in better alignment than that achieved by the current, arbitrarily separated pressure suit effort. The lack of long-term funding and an unclear alignment between the ETDP, the Constellation Program, and the Space and Life Sciences Directorate at JSC that defines the human risks and suit design requirements present a substantial risk to this critical element of future planetary surface exploration effort. No new technologies or design concepts to mitigate the locomotion and mobility issues that will arise during lunar and Mars surface exploration missions were apparent during the committee’s visit to the EVA Suit Laboratory. There was no new materials or systems research presented to address the significant abrasion and dust mitigation problems that will be encountered in the lunar regolith or on the surface of Mars. An environmental facility simulating as closely as possible lunar and/or Mars conditions, including the abrasive lunar regolith or martian soils, could lead to a significant reduction in the risks associated with long-term exploration on the surface of the Moon.

Gaps in the efforts include (1) a fully nested analysis effort to optimize the protection, weight, and sizing of the PLSS; (2) incorporation of radiation protection within the suit elements; (3) identification of new heat-rejection technologies, including both passive and active systems such as new materials for the suit, new phase-change materials, and alternative designs for the present cooling garment; (4) lack of obvious integration of the anthropometric requirements for crew selection with the anthropometric optimization of suit design (relevant HRP risks and lessons learned from past programs using either custom suits, one size fits all, or a small selection of standard sizes should be shared with designers starting at TRL 1); and (5) consideration for integrating advanced technologies into the overall system, rather than relying solely on incremental improvements. In addition, a study of the recent request for proposals (RFP) for the new Constellation suit indicates that the effort will be directed to a single suit for Earth launch to orbit, EVA on orbit, and lunar planetary operations. The RFP further stated that the contractor selected would not be required to initiate new technology research but would be expected to increase the TRL level of NASA-initiated research. This new suit may require research and technologies that are not currently identified within the existing program.

Alignment with the Vision for Space Exploration: Yellow Flag

The benefit of EVA systems is obvious within the VSE; not providing the enabling EVA systems on time and within requirements will jeopardize mission success. The current effort is directed toward general EVA and Lunar Surface Operations. However, the current program and the EVA suit RFP mentioned above explicitly excluded development of a suit for use on the surface of Mars.

18 INTERNATIONAL SPACE STATION RESEARCH

Objective

The International Space Station research project is broadly divided into two elements: direct exploration support and more general microgravity/radiation research. Both elements span the physical and life sciences.

The goal of the exploration element is to employ the ISS as a low-TRL testbed to bring technologies to higher TRLs in the areas of life support, fire safety, power, propulsion, thermal management, material technology, habitat design, and so on.

The goal of the non-exploration element is to sustain U.S. scientific expertise and research capabilities in fundamental microgravity research, primarily in the life and physical sciences. The U.S. Congress mandated the allocation of at least 15 percent of ISS research to ground-based, free-flier, and ISS life and microgravity science research that is not directly related to supporting the human exploration program.

Status

Nearly all exploration-related tasks are research projects onboard the ISS, with a few being ground-based research. All currently funded tasks are carryovers from the original ISS program with a budget that was many times larger in 2005. Some are onboard ISS and some are scheduled to be delivered by the space shuttle or Soyuz up to early 2009. NASA's briefing charts indicate a funding profile of one U.S. research experiment per rack every 2 years.

Ratings

Quality: Green Flag

The ISS research projects will support the following test facilities: Microgravity Science Glovebox (On-Orbit), a Fluids and Combustion Facility, and a Materials Science Research Rack in the ISS National Laboratory. The latter two will be launched in the next 2 years. Because they are in use or qualified to be used in the ISS, the test facilities have met the stringent operational and safety requirements imposed by the ISS.

The ISS Research projects have met some of the National Research Council (NRC) recommendations related to the following:

1. Effects of radiation on biological systems,
2. Loss of bone and muscle mass during spaceflight,
3. Psychosocial and behavioral risks of long-term space missions,
4. Individual variability in mitigating a medical/biological risk,
5. Fire safety aboard spacecraft, and
6. Multiphase flow and heat transfer issues in space technology operations.

Four foundational research efforts have relevance to Exploration:

1. Smoke and Aerosol Measurement Experiment to help design a useful spacecraft smoke detector,
2. Microbe by way of virulence in a rodent infection model might be applicable to human spaceflight,
3. Zero Boil Off Tank (ZBOT) Experiment for spacecraft tanks, and
4. Vegetable Production Unit (VPU) to study space growth of plant species and their supporting equipments, along with assessment of crew member reactions.

These projects would satisfy NRC recommendations related to items 3, 5, and 6 listed above.

There are 8 other exploration research efforts related to physical sciences including fluid physics and combustion science that are led by university professors and researchers from Glenn Research Center. There are 17 other non-exploratory efforts related to physical sciences including fluid physics, combustion sciences, material sciences, and acceleration environment characterization. The principal investigators are mostly university professors. The quality of the research is considered to be very good and is presumed to have been subjected to the NASA peer review process.

Effectiveness in Developing and Transitioning: Yellow Flag

Since most experiments are performed on the ISS in a microgravity environment, they cannot address the fractional gravity application on lunar or Mars surfaces. They can, however, address technology needs for the vehicle transit, assuming a constant microgravity environment. It should be noted that since the Cryogenic Fluid Management project in ETDP cannot validate its technology in microgravity or fractional gravity owing to project costs and schedule requirements, it may not be able to use results from the ISS experiments to support the Constellation Program's development. This is an example of a disconnect or gap that exists between the ISS research and ETDP's customers.

Before each project is launched to the ISS, it has to be assigned a manifest position in the shuttle or the Soyuz cargo manifest. Months of integration are also required before each flight. Therefore, the committee assigned a yellow flag to most of these ISS research projects because it appears that they cannot meet the schedule requirements of the ETDP. The ISS collection of experiments is generally at the lower TRL levels, performed primarily by the university community. The transition of results is an indirect one, through conference papers and reports. There appears to be no regular communication between the ISS research project and other ETDP projects.

Alignment with the Vision for Space Exploration: Yellow Flag

The Exploratory Research Program on the ISS consists of projects that are at or below TRL 3. Therefore, they do not yet meet Constellation's needs. The relevancy of such projects is based on endorsement letters from other ETDP projects. The logic is that these research projects may be successfully picked up for further TRL development in future ETDP projects.

However, most projects are carryovers from previous ISS projects and use facilities onboard the ISS. The pool of investigators is from the original ISS research community, and the selection is based on the ISS project's own interpretation of exploration needs rather than the other way around. Thus, there appears to be a gap between research projects and other ETDP customers such as Constellation. Nonetheless, the projects listed above represent valid scientific research and can be considered to align with future Mars Exploration missions, but the possible application of results toward Constellation is not clear. NASA, in general, should continue a robust utilization of the ISS for both scientific and engineering research to support exploration and mitigate risk, and then it should ensure that those experiments ready for transition into either lunar or martian exploration are put on a clear project path for systems integration.

19 IN SITU RESOURCE UTILIZATION

Objective

The basic concept of In Situ Resource Utilization (ISRU) is to extract elements and minerals from the land and/or atmospheric resources that are present on the Moon and Mars. The idea of "living off the land" has been investigated for the past two decades. The proposed benefits argue that each kilogram of material that is produced on the Moon or Mars saves funds, launch mass, acquisition time, and payload volume. At roughly $100,000 per kilogram to put material on the Moon, these savings have been shown to be considerable. In addition, by producing needed materials at the base, the crew has an increased chance of dealing with unforeseen emergencies.

The near-term goal is to produce oxygen from lunar regolith for life support at about 1 metric ton per year. The midrange goal is to produce about 10 metric tons per year to refuel the propellant tanks on the ascent vehicle. The long-range goal is to use the extracted metals for fabrication of parts.

Status

The ISRU project will demonstrate regolith excavation and transport by both large and small rovers in analog environments. Oxygen production from regolith is to be demonstrated on the scale of an outpost-scaled plant. A precursor demonstration is being developed. It is hoped that this demonstration can be flown through a partnership with Europe, Japan, or India. There is also some support work, in the form of modeling, regolith simulant development, and facility identification. There are some collaborative programs with the Canadian and Japanese space agencies, and limited procurements from industry and academia.

Ratings

Quality: Green Flag

The various elements of the ISRU project appear to have high quality in both development path layout and the knowledge and abilities of the participants. The project has made good use of the expertise at all relevant NASA research centers and works in a well-coordinated manner. This project has also involved several universities and a few industries. The ISRU technology roadmap is closely linked to the NASA Science Mission Directorate and has a good link to NASA's life support development activities. However, the planning between the NASA Exploration Systems Mission Directorate's Lunar Lander Project Office and the ISRU activities is not currently well coordinated enough.

According to the NASA presenters, the TRLs of most of the elements of the ISRU project are about 3, with some concepts around 2. The effort could benefit from the involvement of more universities and others in investigating new concepts at TRLs of 1 or 2.

An important issue to be resolved is whether the implementation of the equipment needed to produce materials from the lunar regolith would cost more than the savings offered by producing the material on-site.

To the extent possible, the project has taken full advantage of related non-NASA work in an ancillary manner—that is, not as part of the critical path to achieving the project's goals. An example is the project's drawing on advances in mining technology developed by the Canadians.

Effectiveness in Developing and Transitioning: Red Flag

The risks in achieving the ISRU project's goals are very high due to insufficient resources: SBIR support will not solve this problem within the necessary time frame for implementation, and relying on foreign partners to maintain this project is problematic. In addition, this project is different from most of the ETDP projects as it has no Apollo experience to build on, and without another application in a commercial market there is no non-NASA entity to develop the technology.

The committee has identified three technology gaps that inhibit the effectiveness of the ISRU project:

1. *High-fidelity lunar environment testbed.* The lunar environment is a hard vacuum, has large temperature swings, is very dry, and possesses a layer of fine, abrasive dust. All of these conditions may strongly impact the performance or lifetime of robotic systems, mobile transports, heat radiators, and human respiration. Except for gravity, these conditions can be duplicated on Earth to validate the performance of candidate systems and operations. In addition to environmental testing, there are currently technology gaps due to funding limitations in lunar soil stabilization studies and operations/control software for startup/operation/shutdown in the low gravity, vacuum, dust, and lunar thermal cycles. NASA's program lacks a facility that duplicates the dusty environment, vacuum, and thermal cycles of the Moon. Without such testing, no quantification of lifetime margins is possible.
2. *Repairs versus spares.* Historically, missions have been of short duration so that systems and components were not expected to break down during the missions; consequently, technology was not pushed to extend reliability. For long-duration missions, however, breakages are inevitable. One solution is to take along an inventory of spare parts. However, this is mass-intensive, and no inventory can be exhaustive. The alternative is to "take the tools, not the parts." Advances in rapid prototyping have produced commercially available machines that can produce parts of a complicated, three-dimensional nature, given power and an electronic file describing the object. The downside of this approach is a higher power requirement and the need to carry the necessary feed materials, furnaces, and so on. However, if a "power rich" approach is part of the architecture, this is readily accommodated. An assessment of the potential benefits of rapid prototyping of spare parts needs to be included.

Studies of trade offs, which must take into account the additional mass associated with the tools, may suggest an optimal solution.

3. *Robotic precursor missions to the Moon prior to human landing.* Every kilogram of equipment taken to the lunar surface needs to perform for as long as practical while remaining cost-effective. Although the surface conditions can be closely approximated, no simulation can totally mimic the lunar environment. NASA has no current plans to fund an ISRU precursor demonstration; a precursor mission is dependent on an opportunity with one of NASA's international partners.

Alignment with the Vision for Space Exploration: Green Flag

The benefits of the ISRU project to both lunar and Mars exploration are well aligned with the goals of the VSE because this technology can dramatically improve the probability of successfully achieving lunar and Mars mission goals. The performance benefit of consumables production on the surface allows an extended science mission for the VSE, not simply a quick visit. This research project is unique in the world; no other country at present is known to be seriously developing technologies for ISRU.

20 FISSION SURFACE POWER

Objective

The objective of ETDP's Fission Surface Power (FSP) systems project is to develop an FSP system concept that meets surface power requirements, including the periodic recharging of long-duration portable power sources, at reasonable cost with added benefits over competitive alternatives. To achieve this objective, NASA has organized a joint NASA and DOE team with representatives from NASA's GRC and MSFC and DOE's Idaho National Laboratory, Los Alamos National Laboratory (LANL), Oak Ridge National Laboratory, and Sandia National Laboratories. In addition, NASA and DOE have involved industrial teams (e.g., Lockheed Martin and Pratt & Whitney Rocketdyne) and universities in their studies. The initial focus is on providing a 40-kWe nuclear reactor that could power the proposed Shackleton lunar base and provide the added assurance that such a concept could also be used to power a Mars base. The FSP concept is at a fairly high TRL, which should reduce both the risk and the cost of developing it.

Status

If NASA chooses FSP as its source of electrical power, the 40 kWe reactor would be designed to operate for at least 8 years at full power within the mass envelope of the Lunar Surface Access Module and could be used at any location on the Moon. Shielding would be provided by the lunar regolith, that is, inserting the reactor in a pre-excavated hole and adding upper plug shielding.

The reactor would use uranium dioxide fuel and Type 316 stainless steel (SS-316) cladding. Both of these materials have been used in terrestrial reactors. The coolant would be a eutectic of sodium and potassium referred to as "NaK." This coolant has also been used in terrestrial reactors. For the power conversion system, NASA is proposing to use Stirling power conversion, a technology that NASA has been studying in various technological forms for about 20 years. A backup power conversion option is Brayton technology, building on what was developed for the proposed Jupiter Icy Moons Orbiter (JIMO) nuclear power system.

Ratings

Quality: Green

Historically NASA and the DOE have been the leaders in space nuclear power, and that continues to be the case now. There is no evidence that international entities will enter this field within the schedule envisioned for the VSE, although it is pointed out that the Russians have or did have space nuclear reactor experience. Given that this project is driven by the VSE and therefore concentrates on relatively small-scale reactors in which there is no obvious commercial interest, it is very doubtful that any non-NASA, non-DOE sources will develop a competing or alternative technology that NASA could use for this purpose.

The project team in place is composed of NASA and DOE personnel who are working well together, and some of the members have worked on previous space nuclear reactor programs (e.g., SP-100 space nuclear reactor power system and JIMO) so they have experience in the field. The members do not have flight experience because the United States has not flown a fission reactor since 1965, nor do they have experience in burying fission reactors on the Moon; both skills will have to be learned.

The FSP Systems project plan, as presented to the committee, lacked detailed specificity on the organizational interactions—for example, the structure of the DOE interrelationships. No lead DOE laboratory was identified. The details of NASA's interaction with the DOE laboratories were not specified.

Effectiveness in Developing and Transitioning: Yellow Flag

The FSP Systems project's technology roadmap envisions an interactive combination of concept definition and risk reduction work through FY 2012 to support an FY 2013 awarding of a prime contract to produce the development test models, engineering models, and flight models. Under this plan, NASA estimates that TRL 6 would be achieved by 2012.

The proposed budget profile for this project incurs a large programmatic risk. Jumping from $14 million in 2013 to over $200 million per year in the subsequent years will strain U.S. industrial capabilities. Industry participation in the 2008-2013 period would serve to get industry vested in the project. However, the industrial base for nuclear engineering technologies has shrunk in the past 20 years owing to the standstill in commercial reactor construction, and there is a concern that that situation, coupled with an aging workforce, may mean that the industry may not be able to react to a sudden call in a few years to a NASA program just as the licensing of new commercial reactors appears to be significantly increasing.

In addition, the committee is concerned about the potential consequences resulting from setting 2013 as the proposed date of decision. Other ETDP project teams, such as those for In Situ Resource Utilization, Lunar Dust Mitigation, and Cryogenic Fluid Management, stated that they would change their tasks if they knew that they would have access to 40 kWe rather than the use of the two or three modules of 6 to 10 kWe per module currently envisioned with a photovoltaic system. To wait until 2013 to make this decision may limit much of the work of these projects over the next few years.

A potential gap in the FSP Systems technology development effort is the absence of a full-up ground test unit that incorporates both the nuclear reactor and the power conversion subsystem in a single, integrated unit that could be tested prior to use in an actual mission in the representative environment. The NASA and DOE team considered this option and concluded that it can demonstrate readiness through a combination of component, subsystem, non-nuclear, and zero-power nuclear testing; nonetheless, there is a concern borne out by other space projects that having a full-up ground test unit can allow the identification and correction of unforeseen problems (the "unknown unknowns") and provide confidence that the flight unit will perform as designed. Before committing to the proposed program of no full-up ground test unit, an independent, detailed technical and programmatic review of the project's proposal by NASA and the DOE would be beneficial.

Alignment with the Vision for Space Exploration: Gold Star

The availability of 40 kWe of continuous electrical power during the day and night would have major architectural benefits. Technologists working to develop In Situ Resource Utilization, Lunar Dust Mitigation, and Cryogenic Fluid Management would greatly benefit from the availability of increased electrical power. Obviously, the life support system and science instruments would benefit from more power. This is a critical enabling technology for human exploration of the Moon and Mars. The committee believes that the implementation of fission power of the magnitude considered by NASA would have a profound effect on major aspects of the entire VSE.

21 SUPPORTABILITY

Objective

The basic concept of supportability is to minimize the logistics footprint required to support exploration missions. Strategies to achieve this objective include broad implementation of commonality and standardization at all hardware levels and across all systems: interoperability, repair of failed hardware at the lowest possible hardware level, manufacture of structural and mechanical replacement components as needed, and logistics.

The Supportability project consists of three elements: Component Level Electronic Assembly and Repair, which is further divided into manual repair, semiautomated diagnostics, and functional test and automated repair; Minimally Intrusive Repair, Detection, and Self-Healing Systems; and Smart Coatings. The goals of these elements are to decrease reliance on terrestrial support, reduce the mass volume of logistics spares, increase the operational availability of spacecraft systems, and provide robust, damage-tolerant systems. The benefits of supportability are such that all three tasks presented to the committee were ranked highly by the Constellation Program based on their impact on life-cycle costs. The selected tasks are already defined as either high ranking or as lunar-critical path items.

Status

The Supportability project team appears to have the expertise and innovation to complete the tasks as defined; however, this project seems to be a small subset of the tasks required for a general implementation of supportability. It needs to be expanded, as it appears to be implemented on the basis of specific technology requests as opposed to a systematic look at all the supportability requirements and options. This approach presents a risk that supportability will be available in some areas but not in others.

The Apollo missions to the Moon were of short duration, and systems and components were not expected to break down during the missions—that is, technology was pushed to extend reliability. For long-duration missions, however, component failure is more probable. The issue of the logistics for the accommodation or replacement of damaged or failed parts must be addressed as part of the architecture.

Historically, this problem of reliable operation was addressed by multiply redundant systems, which usually prevented a component failure from leading to system failure. This solution of multiple redundancies may not be practical for large-scale and prolonged operations such as a lunar or Mars base.

Alternatives to long-term reliability include having spare parts available, commonality, and in situ fabrication. A simple approach to long-term reliability is to take along an inventory of spare parts. This may prove impractical for large-scale operations with thousands of parts. In addition, taking spares is mass-intensive and may not work, as the failure of a part may not have been anticipated. Carrying spares for everything is impractical and expensive. An operational alternative is to design commonality between similar parts used in different systems. If there is actual design commonality (e.g., in displays and controls or processor boards), less critical or no longer operating modules can be scavenged to provide components for more critical operating modules. This may reduce the number of spares needed, but it cannot accommodate all possibilities. A possible technological alternative applicable to some types of components is to "take the tools not the parts." Advances in rapid prototyping have produced commercially available machines that can produce final net-shape parts of a complicated, three-dimensional nature. Fabrication of components made of plastic, ceramics, or metals has been demonstrated. While the committee is aware that NASA has a logistics study effort underway in the Constellation Program, the committee believes that NASA should examine the possibility of funding a technology project to examine if new technologies involving physical commonality and rapid prototyping could reduce the future need for having spare parts and the accompanying logistical burden.

The ETDP Supportability project has recognized the issue of component repair and replacement as key to long-term reliability but is focusing primarily on electronic components. Replacement of Earth-fabricated mechanical or structural components is not being examined for long-term sustainability of lunar and Mars missions.

The ETDP could evaluate the applicability of the current state of the art in rapid prototyping equipment to the exploration mission, and then evaluate the balance between system redundancy, design commonality, logistical supply of spare parts fabricated on Earth, and fabricating components on-site using local resources to achieve the best cost and benefits for maintaining a sustainable exploration program. For those components that might feasibly be fabricated on-site and that would provide cost-benefit advantage over other approaches, a low-TRL ETDP technology development program could be initiated.

There is a significant risk that advancing technology will eclipse many aspects of existing avionics systems. A task needs to be added to assess the impact of technology development on projected supportability options. Technologies developing on parallel tracks to electronics for sensing and control include bacteriorhodopsin-based state machines, artificial opal-based state machines, wavelength-routed fault-tolerant all-optical networks, optical sensors (all implemented in circuit or free space radio-frequency or infrared-based wireless networks), and living biological sensing systems based on “smart yeast.” These technologies reduce the need for a substantial amount of electronics and code, eliminate the need for copper wire carrying telemetry in many cases, and are so low in mass that they allow for massive redundancy, thus reducing the need for repair. Other examples are holographic-crystal-based memories and optical correlators for information processing (which would include Integrated Vehicle Health Management including diagnostics and prognostics) standardized microcontrollers, as well as polymer-based electronics and displays that can be manufactured with bubble jet printers.

In addition to developing chemically responsive insulation polymers that heal themselves under a variety of conditions, approaches for detecting and repairing age-related damage to wiring should address techniques that can be carried out autonomously by microrobotics capable of locating faults by chemical detection of self-healed or degraded materials and by the presence and direction of electric fields or the direction of magnetic fields (stored in particles contained in the insulation) generated by a fault. These types of systems could spin polymers to repair insulation and install antichafing at the damage site and similar sites to prevent recurrence.

Ratings

Quality: Green Flag

The various tasks under the Supportability project appear to have high quality in both the development path layout and the knowledge and ability of participants to complete the projects. The TRLs of the projects are in the TRL 2 range, with some concepts advancing to TRL 4 in 2008. This project has many affiliated universities and industries. The effort would likely benefit from the involvement of more universities examining competing concepts.

Effectiveness in Developing and Transitioning: Yellow Flag

The current level of effort limits the effectiveness of the Supportability project in achieving its goals. The risks are very high owing to this problem—the technology is at a low TRL, is specific to particular technologies, and lacks generality.

The technology gaps identified are as follows:

1. Component-Level Electronic Assembly and Repair
    a. Conformal coating on electronic circuit cards is conducive to neither repair nor diagnostics. Technology development is required to produce systems capable of removing and restoring coatings of arbitrary thickness or sensing parameters without disturbing the coatings.
    b. Diagnostics requires multiple types of complex instruments. Methods are required to sense and evaluate signals in such a way that the required information can be generated with a single analysis instrument. An alternative approach is to reduce the mass, power, and volume of the required diagnostic tools to an acceptable value.
2. Minimally Intrusive Repair, Detection, and Self-Healing Systems
    a. Prototype conductive polymeric outer insulation layers are too dissipative to be used for detecting faults due to insulation failure. This is a materials issue that currently prevents fault detection via wire insulation from becoming a reality.

   b. The self-repair process mediated with chemically reactive microsphere fill-in wire insulation generates by-products that can accelerate the degradation of wire insulation. This is another materials problem that will require finding a reactive system which produces insulating polymers with the correct properties but no problematic by-products.
3. Smart Coatings
   a. Remote detection of corrosion. A system is required to nondestructively detect corrosion in hidden places without the removal of paint and thermal control/protection systems that may cover the structure. This will require the use of chemical indicators, the release of detectable volatiles, or the exploitation of physical effects such as surface acoustic waves to detect the corrosion. Failure to achieve this capability might result in increased program costs; baselining will need to be carried out to verify this point.
   b. Stabilization of flame deflector refractory coatings. The current method of anchoring the refractory material to the flame deflectors has a poor performance record. Failure to develop more effective methods and materials will result in increased risks to personnel and equipment and costs to the program.

Alignment with the Vision for Space Exploration: Green Flag

The performance benefits from self-sufficiency with respect to maintainability and streamlined logistics will enable cost reductions in implementing both lunar and Mars exploration and thus the Supportability project work is well aligned with the VSE.

22 HUMAN-ROBOTIC SYSTEMS/ANALOGS

Objective

The main effort of the Human-Robotic Systems/Analogs project concentrates on reconfigurable, long-range robot vehicles and supporting technologies. This enables In Situ Resource Utilization (the unloading of the lander, the assembly/maintenance/transfer of the lunar base, longer range and longer duration of basic science investigations) and complements and/or augments astronaut safety and productivity. The plan is novel (it is unlike that used for Apollo) and aggressive (it is based around technologies not yet flown), but it appears feasible, and if it is successful it will not only enable the current Constellation Program architecture but will also significantly enhance it.

Status

The basic plan to coordinate the Human-Robotic Systems/Analogs project appears solid and seems to include all relevant expertise within NASA. The team has some outstanding individual members and groups, particularly at JSC in systems design and integration, at JPL in rover and vehicle development, and at ARC in software. It is not clear, however, that the members at the other NASA field centers in the plan add significantly to the effort. The NASA team stated that the technology is generally at TRL 4; it needs to be advanced to TRL 6. NASA appears to be planning to conduct almost all of the effort in-house. By ignoring external expertise, this approach may not produce the highest-quality or even the best-value product possible. The claim is that the team could not be strengthened without additional funding. However, it seems likely that the replacement of several existing components of the current team by external experts might well produce significantly superior results.

Ratings

Quality: Green Flag

In contrast to its position in some other ETDP task areas, NASA is not the international benchmark in this technical area (robotics and human-machine systems). While the NASA team has some outstanding individuals and the project leads are aware of the wider national and international research community, apart from a few small existing grants it appears that the strategy is to "go it alone." While NASA is the clear world leader in planetary rovers and extraterrestrial vehicles and in some aspects of time-delayed teleoperation, the leading expertise in many of the other key technologies for this task lie outside NASA. It appears that the effort could benefit from a wider involvement of experts in academia and industry. However, the committee believes that the team could achieve the objectives and that it is a matter of how well or how cost-effectively the objectives would be achieved.

Effectiveness in Developing and Transitioning: Yellow Flag

Facilities to mature some ground-based aspects of the Human/Robotic Systems/Analogs technology are in place. However, NASA will need to provide significant additional resources if the developed technologies are to be tested in relevant environments, including in-orbit and realistic lunar environment testing. NASA seeks to transition the technology through analog testing, which integrates the testing of multiple subsystems among nine potential test sites. Analog field testing is designed to help identify technology gaps for future systems and to develop requirements for operational concepts. Detailed planning is needed to ensure that the 5-year notional plan on research and technology (RAT) studies can enable the Human/Robotic supporting technologies to achieve the desired TRLs and to ensure that these studies are relevant for all lunar considerations. (RAT studies are performed by a combined group formed of inter-NASA center personnel, collaborating with representatives of industry and academia, to conduct remote field exercises.)

The main risks for meeting the current plan and schedule appear to be budgetary. This effort appears underfunded in the next 5 years or so. While the basic technology concept appears solid, significant costs are likely to arise in development and (particularly) in testing. If NASA does not make the commitment to meet these costs, the deadlines will almost certainly slip, and the effort could fail.

Alignment with the Vision for Space Exploration: Green Flag

The Human/Robotic technology has significant architectural benefits. It enables lower costs by employing a significantly higher percentage of lander mass in in situ operations (more of the landed mass is part of the lunar vehicles). It enables higher payload capability and lower operational risks (the lunar vehicles will robotically handle/transport/assemble high-mass and high-risk components). The technology has significant performance benefits. It enables longer and more distant (from the lunar base) missions (autonomously and with astronauts). It offers the possibility of transporting the entire lunar operation across the lunar surface, to access significantly more sites of scientific interest. The technology is generally robust to changes to the architecture (for example, exploration missions to Mars). The main issue preventing direct transfer to Mars missions is the longer time delay, which would prevent the proposed ground-based control mode for some of the robotic operations.

FINDING AND RECOMMENDATION ON ETDP PROJECTS

Consistent with its statement of task, the committee evaluated each of the 22 ETDP projects on the basis of the following:

1. The quality of the research effort, taking into account the research team, contacts with appropriate non-NASA entities, and the plan for achieving the objectives;
2. The effectiveness with which the research is carried out and transitioned to the exploration program, including progress to date, facilities, apparent gaps in the program, and the likelihood that the required TRL will be reached (the committee decided that simply noting gaps, as requested in the study task, was too narrow an objective and that gauging "effectiveness," as defined here, was more appropriate and inclusive); and
3. The degree to which the research is aligned with the VSE, specifically, the degree to which the program included exploration beyond the Moon.

Finding on Projects: The committee evaluated the 22 individual ETDP projects and rated the quality of the research, the effectiveness with which the research is carried out and transitioned to the exploration program, and the degree to which the research is aligned with the Vision for Space Exploration. The committee found that, with two exceptions, each project had areas that could be improved.

In each of these three areas, the committee rated the projects using a flag whose color represents the committee's consensus view. These ratings are indicated in the descriptions of the individual projects above and are summarized in Table 2.2. A few projects were given two flag colors owing to major distinctions between elements within a given topic.

Recommendation on Projects: Managers in the Exploration Systems Mission Directorate and Exploration Technology Development Program should review and carefully consider the committee's ratings of the individual ETDP projects and should develop and implement a plan to improve each project to a level that would be rated by a subsequent review as demonstrating "appropriate capabilities and quality, accomplishment, and plan" (green flag).

TABLE 2.2 Summary of the Committee's Ratings for Each ETDP Project with Regard to Quality, Effectiveness in Developing and Transitioning Technology, and Alignment with the Vision for Space Exploration

Project Name	Quality	Effectiveness	Alignment
1 Structures, Materials, and Mechanisms	🟨	🟨	🟨
2 Ablative Thermal Protection System	🟨	🟨	🟨
3 Lunar Dust Mitigation	🟩	🟥	🟨
4 Propulsion and Cryogenics	🟩	🟩	🟩
5 Cryogenic Fluid Management	🟨	🟨	🟨
6 Energy Storage	🟩 🟨	🟩 🟨	🟩
7 Thermal Control Systems	🟨	🟩	🟨
8 High-Performance and Radiation-Hardened Electronics	🟨	🟨	🟩
9 Integrated Systems Health Management	🟩	🟨	🟩
10 Autonomy for Operations	🟨	🟨	🟩
11 Intelligent Software Design	🟩	🟨	🟩
12 Autonomous Landing and Hazard Avoidance	⭐	🟩	🟩
13 Automated Rendezvous and Docking Sensors	🟨	🟨	🟨
14 Exploration Life Support	🟨	🟨	🟨
15 Advanced Environmental Monitoring and Control	🟩 🟥	🟩 🟥	🟩
16 Fire Prevention, Detection, and Suppression	🟩	🟨	🟩
17 Extravehicular Activity Technologies	🟨	🟨	🟨
18 International Space Station Research	🟩	🟨	🟨
19 In Situ Resource Utilization	🟩	🟥	🟩
20 Fission Surface Power	🟩	🟨	⭐
21 Supportability	🟩	🟨	🟩
22 Human Robotic Systems/Analogs	🟩	🟨	🟩
Totals			
Gold star	1	0	1
Green flag	12	5	12
Yellow flag	10	16	9
Red flag	1	3	0

Key:

⭐ Gold star: Quality unmatched in the world; on track to deliver or exceed expectations.
🟩 Green flag: Appropriate capabilities and quality, accomplishment, and plan. No significant issues identified.
🟨 Yellow flag: May contain risks to project/program. Close attention or remedial action may be warranted.
🟥 Red flag: This area threatens the success of the project/program. Remedial action is required.

NOTE: A few projects were given two ratings because of major distinctions between elements within a given project.

3

Gaps in the Scope of the Exploration Technology Development Program

The Exploration Technology Development Program (ETDP) is the successor of the human and crosscutting space technology and advanced development programs that have been a part of NASA since its creation. At this time, the ETDP is the primary broad-based space technology program in the agency. Other, historically smaller programs that have existed alongside the general space technology program have either a specific focus or limited funding mechanisms. These include the programs developing technology for science missions in the Science Mission Directorate, space communications technology in the Space Operations Mission Directorate, and hypersonic reentry technology in the Aeronautics Research Mission Directorate, as well as the work being done under the Innovative Partnerships Program (which includes the Small Business Innovation Research [SBIR] Program and the Small Business Technology Transfer [STTR] Program). Given its role as the successor of the broad-based space technology program, it is important that the ETDP invest in a representative portfolio of the space technologies needed to continue the nation's leadership in space exploration.

The role of NASA as a developer of space technology is clearly articulated in the agency's governing policy documents. The National Aeronautics and Space Act of 1958 (as amended) calls for NASA to "materially contribute" to "the preservation of the role of the United States as a leader in aeronautical and space science and technology and in the application thereof to the conduct of peaceful activities within and outside the atmosphere." The Vision for Space Exploration (VSE) calls for NASA to "develop the innovative technologies, knowledge, and infrastructures both to explore and to support decisions about the destinations for human exploration."[1]

The ETDP's responsibilities for and burden of husbanding the civil space technology of the nation must be considered in light of these empowering charters and of the fact that the ETDP is the primary space technology program in NASA. Except as noted above (regarding technology for science missions, space communications, hypersonics, and programs fundable as SBIR and STTR), if the ETDP does not support a particular area of space engineering and technology research and development, *there is likely no other NASA-wide program that acts as a source of support for it.*

Two questions are thus pertinent when assessing the scope of the ETDP:

---

[1] The Vision for Space Exploration initiative was announced by President George W. Bush on January 14, 2004, and is outlined in National Aeronautics and Space Administration (NASA), *The Vision for Space Exploration,* NP-2004-01-334-HQ, NASA, Washington, D.C., 2004.

- Do ETDP-funded activities adequately support the development of the elements of the currently envisioned Constellation Program?[2]
- Does ETDP fund a robust program of technology development necessary, as stated in the VSE, "to explore and to support decisions about the destinations for human exploration" and to preserve the "role of the United States as a leader in aeronautical and space science and technology," as stated in the National Aeronautics and Space Act of 1958?

The second of these questions is discussed in Chapter 4; the first is addressed below.

Finding on the Scope of the ETDP: The range of technologies covered in the 22 ETDP projects will, in principle, enable many of the early endeavors currently imagined in NASA's *Exploration Systems Architecture Study* architecture,[3] but not the entire VSE.

However, as discussed below, the committee did identify two gaps in which the ETDP's portfolio could be strengthened: integration of the human system and nuclear thermal propulsion. The first gap represents the interplay of the ETDP and the Human Systems element of the Advanced Capabilities office. The second reflects a historical struggle by NASA to determine the appropriate timing of the development of the potentially beneficial NTP technology and system.

INTEGRATION OF THE HUMAN SYSTEM

During its assessment, the committee observed that the "human system" was generally not systematically considered in the early requirements, research, design definition, testing, and development of the 22 projects of the ETDP. These human-centered health and human factor requirements are well described in two documents: NASA's *Bioastronautics Roadmap*,[4] and the National Research Council's (NRC's) *Safe Passage: Astronaut Care for Exploration Missions*.[5] The requirements are further documented as flow-down requirements for and from the Exploration Systems Mission Directorate (ESMD).[6]

Described in a 2006 NRC study, NASA's Bioastronautics Roadmap is "the framework used to identify and assess the risks of crew exposure to the hazardous environments of space."[7] The Bioastronautics Roadmap was created to facilitate and support the successful accomplishment of the three following design reference missions:

- A one-year mission to the International Space Station,
- A month-long stay on the lunar surface, and
- A 30-month round-trip journey to Mars.

The more recent Human Research Program Requirements Document (HRP-47052)[8] describes six mission scenarios—a short Earth orbital mission; an International Space Station (ISS) 6-month mission; an ISS 12-month mission; a short-duration lunar sortie; a long-duration lunar mission; and a Mars mission—in determining risk

---

[2] See Appendix F for descriptions of the currently envisioned components of the Constellation Program.

[3] National Aeronautics and Space Administration, *Exploration Systems Architecture Study—Final Report*, NASA-TM-2005-214062, NASA, Washington, D.C., November 2005.

[4] See http://bioastroroadmap.nasa.gov. Accessed May 7, 2008.

[5] National Research Council, *Safe Passage: Astronaut Care for Exploration Missions*, National Academy Press, Washington, D.C., 2001.

[6] National Aeronautics and Space Administration, *Human Research Program Requirements Document, Human Research Program,* HRP-47052, Revision A, NASA Johnson Space Center, Houston, Tex., July 2007.

[7] National Research Council, *A Risk Reduction Strategy for Human Exploration of Space: A Review of NASA's Bioastronautics Roadmap*, The National Academies Press, Washington, D.C., 2006, p. 2.

[8] National Aeronautics and Space Administration, *Human Research Program Requirements Document, Human Research Program,* HRP-47052, Revision A, NASA Johnson Space Center, Houston, Tex., July 2007.

assessment and vehicle and systems designs. In both documents, lunar surface operations and martian surface operations are identified as research and development (R&D) design drivers.

Human health and human factor risks are interdependent with spacecraft and extravehicular activity (EVA) system design risks. Changing one risk can have unanticipated consequences on another risk. A classic example of such unanticipated interactions is well illustrated by the interaction between the mitigation of the risk posed for water contamination aboard the NASA orbiters and consequent thyroid dysfunction in crew members. Iodine was used as the bacteriostatic agent in drinking water aboard the U.S. space shuttle orbiters—a seemingly reasonable approach to water purification. However, the concentration of iodine resulted in a daily iodine intake that far exceeded the recommended daily allowance and was sufficient to cause chemical evidence of thyroid dysfunction (e.g., increases in thyroid-stimulating hormone) in many astronauts and clinical hyper- or hypothyroidism in several astronauts.[9]

Finding on Integration of the Human System: The committee did not find a high degree of awareness of the interdependencies between the ETDP technology projects and associated human health risks and human design factor considerations.

In fact, the Bioastronautics Roadmap, the *Safe Passage* study, and HRP-47052 were not clearly identified as guiding requirements in the material presented to the committee. In the period that during which study was conducted, NASA formulated a set of evidence books[10] related to operationally relevant human health risks. The scope of these risks and associated gaps in knowledge that inform R&D programs is currently under review in another NRC study, and the final list of health risks is potentially subject to change. For this reason, reference is made here to the 2005 Bioastronautics Roadmap rather than to the more recent naming and numbering of human health risks. However, the essential linkages between ETDP projects and human health risks outlined here remain valid.

Appendix G shows some of the relationships that exist between various ETDP projects and risks identified in the Bioastronautics Roadmap.

Recommendation 1 on the Human System: ETDP project managers should clearly identify the interrelationships between human health and human factor risks and requirements[11] on the one hand and technology development on the other and should ensure that those risks and requirements are addressed in their project plans. Each ETDP project manager should be able to show clearly where that project fits within the integrated Exploration Systems Mission Directorate Advanced Capabilities Program (which includes the ETDP, the Lunar Precursor Robotic Program, and the Human Research Program), and this integrated program plan should include all elements necessary to achieve the Vision for Space Exploration.

Recommendation 2 on the Human System: Exploration Technology Development Program (ETDP) project managers should systematically include representatives of the Human Research Program on the ETDP technology development teams.

For example, the risks associated with EVA suit anthropometric sizing and motion loads should be introduced to both the NASA and the contractor teams as soon as possible. The committee understands that a contractor to build a common launch/entry, EVA, and lunar surface suit is being selected. If the contractor is not familiar with the risks associated with (1) the past history of ill-fitting suits that degrade crew performance at both ends of the

---

[9] Institute of Medicine, *Review of NASA's Longitudinal Study of Astronaut Health*, The National Academies Press, Washington, D.C., 2004.

[10] National Aeronautics and Space Administration, *Human Research Program Evidence Book*, NASA Johnson Space Center, Houston, Tex., 2008.

[11] As identified in such documents, as appropriate, as NASA, *Human Research Program Requirements Document, Human Research Program*, HRP-47052, Revision A, NASA Johnson Space Center, Houston, Tex., July 2007; NASA, *NASA Space Flight Human Systems Standards*, Volumes I and II, NP-2006-11-448-HQ, Washington, D.C.; and the Risk Mitigation Analysis Tool developed under the direction of Jeffrey R. Davis.

anthropometric spectrum (large and small), (2) the worst-case scenario of the resulting suit design not fitting the anthropometric range of the selected and trained crew population, or (3) the requirement for loads and forces of the suit to accommodate worst-case deconditioned crew members on the surface of the Moon or Mars, or on the ISS, then EVA operations, and therefore mission success, may be significantly compromised.

PRESERVING THE OPTION FOR NUCLEAR THERMAL PROPULSION

A member of NASA's Mars Architecture Working Group study briefed the committee on those activities results during the committee's visit to the Johnson Space Center (JSC). That briefing summarized the trade-offs in technologies that had been considered for a human mission to Mars. For propulsion, the propulsion system selected was nuclear thermal propulsion (NTP). This choice is consistent with advice given in previous Mars mission architecture studies.[12,13]

In 2005, an NRC committee reported on its examination of the potential benefits of a nuclear thermal rocket (NTR) to enhance uncrewed exploration of the outer solar system and for human exploration:

> *Finding:* Nuclear propulsion technologies will likely be used initially for moving relatively large scientific payloads (~1,000s kg) to destinations in the outer solar system and beyond and extremely large payloads (~10,000s kg) in support of human exploration activities in the inner solar system. But it is necessary to investigate nuclear propulsion technologies more thoroughly to determine if they can provide fast, affordable access to the outer solar system and beyond and can move large payloads in the inner solar system cost-effectively and efficiently.[14]

The basic feasibility of the NTR was demonstrated in the Rover and the Nuclear Engine for Rocket Vehicle Applications (NERVA) programs in the 1960s, which tested an integrated engine/stage system to TRL 6. Because of its high performance, the NTR offers the potential of reduced mass in orbit (one-half to one-third that of chemically propelled systems), freedom from the need to develop aerobraking/aerocapture technologies for Mars, and the option of executing opposition-class missions with a stay on the surface that might extend to a few months. Total round-trip times of less than 500 days are possible for spacecraft that have an initial mass in low Earth orbit equivalent to those of chemically propelled missions lasting 900 days. Shorter trip times translate into reduced radiation doses from cosmic rays, microgravity effects, and psychological stresses associated with being confined in a spacecraft for months at a time.

The NERVA engines used fuels clad in graphite that had a tendency to crack, erode, and leak fission products into the exhaust. Such performance is not acceptable in today's environment. However, one of the alternative fuel forms investigated in the 1960s, tungsten loaded with uranium dioxide, demonstrated the ability to retain radioactivity and did not lead to cracking or to erosion due to thermal loading under the hydrogen flow conditions. Thus, the major issue for fuel development is materials behavior, including cracking, erosion, and thermal expansion. Electrical heating of candidate fuel elements can be accomplished in university or government laboratories—no nuclear conditions need be considered in the early stages of research. Development and demonstration of improved fuel material behavior would be a first, modest-cost step.

According to one NASA Glenn Research Center estimate, the cost to develop a flight-ready NTR system is on the order of $3 billion (in 1996 dollars).[15] The committee recognizes that constraints on the program may preclude

---

[12] T.P. Stafford, *America at the Threshold: Report of the Synthesis Group on America's Space Exploration Initiative,* U.S. Government Printing Office, Washington, D.C., 1991.

[13] Space Task Group, "The Post-Apollo Space Program: Directions for the Future," available in NASA Historical Reference Collection, History Office, NASA, Washington, D.C., September 1969.

[14] National Research Council, *Priorities in Space Science Enabled by Nuclear Power and Propulsion,* The National Academies Press, Washington, D.C., 2006.

[15] S.K. Borowski and L.A. Dudzinski, "High Leverage Space Transportation System Technologies for Human Exploration Missions to the Moon and Beyond," Paper AIAA-96-2810 in *32nd Joint Propulsion Conference Proceedings,* American Institute of Aeronautics and Astronautics, Reston, Va., 1996. Also published as NASA-TM-107295, available at http://trajectory.grc.nasa.gov/aboutus/papers/AIAA-96-2810.pdf.

the full development of an NTR system at this time, but it believes that NASA should take steps to maintain this technology as a potential option for future decisions.

Finding on Nuclear Thermal Rocket Technology: NASA has no project for examining the fundamental issues involved in recovering the nuclear thermal rocket (NTR) technology even though the utility and the technical feasibility of the NTR have been established.

Recommendation on Nuclear Thermal Rocket Technology: The Exploration Technology Development Program should initiate a technology project to evaluate experimentally candidate nuclear thermal rocket (NTR) fuels for materials and thermal characteristics. Using these data, the Exploration Systems Mission Directorate should assess the potential benefit of using an NTR for lunar missions and should continue to assess the impact on Mars missions.

SUMMARY COMMENTS

NASA must couple the human aspects of its mission with its technology development program in order to succeed. NASA could return humans to the Moon without nuclear thermal propulsion technology, but the ability to go beyond the Apollo program would be substantially reduced. Such a reduction would call into question the rationale for exploration provided in the Vision for Space Exploration, the national space policy, and the NASA Authorization Act of 2005 (Public Law 109-155).

Adding nuclear thermal propulsion would provide NASA with a technology that would support decisions about future destinations and potentially significantly enhance the capability of NASA’s systems and vehicles. A better integration of the human systems would help to ensure the efficient completion of mission objectives by reducing barriers or obstacles to the human operation of Constellation systems.

4

Management and Execution of the Exploration Technology Development Program

The previous chapter outlined gaps in the substance of what the Exploration Technology Development Program (ETDP) should be doing in addition to its existing projects; this chapter deals largely with how the program is managed and executed and how that process could be improved. Following its review of the context of the ETDP, the committee examines four topics: the program management and implementation methodology, the balance between near-term and far-term technology investment, the involvement of the broader community, and the need for testing in the development program.

The committee reviewed the presentations offered by ETDP management, the formal project plans of each of the 22 ETDP projects, and other overviews of the program, including "The Exploration Technology Development Program" and "Technology Infusion Planning Within the Exploration Technology Development Program."[1] In general, the committee found a thoughtful and well-designed planning and administrative process that seeks to accomplish the following:

- Identify the benefit of a new technology to the flight element,
- Set requirements for the technology,
- Develop the new technology to a technology readiness level (TRL) of 6, and
- Programmatically infuse the outcomes of the technology development into the design and development cycle of the flight element.

CONTEXT OF THE PROGRAM

Finding 1 on Program Context: In general, the *ETDP is making progress toward its stated goals.* It has a technology development planning process responsive to the needs of the Constellation Program, and if adequately and stably funded and executed in a manner consistent with the planning process, the ETDP would probably make the required technology available on schedule to its customers in the Constellation Program.

---

[1] C. Moore and F. Peri, "The Exploration Technology Development Program," AIAA Paper 2007-136 in *45th Aerospace Sciences Meeting Conference Proceedings*, American Institute of Aeronautics and Astronautics, Reston, Va., 2007; D.C. Beals, "Technology Infusion Planning Within the Exploration Technology Program," IEEEAC Paper #1108, 2007, available at http://ieeexplore.ieee.org/iel5/4161231/4144550/04161576.pdf.

However, the committee found that the program operates within significant constraints. In an effort to be responsive to the needs of the Constellation Program, the ETDP has accepted schedule targets for deliverables that are, in some cases, quite aggressive. The ETDP has constructed an annual review process in which the flight program management recommends initiation, termination, and reprioritization of ETDP project elements. The Constellation Program itself is still undergoing change, however, which introduces a level of instability into the ETDP and which many managers find creates challenges to meeting overall goals.

The ETDP also operates within a highly constrained budget, which has been diminishing annually. The fiscal year (FY) 2005 budget, the first budget prepared after the establishment of the Vision for Space Exploration (VSE), called for $1,093.7 million in FY 2005, ramping up to $1,386 million by FY 2008. The actual FY 2008 budget is $326 million, with a planned reduction in FY 2009 to $244.1 million.[2] Not unlike other aspects of the Exploration Systems Mission Directorate (ESMD) program, the agency has high expectations for a rather tightly constrained budget.

The ETDP operates under the current NASA management policy of “ten healthy centers,” that is, the work of NASA should be preferentially assigned to the NASA center civil service workforce and that all 10 NASA centers should be engaged in the main programs of NASA, to which exploration is central. The application of this policy has had the beneficial effect of drawing in the appropriate centers of NASA and the expertise of its personnel. In fact, the committee was genuinely impressed at the degree of intercenter involvement and cooperation evident in the ETDP. In many cases the most appropriate place for this technology development is within NASA because of its unique capabilities, infrastructure, and skills, but there are other cases in which academia, research laboratories, or industry might be better suited to perform the research. Especially when coupled to near-term schedule demands, the annual planning cycle, and the tight budget, NASA’s current policy tends to exclude the productive engagement of others in the nation who could contribute to the research effort.

Finding 2 on Program Context: The *ETDP is operating within significant constraints.* These constraints include the still-dynamic nature of the requirements handed over from the Constellation Program; the constraints imposed by a limited budget, both from a historical perspective and relative to the larger exploration goals; the aggressive timescale of early technology deliverables; and the desire within NASA to fully employ the NASA workforce at its “ten healthy centers.” These constraints have posed many management and programmatic challenges, which in some cases have impeded the efficiency and effectiveness of the ETDP.

The close coupling of the ETDP to the needs of the Constellation Program represents a strategy for technology development at one extreme end of the spectrum of approaches to the management of technology approaches. The ETDP is almost indistinguishable from a totally contained, closely coupled, *supporting technology program* that might be found within the Constellation Program itself. In fact, the committee often found it difficult to understand why the bookkeeping for some projects handled within the ETDP and that for other projects of seemingly equal timescale and technology readiness was done within the Constellation Program. Also, without insight into all of the technologies being developed within the Constellation Program itself, the committee could not evaluate these efforts and how they are coupled with the ETDP to meet VSE goals.

At the opposite end of the technology management spectrum is the model of an *advanced technology program*, including preliminary and innovative research at a low TRL, which could be conducted at universities, at NASA centers, and in industrial research centers. Such investments often develop new enabling approaches, which are then matured through low-to-mid-TRL projects (similar to those found in the Defense Advanced Research Projects Agency) in order to assess their actual impact on eventual flight systems. The conventional wisdom, reflected for example in the FY 2005 exploration technology program, is to have a balanced portfolio of low-, low-to-mid-, and mid-level-TRL projects.[3] Generally in this model, most of the projects in a balanced portfolio are toward the low end of the spectrum owing to relatively low per project cost, but the larger fraction of the budget is usually

---

[2] See http://www.nasa.gov/pdf/55408main_25%20HRT.pdf and http://www.nasa.gov/pdf/210019main_NASA_FY09_Budget_Estimates.pdf pg Exp-75.

[3] NASA FY 2005 Budget Request, p. EC 2-1.

allocated the more mature end of the spectrum due to the scope of these efforts. As an example, in the current Homeland Security Advanced Research Projects Agency, about 20 percent of the total funds are invested in low-TRL projects.[4]

The ETDP manager informed the committee that NASA management has made a deliberate decision to “balance” the space technology budget of the agency entirely toward the mid-TRL range, with the intent of maturing technologies that have already reached at least TRL 3 (in a few isolated cases TRL 2) to TRL 6 in order to meet the near- and mid-term needs of the Constellation Program.[5]

Given that the ETDP is the primary space technology program in NASA as pointed out at the beginning of Chapter 3, it is important to consider whether the scope of ETDP funding is sufficient to support the robust technology development necessary to “explore and to support decisions about . . . destinations” as called for by the VSE and to preserve the “role of the United States as a leader in aeronautical and space science and technology,” as called for by the National Aeronautics and Space Act of 1958, as amended. It is not clear to the committee that the near- to mid-term supporting technology focus of the ETDP can sustain either the role of supporting “decisions about . . . destinations” or the broader leadership of the U.S. in space.

This investment strategy has effectively eliminated the low-TRL, long-term technology investments of NASA. Other than unsolicited proposals and Small Business Innovation Research (SBIR), there is no effective mechanism to propose or fund such efforts. For example, while there have been several focused NASA Research Announcements issued under the ETDP, there has not been a call for broad technology. Such a request would invite a broader set of proposed technologies that could benefit NASA in the short, medium, or long term. If unsolicited proposals were received in the current environment, they would be reviewed by NASA center personnel with no or extremely limited discretionary budgets to fund them.

From the perspective of recent history, this shift in policy has also caused some entire areas of the NASA technology effort to become unfunded. For example, as recently as the FY 2003 budget, NASA funded a robust program in a wide variety of technologies, such as advanced information systems and synthetic design environments. Since the FY 2005 budget, areas such as system engineering methods and nuclear thermal propulsion have been eliminated. No funding for these areas is contained in the current ETDP or anywhere else within NASA.

Finding 3 on Program Context: The *ETDP has become NASA’s principal space technology program. It is highly focused and is structured as a supporting technology program to the Constellation Program*, designed to advance technologies at TRL 3 and above toward TRL 6. Because of this shift toward the relatively mature end of the technology investment spectrum, which is very closely coupled to the near-term needs of the Constellation Program, NASA has also in effect suspended research in a number of technology areas traditionally within the agency’s scope, and it has in many areas essentially ended support for longer-term (TRL 1-2) technology research.

PROGRAM MANAGEMENT AND IMPLEMENTATION METHODOLOGY

The ETDP spans the full panorama of elements that are part of large-systems design, planning, and engineering—from requirements, risk mitigation, and allocation to systems testing. It is thus imperative that sound systems engineering principles be applied across the management of the ETDP itself.[6] Three main areas in which the committee developed findings that relate to effective systems engineering and management of the ETDP are operational risk reduction, requirements control, and effective technology transfer.

The ETDP has a well-designed approach to managing the programmatic risk of its own technology development. It is necessary, however, to consider the impact of ETDP technologies on the Constellation Program, on engineering, and on human health risks for crewed space systems, which interact in a variety of complicated and

---

[4] Jay M. Cohen, Under Secretary for Science and Technology, U.S. Department of Homeland Security, Testimony before the U.S. House of Representatives Homeland Security Subcommittee on the Prevention of Nuclear and Biological Attack, September 14, 2006, p. 6.

[5] See the presentation of Frank Peri, Program Manager, ETDP, NASA, to the committee, October 10-11, 2007, in Washington D.C., included as Appendix H of this report.

[6] See NASA, *NASA Systems Engineering Handbook—2007 Revision*, NASA/SP-2007 6105 Rev1, NASA, Washington, D.C. The committee agrees with the principles put forth in this document, particularly in Appendix G, “Technology Insertion.”

sometimes subtle ways. A continuous systems approach is required to anticipate the potential interactions and impacts of risk mitigation in one area (e.g., engineering risk reduction for a component) on risk in a seemingly unrelated area (e.g., human health). Ideally, this systems approach to risk should be applied at all levels, from the most minute components to the overall system in its broadest context, in order to anticipate and identify interactions among sources of risk and approaches to risk mitigation.

Human systems integration (called human-centered design in the NASA Human Research Program [HRP]) is also an integral part of the systems engineering of human and operational risk. The use of the term "human systems integration" (or "human-centered design") in this report and its application to operational risk reduction are inclusive of both human health risk and human factors considerations for operations. The key to a successful technology development program for space exploration is to ensure that human considerations are integrated into the full range of systems design, development, manufacturing, operations, sustainment, and disposal. The complex trade-offs between the human discipline areas and the full integration of the attributes produced by these trade-offs are essential if systems are to be truly usable and maintainable.[7] The application of systems engineering processes and best practices using an integrated systems approach to technology management and transition is needed. In the words of a recent NRC report:

> The link between humans and engineering is essential for enhancing mission success and crew performance. For example, Callaghan et al. (1992) observed that the development of methods was as important as the development of standards. Similarly, Whitmore et al. (1999) indicated that the first research priority for the ISS should be in-flight research tools to understand habitability. The second priority was to identify human factors critical to habitability and determine how these could be tested in microgravity and analog environments. Adams (1999) also emphasized the need for habitability studies. Other researchers have highlighted the importance of human systems integration. Peacock et al. (2001), for example, identified the following technology issues for manned space missions: (1) limitations to astronaut mobility and force output while wearing extravehicular activity (EVA) clothing, (2) need for physical restraints and mobility aids in microgravity, and (3) maintaining spatial orientation. The need for enhanced human–robot interactions was identified by Gross et al. (2002), and Hartman (2003) identified the human systems interaction considerations associated with the Martian weather, which includes temperature extremes (–87°C to –25°C) and windstorms that will cause dust to lodge in seams and crevices and reduce visibility to less than 1 meter at times, all in an atmosphere that is almost pure CO_2, with a barometric pressure that is 1 percent that of Earth's surface (about equivalent to the pressure at 110,000 feet above Earth).[8]

Another domain of risk is associated with system reliability. From a systems engineering perspective, missions to the Moon have historically been of short duration, and therefore systems and components were not expected to break down during the missions—that is, technology was not pushed to meet extended reliability requirements. For long-duration missions, however, component failure has a higher probability. The entire issue of the replacement of broken parts and components must be addressed as part of the risk allocation for architectures under consideration. Selecting an appropriate balance of methods to replace parts and components may ensure significant cost savings (see the discussion in the assessment of the Supportability project in Chapter 2).

Reflecting on the potential subtle interactions among risks and their mitigation, the significant sources of risk arising from human system design, and the additional sources of risk such as long-duration reliability, the committee did not observe a systematic approach to the management of the impact of technology on Constellation programmatic, operational, and human health risk.

Finding 1 on Management: Although the ETDP has a well-conceived process for managing the programmatic risk of its own technology development, the committee found a lack of clarity in the way that the ETDP accounts for the contributions of its technology developments to reducing exploration (i.e., Constellation) program risk, to reducing operational and human health risks, and to considering human-design-factor issues in operations.

---

[7] National Research Council, *Human-System Integration in the Systems Development Process: A New Look,* The National Academies Press, Washington, D.C., 2007.

[8] National Research Council, *A Risk Reduction Strategy for Human Exploration of Space: A Review of NASA's Bioastronautics Roadmap,* The National Academies Press, Washington, D.C., 2006, p. 36.

The ETDP has a formal process for handing requirements from the customer (i.e., elements of the Constellation Program) to the technology deliverer (i.e., projects within the ETDP). These requirements are recorded in the 22 ETDP project plans. Operational risk passes to the ETDP projects through the requirements passed down from the Constellation Program. The management of programmatic risk in the development of technologies is addressed in Section 8 of each project plan, without reference to how these risks interact with one another and with the engineering and human health risks associated with the technologies.

The committee therefore found significant uncertainty regarding how the requirements were established and interpreted. For example, reduction and allocation of operational risk are not treated uniformly among the 22 projects. Some projects are associated with minimizing "allocated risks." Examples include the Energy Storage project, which has as its objective reducing risks associated with lithium batteries, fuel cells, and regenerative cells; and the project on Automated Rendezvous and Docking sensors, which has as its objective reducing risks associated with alternative navigation sensors. Other projects are charged with qualitative risk reduction but do not have quantitative goals—for example, the Fire Prevention, Detection, and Suppression project, which has as one of its goals "minimizing the risk to crew, mission and system." Still other projects have no role in operational risk reduction but are focusing instead on new capabilities—for example, the Radiation-Hardened Electronics for Space Environments (RHESE) project, which has as its objective expanding the current state of the art for radiation-hardened electronics.

The committee repeatedly had difficulty identifying the application of systems engineering principles to the requirements allocation process across the ETDP. Many projects appear to lack clear ties to an integrated systems plan. For example, during individual project reviews, the committee noted the following:

- Lack of requirements—working to assumed performance targets (e.g., the RHESE project);
- Lack of connection between project and requirements (e.g., the Structures, Materials, and Mechanisms and the Autonomy for Operations projects);
- Lack of requirement specificity (e.g., the International Space Station Research and the In Situ Resource Utilization projects); and
- "Wrong" requirements—requirements do not drive to TRL 6 demonstration or are not derived from system considerations (e.g., the Lunar Dust Mitigation project)

It is clear from ETDP project plans that each individual project has requirements that it is trying to meet. It is not clear, however, how these requirements are integrated or that there is cognizance within the individual projects of the requirements of other projects. It is also not clear how the individual projects would influence the development of or changes in requirements, or even the validation or retirement of its set of requirements.

Finding 2 on Management: Recognizing the well-established annual process of reviewing and revising the requirements levied on the ETDP by the Constellation Program, the committee nevertheless found a lack of clarity and completeness in the requirements as perceived by ETDP project personnel and a lack of integration of technology requirements (as would be expressed, for example, in a technology roadmap).

Beyond responding to requirements and effectively developing technology, the crucial remaining link is the effective transfer of technology to the customer. *Technology transfer* is defined as a "managed process of conveying a technology from one party to its adoption by another party."[9] The committee reviewed the higher-level ETDP documents and the 22 project plans discussing this aspect of the process, and it found that the ETDP has developed a sound *administrative approach* to technology transfer—that is, the process by which the technology developer (from the ETDP) meets on a regular basis and participates in program reviews with the customer (from the Constellation Program). Through this interaction, the developer and customer arrive at decisions as to whether the technology is ready in time and will be effective in meeting program needs. The ETDP calls this process *technology transition*, and this is the process described in the project plans.

---

[9] W.E. Souder, A.S. Nashar, and V. Padmanabhan, "A Guide to the Best Technology-Transfer Practices," *The Journal of Technology Transfer* 15(1-2):5-16, 1990.

However, the experience of the committee, supported by a substantial literature on effective technology transfer, is that this administrative step is usually not the stumbling block. The more difficult aspect of the "managed process of conveying a technology" is the actual human-centered transfer of the tacit and implicit knowledge, the know-how, the analysis tools, and the development and quality processes that represent the effective exchange of knowledge between the developing organization and the deploying organization. How will the people who developed the new technology effectively transfer it to the people who now need it? This is effectively a human, not an administrative, process.

The literature in this field extensively examines the exchange of knowledge from universities to industry, giving less coverage to the transfer of technology from industrial research laboratories to industrial product divisions. The topic of transfer from a technology development group within government to a technology user within government is examined less often, but there is now reason to think that the general lessons learned in the other areas would benefit the ESMD in its development of more robust human-centered knowledge-exchange plans. A number of best practices are used by federal agencies, federally funded research and development centers, and universities to help facilitate the process (see Box 4.1).

BOX 4.1
Some Frequently Cited Best Practices for Technology Transfer

1. *Close interaction of individuals in sending and receiving organizations.* Effective technology transfer has been called a "contact sport." The sending and receiving organizations should both cultivate a strong sense of partnership and develop a culture of ongoing, close, and open communication and trust. These interactions should also help bridge potential culture gaps between the two organizations. Successful technology transfer efforts often have "champions," or facilitating agents, on both the sending and the receiving ends to act as catalysts to the process and to provide leadership in their respective organizations. The sending organization must have a good understanding of the needs of the receiving organization; this can be achieved through close personal interactions and communication. The Exploration Technology Development Program (ETDP) could encourage close interactions between individuals on the developing and receiving teams, for both government and contractor personnel.

2. *Personal incentives for employees to engage in technology transfer.* Technology transfer works best when employees are offered personal incentives to contribute to technology transfer activities. In the commercial world, incentives often take the form of financial reward, such as royalties or equity in companies adopting the new technology. However, incentives can also take other forms, such as the freedom to work on technology transfer projects to further personal satisfaction, or the opportunity to achieve professional recognition by winning awards, publishing journal articles, or presenting results at industry workshops. The ETDP could consider specifically incentivizing good performance in technology transfer.

3. *Adequate resources dedicated to the technology transfer process*. The ETDP could ensure that there is dedicated funding within the project for technology transfer.

4. *Mobility of technical personnel among institutions.* One of the most important means of technology transfer can be the movement of scientists and engineers between the two organizations, whether for temporary exchange or permanent transfer. The movement of researchers allows for the direct transfer of highly specialized knowledge and skills. The ETDP could achieve this objective by encouraging mobility of personnel on the NASA side and by ensuring that the development partner has close contact with the receiving partner.

5. *Development of technology roadmaps to help direct the development of technology through the research, development, transfer, and commercialization process.* Part of the technology development roadmap for each ETDP project element should be an explicit plan for technology transfer, not only of the administrative type, but also to ensure an effective exchange of tacit and implicit knowledge, know-how, tools, and approaches, as well as ownership and advocacy.

Finding 3 on Management: While the ETDP has a good administrative process for determining the formal mechanics of technology transfer, it could improve the effectiveness of the human side of the process by reviewing and adopting effective practice in this area, with the objective of developing a methodology of technology transfer from the development project to the flight project that ensures the successful infusion of the technology.

Based on its three findings on the nature of the program management and implementation methodology of the ETDP, the committee offers the following recommendation.

Recommendation on Management: The Exploration Systems Mission Directorate (EMSD) should review its process for the management of technology development to ensure the timely delivery of technologies for seamless integration into its flight programs. In particular, the ESMD should (1) review and incorporate the considerable expertise in the management and transfer of technology in the larger aerospace, government, and industrial communities; (2) strengthen its management approach by, for instance, appointing a program-level system engineer to ensure that requirements are developed, maintained, and validated in a consistent and complete manner across the entire program; and (3) address the following three issues in particular: (a) the need for a careful assessment of the impact of its technologies on human and operational risk, (b) the need for definition and management of technology requirements, and (c) the importance of recognizing the human elements in the eventual effective transfer and infusion of technology.

BALANCE BETWEEN NEAR-TERM AND FAR-TERM TECHNOLOGY INVESTMENTS IN THE ETDP PORTFOLIO

The vast majority of the projects carried out within the ETDP are focused on TRL 3 or above. When compared with the historical balance of low- and mid-TRL-level investments, the recent and significant reduction and/or termination of low-TRL research could have major negative impacts (loss of sustainability in both technologies and personnel) on the ability of the United States to participate successfully in future human space exploration programs. In particular, the committee concluded that by not taking advantage of low-TRL projects, the capability of NASA to minimize life-cycle costs and develop the technology needed for achieving the larger objectives of the VSE is being compromised.

Investment in innovative TRL 1-2 research creates new knowledge in response to new questions and requirements, stimulates innovation, and allows more creative solutions to problems constrained by schedule and budget. Moreover, it is investment in that level of research that has historically benefited the nation on a broader basis, generating new industries and spin-off applications.

The ETDP projects reviewed by the committee tend to focus on supporting near-term aspects of the VSE and largely exclude Mars. Some are linked exclusively to Orion and Ares 1, and others to the Altair Lunar Lander and lunar surface operations. The committee did not commonly find evidence that the projects consider the extensibility of technologies to Mars. In addition, little emphasis appears to have been placed on the exploration of cost-enabling technologies, which could provide significant cost reductions in some areas and thus allow consideration of alternative technologies in other areas.

The ETDP is opting largely for incremental approaches to supporting VSE goals. In most cases, incremental changes to proven technologies or to concepts at TRL 3 or above are projected to enable a return to the Moon. However, only a few such technologies or concepts are also expected to be applicable to the VSE objectives beyond the Moon.

For the projects expected to enable Mars exploration with technologies that are TRL 3 or above, the question of investing in innovative concepts at lower TRLs is more philosophical than urgent at this point. However, this is not to say that there should not be a conscious effort across the board now to invest more on ideas at TRL 2 or lower that might become the game changers and enablers for human exploration of Mars and beyond. Therefore, the current balance of incremental and innovative research can be understood in the context of a compromise between achieving the initial goals of the VSE (continuing to support the ISS and a return to the Moon) with tight budgets and schedules—but serious consideration should be given by the ETDP and its

Constellation customers to starting now to seed more revolutionary concepts, which will be needed to meet the next objectives of the VSE.

Finding 1 on Balance: The ETDP is currently focused on technologies at or above TRL 3, a focus driven by the need to bring together all of the available resources of NASA to reduce nearer-term Constellation mission risk and at the same time reduce potential Constellation Program schedule slippages within the assigned budget profile.

Finding 2 on Balance: Most ETDP projects represent incremental gains in capability, which is not inconsistent with the focus on projects at TRL 3 and above. NASA has largely ended investments in longer-term space technologies that will enable later phases of the VSE, allow technology to "support decisions about . . . destinations," in the words of the VSE, and in general preserve the technology leadership of the United States. In assessing the balance between near-term and far-term technology investments, the committee found that the current balance of the ETDP is too heavily weighted toward near-term investments.

Recommendation on Balance: The Exploration Systems Mission Directorate should identify longer-term technology needs for the wider Vision for Space Exploration (VSE) that cannot be met by the existing projects in the Exploration Technology Development Program (ETDP) portfolio, which are currently at technology readiness level (TRL) 3 or above. To meet longer-term technology needs, the committee recommends that the ETDP seed lower-TRL concepts that target sustainability and extensibility to long-term lunar and Mars missions, thus opening the TRL pipeline, re-engaging the academic community, and beginning to incorporate the innovation in technology development that will be necessary to complete the VSE.

INVOLVEMENT OF THE BROADER COMMUNITY

A number of the ETDP projects are carried out primarily within NASA. For these projects, input from industrial and academic organizations that are already known to be proficient in relevant or germane research, technologies, or tasks is sometimes lacking. Examples of relevant areas include optical communication and processing, composite structures and superalloys, portable power sources, high-performance and radiation-hardened electronics, intelligent software design, exploration life support, and human-robotic systems/analogs. All of these are areas being vigorously pursued by others and areas in which the ETDP could benefit from external collaboration. Engaging in such collaboration would be consistent with the ESMD requirement that programs "engage national, international, commercial, scientific, and public participation in exploration to further United States scientific, security, and economic interests."[10]

Finding 1 on Community: Some ETDP projects have made alliances with others in the broader community that will add to the effectiveness or efficiency of the project. However, the committee observes that in general, the ETDP has not taken advantage of many external resources that could potentially reduce cost or schedule pressure, aid in the development of NASA's proposed technology, and/or provide alternative and backup technologies.

Because of the reliance on internal ETDP personnel to carry out ETDP projects, leadership expertise in some areas is still developing (e.g., see the section on Project 08, RHESE, in Chapter 2), and external peer review of these projects is often lacking. One method of increasing collaboration and information exchange with external sources and at the same time contributing to the further development of project leadership is to incorporate an external peer review process.

Finding 2 on Community: In many cases, ETDP projects do not take advantage of external technical peer review.

---

[10] National Aeronautics and Space Administration, *Exploration Systems Mission Directorate Implementation Plan*, p. 5. Available at www1.nasa.gov/pdf/187112main_eip_web.pdf.

Finding 3 on Community: While many ETDP projects are technically or programmatically led by distinguished NASA personnel, certain other projects would benefit significantly from having a nationally recognized technical expert on the leadership team.

NASA has a long history of a very close relationship with the academic community, which it has engaged to help produce new technologies and to provide a pipeline of talented human resources: undergraduates, faculty, and masters- and Ph.D.-level students. Universities have often been the space program's incubator for both technical and human resources. However, many of the development projects reviewed by the committee had eliminated most of their collaborations with university faculty and students.

At the period of the review in late 2007, the ETDP was emerging from the reorganization that had taken place in 2005: two former technology and research programs—Exploration Systems Research and Technology Program and the Human Systems Research and Technology Program—were the predecessors of the ETDP and the Human Research Program. During this transition the total budget was reduced and approximately 320 University Research Grants were terminated midstream, impacting hundreds of graduate students and their supporting faculty. Many of the researchers interviewed by the committee indicated that this had had an adverse impact on their research programs. The level of university research has not recovered since that time.[11] Since it was also apparent that NASA was funding very little of the low-TRL research in-house, it was not clear to the committee how new or currently nonexistent required technology would become available for the current and future programs in the next 10 to 30 years, or where the expertise required by both NASA and the contractor community will be generated from. The significant reduction and/or termination of low-TRL research and the concomitant lack of personnel either to conduct the research or to apply it will have significant negative impacts on the ability of the United States to participate in future human exploration programs.

Finding 4 on Community: In the transition to the ETDP's current structure, NASA has terminated support for hundreds of graduate students. The development of human resources for future space development may be significantly curtailed by reductions in NASA support for university faculty, researchers, and students.

Recommendation 1 on Community: The Exploration Technology Development Program (ETDP) should institute external advisory teams for each project that (1) undertake a serious examination of potential external collaborations and identify those that could enhance project efficiency, (2) conduct peer review of existing internal activities, and (3) participate in a number of significant design reviews for the project.

Recommendation 2 on Community: The Exploration Systems Mission Directorate should implement cooperative research programs that support the Exploration Technology Development Program (ETDP) mission with qualified university, industry, or national laboratory researchers, particularly in low-technology-readiness-level projects. These programs should both support the ETDP mission and develop a pipeline of qualified and inspired future NASA personnel to ensure the long-term sustainability of U.S. leadership in space exploration.

TESTING

The need for adequate testing is a recurrent theme in program failure reports: for example, a proximate cause of the Mars Polar Lander, Deep Space 2, Mars Expedition Rover, Titan IVB, and Sea Launch failures was inadequate testing.[12] The Columbia Accident Investigation Board concluded that "organizational practices detrimental to safety were allowed to develop, including reliance on past success as a substitute for sound

---

[11] Christopher Moore, Program Executive, Exploration Systems Mission Directorate, NASA, presentation to the committee, October 10, 2007.

[12] J. Ganssle, "Crash and Burn," available at http://www.ganssle.com/articles/crashburn.htm; J. Ganssle, "Disaster!" available at http://www.ganssle.com/articles/Firmwaredisasters1.htm; J. Ganssle, "Disaster Redux!" available at http://www.ganssle.com/articles/Firmwaredisasters2.htm.

engineering practices (such as testing to understand why systems were not performing in accordance with requirements).”[13]

Testing is needed to specifically address the risks inherent with any new technology. The lack of sufficient testing in the current ETDP poses the threat that technologies will not ultimately be available to be integrated into the Constellation Program, which increases overall programmatic risk.

The lack of systems testing affects how requirements from the broader system can be integrated into the technology at an early enough time to impact the technology’s development. The lack of systems testing also limits the rate at which the technology will mature, which affects how their importance is viewed. Early identification of issues from testing greatly reduces programmatic costs.

The committee identified a lack of sufficient testing (ground or flight) in 12 ETDP projects (Ablative Thermal Protection System for the Crew Exploration Vehicle, Lunar Dust Mitigation, Cryogenic Fluid Management, High-Performance and Radiation-Hardened Electronics, Intelligent Software Design, Autonomous Landing and Hazard Avoidance Technology, Automated Rendezvous and Docking Sensor Technology, Extravehicular Activity Technologies, International Space Station Research, In Situ Resource Utilization, Fission Surface Power, and Human-Robotic Systems/Analogs). In several projects the missing tests will prevent the achievement of TRL 6 in key technologies and will risk their incorporation into the Constellation Program architecture. The reason for omitting these tests is usually a lack of time (scheduling) and/or a lack of funding to develop the needed test facilities or to carry out necessary flight tests.

The present ETDP lacks the systematic progression of testing, especially in a flight-like environment, needed for the following purposes: (1) to decide which of the alternative technologies should be brought forward and how they will have to be modified to be successful in their final form, (2) to ensure that the different technologies mature and are ready when they are needed, and (3) to validate that technologies will function as expected when integrated into the larger system and operating in the space and lunar environments.

Within the ETDP there appears to be no consideration of using missions in the Lunar Precursor Robotic Program to demonstrate technologies that are candidates for the crewed missions. This is an example of the need for a tighter coupling to occur between the Lunar Precursor Robotic Program and the ETDP, both in the ESMD Advanced Capabilities area. At the time of this review the Lunar Precursor Robotic Program had been limited to the Lunar Reconnaissance Orbiter (LRO) and the Lunar Crater Observation and Sensing Satellite (LCROSS). However, with the Science Mission Directorate’s recent selection of the Gravity Recovery and Interior Laboratory for the Discovery program (whose gravity mapping science is also important to lunar navigation engineering) and the identification of some other small lunar missions (an orbiter and a lander), there is evidence that NASA may look beyond LRO and LCROSS in terms or robotic precursor missions. The question of whether these missions could also serve a technology demonstration role is worth investigating. Apollo had numerous precursor missions before men headed to the Moon. While that may not be necessary for this return to the Moon, some technology demonstration by robotic precursors is likely prudent.

Three of the ETDP projects (Lunar Dust Mitigation, In Situ Resource Utilization, and Human-Robotic Systems/Analogs) require but do not at present include tests in a realistic lunar environment including the effects of dust, vacuum, and lunar thermal cycles. The Lunar Dust Mitigation project requires tests at full scale. The construction of a new facility or a significant upgrading of an existing facility would enable needed tests for all three projects. Such tests could also be performed during early lunar missions in preparation for the later, longer-duration missions.

The most important flight test is that required for the Orion reentry heat shield. Even though 40 years have elapsed since the Apollo 4 flight test and the state of the art in heat shield design has advanced significantly, it is still not possible to simulate a lunar-return Earth entry in ground-based facilities. Within the present state of the art, it is not possible to build ground-test facilities that will duplicate (or even adequately approximate) reentry flight conditions. Only a reentry flight test at lunar-return velocity and at a scale sufficient to assess the effects of joints and gaps between the heat shield panels will qualify the heat shield for use on a crewed lunar-return mission.

---

[13] Columbia Accident Investigation Board and the National Aeronautics and Space Administration, *Columbia Accident Investigation Board Report*, U.S. Government Printing Office, Washington, D.C., 2003, available at http://caib.nasa.gov/.

Finding on Testing: The present ETDP lacks an integrated, systematic test program. Of particular importance is that several ETDP projects, as currently formulated, do not include mission-critical tests—that is, system or subsystem model or prototype demonstrations in an operational environment—that are needed to advance the technology to TRL 6.

A key facility currently missing is a large-scale, combined thermal, vacuum, and dust simulator, which is required for three ETDP projects (Lunar Dust Mitigation, In Situ Resource Utilization, and Human-Robotic Systems/Analogs). A flight test of the Orion reentry heat shield that is required to advance the technology to TRL 6 is not in the present Ablative Thermal Protection System for the Crew Exploration Vehicle project.

Recommendation on Testing: The Exploration Systems Mission Directorate should evaluate its test capabilities and develop a comprehensive overall integrated test and validation plan for all Exploration Technology Development Program (ETDP) projects. All ETDP projects should be reviewed for the absence of key tests (ground and/or flight), especially those that are required to advance key technologies to TRL 6. Where new facilities or flight tests are required, conceptual designs for the facilities or flight tests should be developed in order to establish plans and resource requirements needed to include the necessary testing in all ETDP projects.

CONCLUDING SUMMARY

The committee was deeply cognizant of its responsibility to provide a careful, fair, and balanced, albeit rapid, review of the ETDP in order to ensure that this nation may fully participate in the future of human space exploration. In the process of reviewing 22 advanced technology projects within the ETDP, it became acutely apparent to the committee that (1) this was the primary technology development program for human exploration within NASA, and (2) many program and project managers had made and were making decisions based not on the advantage of best practice on a blank page but based instead on declining budgets and constrained schedules.

The ETDP technical and programmatic leaders should focus on the broader messages of this review: that the technology development program must be robust at all TRL levels, whether residing in the ETDP or not; that the external community must be engaged and made use of for its expertise and its support; that testing at the required TRLs must be implemented to ensure mission success and crew safety; that the “human system” should be a well-recognized and well-documented component of all of the technology development programs; and that each project should be easily recognized by all members of the development team as part of an integrated agency strategy that can be effectively communicated to the external community.

Many historical technology development lessons learned from the Apollo, space shuttle, and ISS programs apply to the ETDP. Therefore the ETDP has the opportunity to integrate the successful technology development strategies and lessons learned from NASA’s past as well as from current benchmark programs within other agencies.

While the committee has offered findings and related recommendations that are designed to develop a forward path for success, the dedication and commitment of the men and women of the Exploration Technology Development Program are not questioned and must be recognized. NASA, in its 50th year, has a proud legacy and has shaped the history of human spaceflight beyond Earth orbit. It has the opportunity to continue to do so, but only with the necessary strategies, tools, and support required by its technical and programmatic leaders to accomplish those goals.

The committee hopes that the observations, findings, and recommendations offered in this report will contribute to the ultimate success of the ETDP, and through the ETDP to the success of the nation’s space exploration program.

Appendixes

Appendix A

Statement of Task

In the House report accompanying the fiscal year 2007 appropriations bill that includes NASA (the Science, State, Justice, Commerce appropriations bill), NASA was directed to "enter into an arrangement with the National Research Council (NRC) for an independent assessment of NASA's restructured Exploration Technology Development Program (ETDP) to determine how well the program is aligned with the stated objectives of the Vision for Space Exploration (VSE), identify any gaps, and assess the quality of the research." [1] Following is the statement of task developed by NASA and the NRC for this assessment.

The Aeronautics and Space Engineering Board of the NRC will form a committee to perform this independent assessment. The committee's assessment will include findings and recommendations related to the relevance of ETDP research to the objectives of the Vision for Space Exploration, to any gaps in the ETDP research portfolio, and to the quality of ETDP research. The scope of the assessment will include all internal, collaborative, and competitively sourced research, development, analysis, etc., funded by the ETDP. While the primary objective is to conduct peer assessments that provide scientific and technical advice, the committee may offer programmatic advice when it follows naturally from technical considerations. The specific criteria for the committee to use are:

- Alignment with the stated objectives of the Vision for Space Exploration;
- The presence of gaps in research; and
- The quality of research.

NASA believes that it will be beneficial for the NRC to make additional comments and recommendations in the following areas:

- The effectiveness of the program in developing technology products and transitioning them to its customers;
- The balance between near-term and far-term technology investments;
- The metrics used for assessing progress in technology development;
- The involvement of the broader community;

---

[1] National Aeronautics and Space Administration (NASA), *The Vision for Space Exploration*, NP-2004-01-334-HQ, NASA, Washington, D.C., 2004, p. iii.

- The program management and implementation methodology; and
- The overall capabilities of the research team.

The committee will not make budget recommendations.

The committee will meet as required during the study to receive technical presentations about the projects under review by their group and formulate final findings and recommendations. Committee members will also make site visits as deemed necessary in formulating the assessment. Meetings will involve interactive discussions with NASA personnel from the programs. The committee may use NASA's Global Exploration Strategy, which establishes themes and objectives for lunar exploration and was presented at the 2nd Space Exploration Conference in Houston, Texas, in December, 2006; the reference architecture for lunar missions developed by the Lunar Architecture Team of the Exploration Systems Mission Directorate (ESMD); and the Constellation Systems Program's Technology Priorities documents that identify the critical technologies needed to enable the design of flight systems such as the Orion crew exploration vehicle, the Ares launch vehicle, and the Lunar Lander.

The final report will be provided no later than twelve months from the contract award. The NRC will provide a letter to the ESMD Associate Administrator that summarizes significant interim findings of the committee no later than seven months from contract award. The committee chair(s) will also provide an oral briefing to NASA on significant interim findings.

Appendix B

Biographies of Committee Members

Edward Crawley, *Co-Chair,* is the Ford Professor of Engineering at the Massachusetts Institute of Technology (MIT) and a professor of aeronautics and astronautics and of engineering systems. He received an S.B. and an S.M. in aeronautics and astronautics and an Sc.D. in aerospace structures from MIT. Dr. Crawley's earlier research interests centered on structural dynamics, aeroelasticity, and the development of actively controlled and intelligent structures. He is the author of numerous journal articles in *AIAA Journal, ASME Journal, Journal of Composite Materials,* and *Acta Astronautica*. Dr. Crawley is credited with being one of the early contributors to the field of active structural control, and several of these articles have more than 100 citations; one has more than 700. For his work in the field, Dr. Crawley was awarded the American Institute of Aeronautics and Astronautics (AIAA) Structures, Structural Dynamics, and Materials Award and the American Society of Mechanical Engineering (ASME) Adaptive Structures Medal. He is coauthor of two books in the field. Recently, his research has focused on the domain of the architecture and design of complex systems. His work spans a range from the development of underlying theory, typified by a recent paper on the algebra of systems, to the development of methods and tools, such as object process networks. It extends as far as a consulting role on the design of actual systems. Dr. Crawley is a fellow of the AIAA and the Royal Aeronautical Society (United Kingdom), and a member of three national academies of engineering: the Royal Swedish Academy of Engineering Science, the Royal Academy of Engineering (United Kingdom), and the National Academy of Engineering (United States). He has also served on numerous committees of the National Research Council (NRC).

Bonnie J. Dunbar, *Co-Chair,* is president and chief executive officer of the Museum of Flight in Seattle, Washington. Dr. Dunbar holds B.S. and M.S. degrees in ceramic engineering from the University of Washington and a Ph.D. in mechanical and biomedical engineering from the University of Houston. She recently retired from the NASA Johnson Space Center where she was the associate director, technology integration and risk management, for the Space Life Sciences Directorate. Prior to working for NASA, Dr. Dunbar was a senior research and operations engineer with Rockwell International Space Division, working on the design and manufacture of the space shuttle thermal protection system. She was a guidance and navigation flight controller and payload officer in NASA Mission Control. Following her selection as a mission specialist astronaut, she flew five times and logged more than 50 days in space. She trained in Russia on the Soyuz spacecraft and was on the first space shuttle flight to dock with the Russian Mir Space Station. She has served as the payload commander on two flights: a Spacelab mission dedicated to microgravity research, the United States Microgravity Laboratory, and on the eighth shuttle docking flight to Mir. Her flight experience includes operating the robotic manipulator system and training for contingency extravehicular-activity spacewalks. She is a member of the American Ceramic Society (fellow), the AIAA (fellow), the National Institute of Ceramic Engineers, and the Society of Women Engineers. She has been awarded the NASA Space Flight Medal, the NASA Distinguished Service Medal, the NASA Outstanding Leadership Medal, and the NASA Exceptional Achievement Medal. In 2000, Dr. Dunbar was elected to the Royal Academy of Edinburgh, and in 2002, to the National Academy of Engineering.

Gary L. Bennett is a consultant in aerospace power and propulsion systems for Metaspace Enterprises. Dr. Bennett received an A.A. (science) from Boise State University, a B.S. (physics) and a master of nuclear science (physics) from the University of Idaho, and a Ph.D. (physics) from Washington State University. He was the manager of advanced space propulsion systems and earlier the manager of advanced space power systems at NASA Headquarters, Washington, D.C., until 1994. He was responsible for managing a number of transportation technology programs, including hybrid propulsion, electric propulsion, low-thrust chemical propulsion, and advanced propulsion concepts. Prior to working at NASA, Dr. Bennett held positions in the Department of Energy's (DOE's) space radioisotope power program supporting the Lincoln Experimental Satellite (LES) 8/9, Voyager, Galileo, and Ulysses missions. He has authored or coauthored more than 150 technical papers, reports, and articles on power, propulsion, and space missions. Dr. Bennett has received a number of citations and awards from NASA, DOE, NRC, and AIAA for his work on space and terrestrial power and space propulsion. He has been elected a fellow of the American Institute of Aeronautics and Astronautics, the American Physical Society, and the British Interplanetary Society.

Elizabeth Cantwell is the interim division leader for the International, Space and Response (ISR) Division at the Los Alamos National Laboratory. She earned her Ph.D. in mechanical engineering from the University of California, Berkeley. She received her M.B.A. from the University of Pennsylvania. Dr. Cantwell is responsible for the execution of projects from small principal-investigator-driven basic science through the delivery of large satellites and instruments into the space environment or other field deployments. She is also responsible for program execution across the entire ISR portfolio, including project management, strategic planning and execution of those plans for new business opportunities, and resource planning and allocation. Dr. Cantwell routinely works with senior program leaders and ISR management to maintain and strengthen the science and technology base for ISR activities, manage and develop the workforce, plan for and execute new facilities, and ensure effective line and program integration. She also identifies and develops relationships with external and internal customers, promotes and leads new initiatives, and creates national recognition for ISR's capabilities. Dr. Cantwell has written and delivered numerous technical reports and presentations to academic conferences and journals, oversight bodies, and other clients. She has served as the academic reviewer for various societies and journals. Dr. Cantwell recently served on the NRC Committee on the Review of NASA's ISS Roadmap and has participated in other NRC committees and panels.

Shyama P. Chakroborty is currently the engineering manager and chief systems engineer in space exploration systems at Northrop Grumman Integrated Systems and formerly was the vice president and chief engineer of Microcosm heading a number of defense and space programs. Dr. Chakroborty received an M.S.M.E. from Ohio State University, a doctorate from Cleveland State University, and an M.B.A. from the University of California, Davis. Prior to joining Microcosm, he was the chief engineer and senior engineering manager of Aerojet in Sacramento, California. He has been involved in the design, development, and flight qualification of launch vehicles and spacecraft subsystems and systems. He is also an adjunct professor of aerospace and astronautical engineering at the University of California, Los Angeles (UCLA). Dr. Chakroborty is the author of a comprehensive design manual on solid rocket motor and liquid rocket engine design. He has authored and presented a number of technical papers at various national and international conferences and for a number of journals and is a member of several professional organizations. He is a Federal Aviation Administration-licensed pilot and has flown fighter planes, including the MiG-25. He holds a certificate for completion of the cosmonaut training program from the Yuri Gagarin Cosmonaut Training Center in Star City, Russia.

Ramon L. Chase is a Defense Advanced Research Projects Agency (DARPA) consultant for Analytic Services, Inc. He received his master's degree in public administration from the University of California. Mr. Chase consults for an advanced aircraft conceptual design activity under the FALCON program. He is a member of the DARPA government oversight team (Science, Mathematics, Engineering, and Technology). Mr. Chase has supported DARPA advanced launch vehicles; Responsive Access Small Cargo Affordable Launch (RASCAL); Force Application and Launch from Continental United States (FALCON); Common Aero Vehicle (CAV); and immune building programs and is an expert in the following fields: aircraft, missiles, weapons (including penetrators), reentry vehicles, and spacecraft design and analysis; expendable and reusable space launch vehicle design and analysis; long-range strategic planning; investigative studies; space policy; hypersonics; and technology readiness assessment. Mr. Chase has written more than 30 technical papers on advanced space transportation systems, military space planes, single-stage-to-orbit launch vehicles, orbital transfer vehicles, technology readiness assessment, and advanced propulsion systems. He is an AIAA associate fellow and has served on the AIAA Hypersonics Program Committee and the AIAA Space Transportation Technical Committee. Mr. Chase has chaired the Society of Automobile Engineers (SAE) Hypersonic Committee and the SAE Space Transportation Committee.

Gary S. Geyer, U.S. Air Force (retired), currently a private consultant, has 39 years of experience in space engineering and program management. He holds a B.S. in electrical engineering from Ohio State University, an M.S. in electrical engineering, and an M.S. in aeronautical engineering from the University of Southern California. Colonel Geyer served for 26 years with the National Reconnaissance Office (NRO) and was the NRO System Program Office director for two major programs, responsible for the design, manufacture, test, launch, and operation of several reconnaissance satellites. He was one of 46 "Pioneers of National Reconnaissance" honored by the NRO in 2000 for their "significant and lasting contributions to the discipline of national reconnaissance." Following his NRO service, he was vice president for a major classified program at Lockheed Martin, where he was responsible for all aspects of program and mission success. Colonel Geyer teaches courses in space design and in system engineering/program management at New Mexico State University.

Kenneth Gwinn joined Sandia National Laboratories after receiving his master's degree from Oklahoma State University. He works in the Solid Mechanics Department as a principal member of the technical staff. He has worked in many different engineering areas within the Engineering Sciences Center. This work includes vibration and shock design and analysis, in addition to nonlinear impact analyses. Mr. Gwinn has also worked in the Weapon Systems Center as the lead mechanical engineer for a reentry vehicle. He took entrepreneurial leave in 1995 from Sandia to assist in the commercialization of the Sandia air-bag technologies, which he helped invent. Mr. Gwinn has also published more than 40 technical papers and has been awarded eight patents dealing with air-bag research and development.

Ayanna Howard is an associate professor at the Georgia Institute of Technology, where she also holds the title of director of the Human-Automation Systems Laboratory, which carries out research and design of autonomy software based on human cognition. She holds a Ph.D. in electrical engineering with a minor in computer science from the University of Southern California. Her specialty is the development of techniques for reasoning and learning in space applications. Prior to joining Georgia Tech, she was employed by the Jet Propulsion Laboratory as a researcher in robotics. She has published more than 60 written works and released 10 software and hardware technologies for public licensing. Dr. Howard won the Institute of Electrical and Electronics Engineers (IEEE) Early Career Award in Robotics and Automation and the Lew Allen Award of Excellence for significant technical contributions, as well as a number of awards from NASA. She is the associate editor of the *International Journal of Intelligent Automation and Soft Computing*, a senior member of IEEE, a member of the American Association for Artificial Intelligence, and a senior member of the Society of Women Engineers.

Steven D. Howe is the director of the Center for Space Nuclear Research (CSNR) operated by the Universities Space Research Association and the Idaho National Laboratory. He received his Ph.D. in nuclear engineering from Kansas State University. The CSNR facilitates research in and education about nuclear technologies for space exploration and is currently engaged in developing new initiatives in nuclear power, nuclear propulsion, and advanced radioisotope power for space exploration. Prior to working at CSNR, Dr. Howe was employed at the Los Alamos National Laboratory (LANL). There, he oversaw the experimental nuclear data program element for the LANL nuclear weapons program. Dr. Howe has also worked on achieving several patents, including a container for transporting antiprotons and the antiproton production and delivery for the imaging and termination of undesirable cells. He has served as the chair of the NRC panel reviewing two of the NASA technology roadmaps: (1) In-Space Transportation and (2) High-Energy Power and Propulsion. He also served on the NRC Committee on Priorities for Space Science Enabled by Nuclear Power and Propulsion.

John R. Howell is the Ernest Cockrell, Jr., Memorial Chair and Baker Hughes Incorporated Centennial Professor of Mechanical Engineering at the University of Texas at Austin. He is a former director of the Advanced Manufacturing Center at the University of Texas. Professor Howell received his Ph.D. in engineering, his M.S. in chemical engineering, and his B.S. in chemical engineering, all from the Case Institute of Technology (now Case Western Reserve University). Professor Howell joined the faculty of the University of Texas at Austin. He has received national and international recognition for his continuing research in radiative transfer, particularly for adapting Monte Carlo techniques to radiative transfer analysis. His recent research has centered on inverse analysis techniques applied to the design and control of thermal systems with significant radiation transfer. Professor Howell served on the NRC Committee to Review and Assess Developmental Issues Concerning the Metal Parts Treater Design for the Blue Grass Chemical Agent Destruction Pilot Plant as well as on the NRC Panel on Benchmarking the Research Competitiveness of the United States in Mechanical Engineering. He is a member of the National Academy of Engineering.

John E. Hurtado is an associate professor in the Department of Aerospace Engineering for Texas A&M University. He received his Ph.D. in aerospace engineering from Texas A&M University. His current research interests include theoretical mechanics, structural dynamics, games, controls, and dynamics. Dr. Hurtado has worked in the Department of Aerospace Engineering for the past 6 years. Through his theoretical studies, his research has led to a better and clearer understanding of dynamic principles in three dimensions and to strong relationships between models of many-degrees-of-freedom physical systems and their representations as higher-dimensional bodies. Dr. Hurtado has published many technical papers and holds the following patents: Cooperative System and Method Using Mobile Robots for Testing a Cooperative Search Controller, Distributed Optimization System and Method, and Cooperating Mobile Robots.

Ramkumar Krishnan is a senior staff materials engineer in the Energy Technology Laboratory of Motorola's Embedded Systems Research Laboratories in Tempe, Arizona. He has also served as a lecturer and adjunct faculty in the Department of Electronic Systems at Arizona State University. He received his Ph.D. in materials science and engineering from MIT; an M.S. in chemical engineering from the University of Florida, Gainesville; and a bachelor's degree in technology, chemical, and electrochemical engineering from the Central Electrochemical Research Institute in Tamil Nadu, India. Dr. Krishnan's research interests are in the fields of fuel cells, batteries, and photovoltaics; the modeling of transport and kinetic processes in chemical and electrochemical systems; chemical and biological self-assembly; and the synthesis of nanoparticles, nanowires, nanotubes, and nanoporous materials for nanoelectronics and magnetic storage applications. He has published a variety of journal articles in nanotechnology-related areas and has delivered two invited lectures on portable energy technologies.

Ivett A. Leyva is a senior aerospace engineer in the Aerophysics Branch of the Space and Missile Propulsion Division of the Air Force Research Laboratory. There she focuses on the design of liquid rocket engines. She is an experimentalist, and currently she is studying the effects of acoustic fields on coaxial jets. She also works in the area of hypersonic boundary-layer transition. Previously, she was a senior aerodynamicist at Microcosm, Inc., where she was responsible for the development of ablative chambers and also performed numerical and analytical studies of subcomponents of Microcosm's launch vehicles. Prior to working at Microcosm she was employed at General Electric's (GE's) Global Research Center, where she led the design, development, and testing of several pulse detonation concepts. There, she coordinated joint projects with scientists from the former Soviet Union. Dr. Leyva holds several patents in the United States and Europe in the area of propulsion. She served on the NRC Committee on Air Force/Department of Defense Aerospace Propulsion and the Steering Committee on Decadal Survey of Civil Aeronautics. She also serves on the Aeronautics and Space Engineering Board.

Raymond Mariella is senior scientist for biosecurity and the director of the Lawrence Livermore National Laboratory's Center for Micro- and Nanotechnology. He received a Ph.D. from Harvard University in physical chemistry. Dr. Mariella is also chair of NASA's Science and Technology Working Group for the Advanced Environmental Monitoring and Control program. His previous employment was as a research associate at Allied Signal Corporate Research Center. His field of expertise is environmental monitoring and control. Dr. Mariella has delivered numerous talks and invited lectures in the general subject area of biodetection using nanoscale and microscale technologies. He is a recipient of the American Chemical Society's Award in Analytical Chemistry and the Texas Society of Professional Engineers' Award for Excellence in Mathematics, and he received the R&D 100 Award for the Autonomous Pathogen Detection System in 2004. He has participated in a number of workshops organized by the NRC.

Daniel Masys is professor and chair of the Department of Biomedical Informatics and professor of medicine for the Vanderbilt University School of Medicine. He received his M.D. from the Ohio State University College of Medicine. Dr. Masys's research interests include methods for analysis and metaanalysis of human immunodeficiency virus (HIV)-related epidemiology data, Internet utilities for conducting clinical research, and the analytical informatics of gene expression profiling using microarray technologies. Previously he served as the director of biomedical informatics at the University of California, San Diego (UCSD), School of Medicine; as the director of the UCSD Human Research Protections Program; and as professor of medicine. Dr. Masys served as chief of the International Cancer Research Data Bank of the National Cancer Institute, National Institutes of Health, and from 1986 through 1994 he was the director of the Lister Hill National Center for Biomedical Communications, which is the computer research and development division of the National Library of Medicine. In this capacity he was the principal architect and first director of the National Center for Biotechnology Information, which hosts the data from the Human Genome Project and other resources and tools for molecular biology. Dr. Masys was elected a member of the Institute of Medicine in 2001.

Edward McCullough is a principal scientist at the Boeing Company. He has received his professional schooling mainly in nuclear engineering through the U.S. Navy (gaining a certification for nuclear engineering). Mr. McCullough focuses on concept development and advanced technology at Rockwell Space System's Advanced Engineering and Boeing's Phantom Works. He has researched innovative methods to reduce the development time of technologies and systems from between 10 and 20 years down to 5 years. He has experienced successes in the area of chemistry and chemical engineering for extraterrestrial processing and photonics for vehicle management systems and communications. These efforts included leading a chemical process development research team in a Skunk Works environment for 4 years. Mr. McCullough has led efforts for biologically inspired multiparallax geometric situational awareness for advanced autonomous mobility and space manufacturing. He recently developed several patents, including patents for an angular sensing system, a method for enhancing the digestion reaction rates of chemical systems, and a system for mechanically stabilizing a bed of particulate media. Mr. McCullough has served in a variety of professional societies and councils. He is a member of the board of trustees for the University Space Research Association, a member of the Science Council for the Research Institute for Advanced Computer Science, and a charter member of the AIAA Space Exploration Program Committee.

Douglas Mehoke is the assistant group supervisor and advanced technology manager in the Space Department Mechanical Design Group and supervisor of the Thermal Design Section at the Johns Hopkins University Applied Physics Laboratory (JHU/APL). He holds an M.S. degree in mechanical engineering from Stanford University. He has worked in the field of spacecraft and instrument thermal design for more than 25 years and has a wide background in the fields of heat transfer and fluid mechanics. His current research interests include heat transfer in composite materials with high thermal conductivities and the design of thermally stable structures; he has detailed experience in the areas of thermal control materials, thermal modeling, electronic board thermal analysis, and convective heat transfer. Prior to joining the JHU/APL in 1983, he worked at the Lockheed Missiles and Space Company in the area of spacecraft thermal control. Mr. Mehoke has published extensively on the thermal aspects of spacecraft design. He received the Robert W. Hart Research and Development Award in 1998.

James F. Miller is the director of the Electrochemical Technology Program at the Argonne National Laboratory (ANL). Dr. Miller received a Ph.D. and a master's degree in physics from the University of Illinois at Urbana-Champaign. He also received a B.S. in physics from the University of Missouri at Columbia and an M.B.A. from the University of Chicago. He coordinates ANL's electrochemical technology efforts in six divisions, including research on advanced batteries and fuel cells for stationary, transportation, and portable power applications. Dr. Miller also coordinates all Argonne work on hydrogen production and storage for DOE/Energy Efficiency and Renewable Energy. He provides strategic planning and program development for ANL's battery and fuel cell efforts. Dr. Miller served as the conference chair for the 2nd International Symposium on Hydrogen in Matter. He is an author or coauthor of more than 100 publications or presentations in journals, books, technical reports, or conference proceedings and has served on numerous committees, including the NRC Committee on Wright Centers of Innovation, the NRC Review Committee for NASA's Low Emission Advanced Propulsion, the FreedomCAR Fuel Cell Tech Team, the ASME Fuel Cell Power Systems Committee, the International Energy Agency Advanced Fuel Cells for Transportation, and the U.S. DOE's Depleted Uranium R&D Uses Advisory Panel.

Todd J. Mosher is the director of advanced systems at Microsat Systems, Inc. Before working for Microsat Systems, he was the senior manager of advanced exploration systems for Lockheed Martin Space Systems Company. He has focused on the pursuit of NASA business associated with the Vision for Space Exploration, concentrating on in-space elements of the architecture. He also serves as the principal investigator for a strategic internal research and development project in autonomous rendezvous and docking. Dr. Mosher joined Lockheed Martin in the summer of 2005 after having served as an assistant professor at Utah State University (USU) in the Mechanical and Aerospace Engineering Department since 2002. While there, his research interests were small satellites and payloads, advanced space system concepts, and new design methodologies. He joined USU after serving as the associate director of the Space Architecture Department at the Aerospace Corporation. He led many of Aerospace's efforts in small spacecraft design. Dr. Mosher has more than 15 years of expertise in space systems engineering, especially related to NASA science missions and space transportation. Over the course of his career, he has also supported a variety of launch programs. Dr. Mosher previously served the NRC as chair of the Committee on NASA Communications and Navigation Capability in 2005 and as a member of the Committee for the Review of NASA's Pioneering Revolutionary Technology Program and its supporting Panel on Enabling Concepts and Technologies from 2001 to 2003.

Guillermo Trotti is the president of Trotti and Associates, Inc. (TAI). He received a master's degree in architecture from Rice University. TAI is a design and consulting firm helping private and public organizations around the world design and develop new solutions for buildings, structures, products, and technologies in the areas of architecture, industrial design, and aerospace. The company specializes in designing habitats, structures, and systems to operate in extreme environments. TAI has worked under contract with the NASA Institute of Advanced Concepts on a revolutionary mission architecture to explore the Moon with habitable rovers. The project Extreme Expeditionary Architecture: Mobile, Adaptable Systems for Space and Earth Exploration proposes self-mobilizing, transformable systems combining robotics, inflatable and foldable lightweight structures, intelligent materials, and highly autonomous systems to revolutionize human and machine exploration. TAI is also working with MIT on the Biosuit project, an advanced mechanical-counterpressure space suit for lunar and Mars surface exploration. Mr. Trotti is personally involved in every project as the lead designer and project director. He is a member of the American Institute of Architects as well as the Boston Society of Architects.

Gerald D. Walberg is the president of Walberg Aerospace. He received his Ph.D. in aerospace engineering from North Carolina State University and his M.S. and B.S. in aerospace engineering from Virginia Polytechnic Institute and State University. From 1957 to 1989, Dr. Walberg was employed at the NASA Langley Research Center, where he held positions ranging from research engineer to deputy director for space. Following his retirement from NASA, Dr. Walberg taught at the NASA/George Washington University Joint Institute for Advancement of Flight Sciences and then at North Carolina State University, where he was the director of the Mars Mission Research Center in the Department of Mechanical and Aerospace Engineering. In 1999 he retired from teaching and established Walberg Aerospace, a research company specializing in entry aerothermodynamics, trajectory optimization, and planetary mission analysis. Dr. Walberg was elected an AIAA fellow in 1988 and also gained Presidential Rank in the Meritorious Government Executive in 1988. He served on the NRC Committee on Space Facilities from 1993 to 1994.

Ian Walker is a professor in the Department of Electrical and Computer Engineering at Clemson University. He received his Ph.D. in electrical engineering from the University of Texas at Austin. Professor Walker's research centers on robotics, particularly novel manipulators and manipulation. His group is conducting basic research in the construction, modeling, and application of biologically inspired "trunk, tentacle, and worm" robots. Professor Walker is a fellow of the IEEE and a senior member of the AIAA. He currently serves as vice president for financial activities for the IEEE Robotics and Automation Society and is chair of the AIAA Technical Committee on Space Automation and Robotics. He has served on the editorial boards of *IEEE Transactions on Robotics*, *IEEE Transactions on Robotics and Automation, International Journal of Robotics and Automation, IEEE Robotics and Automation Magazine*, and *International Journal of Environmentally Conscious Design and Manufacturing.*

William W. Wang is currently a senior engineering specialist in the Propulsion Department of the Vehicle Systems Division of the Aerospace Corporation. He holds M.S. degrees (aeronautics and astronautics) from the University of Washington and a master of engineering from the Engineering Executive Program at UCLA. Mr. Wang has more than 25 years of experience in liquid propulsion systems and is an expert in liquid rocket engines for both U.S. and foreign space launch vehicles. He was a key member of several engine development programs. In addition, he has led many successful major engine test programs at both contractor and government test sites. His technical expertise is in propulsion system dynamics, combustion instability, and engine cycle performance.

Marilee J. Wheaton is the general manager of the Systems Engineering Division of the Aerospace Corporation. She held numerous positions at Aerospace between 1980 and 1999 and from 2002 to the present, with particular expertise in cost engineering using parametric modeling. Most recently, as general manager of the Computer Systems Division, she provided management and technical leadership for computer science and technology, computer systems engineering, and software acquisition. Ms. Wheaton started with Lockheed in 1979 as a manufacturing engineer and joined Aerospace the next year. In 1999, she moved to TRW Systems (now Northrop Grumman Mission Systems) as a director in the office of cost estimation. In 2002, she returned to Aerospace. Ms. Wheaton is the recipient of both the Parametrician of the Year Award and the Keith Burbridge Service Award from the International Society of Parametric Analysts and is the 2007 recipient of the University of Southern California (USC) Center for Systems and Software Engineering Lifetime Achievement Award. Ms. Wheaton has a B.A. in mathematics and Spanish from California Lutheran University and an M.S. in systems engineering from USC, and she is a graduate of the UCLA Executive Program in Management.

Appendix C

Questions Used by the Committee to Gather Data on Each Project

The questionnaire that the Committee to Review NASA's Exploration Technology Development Program used to gather data on the 22 individual projects that form the program contained the following questions.

1. *Status of the technology and the quality of the development effort:*
    a. What is the description of the technology? What function does it facilitate (i.e., what does the technology allow the system to do)?
    b. What is the development status (technology readiness level [TRL], etc.)?
    c. Are there gaps in the technology development effort within the technology area?
    d. What is the quality of the NASA effort in development, and what are the international benchmarks against which this technology development is compared?
    e. What is the degree of non-NASA development of the technology, and what is the possibility that non-NASA sources will develop a competing or alternative technology that NASA could use?
    f. What is the team involved? Does the team have adequate training, experience, and capabilities? Is the team working in a coordinated manner? Could additional members strengthen the team?
    g. Are appropriate non-NASA entities involved (other national laboratories, universities, industry)?
    h. Are facilities identified adequate to mature the technology?
    i. Are metrics appropriate and in use?

2. *Technology development plan:*
    j. What is the technology roadmap or plan for development?
    k. What is the projected date by which the technology will become available (e.g., TRL 6)? How does this compare with the timing of the need?
    l. What are the risks in meeting that schedule?
    m. Does the development depend in a critical way on non-NASA outcomes?
    n. What is the projected cost of development (including testing and verification to allow insertion)?
    o. Is there a plan to transition the technology, and an industrial base equipped to absorb the technology and successfully deploy it into working systems?

3. *Impact of the technology and the capacity for transitioning to customers:*
   - p. Does the technology have architectural benefit (i.e., does it enable new design or operational architectures that deliver significant improved capability, lower costs, or operational risks)?
   - q. Does the technology have performance benefit (i.e., significantly change the performance, risk, or cost, but not differentiate among architectures)?
   - r. Is the technology robust in the face of possible changes to the architecture, and extensible to other exploration class missions, e.g., Mars?
   - s. What is the backup plan to high-risk development efforts?

Appendix D

Definitions of Technology Readiness Levels

Table D.1, “Technology Readiness Levels (TRLs),” is reprinted from Appendix J of NPR [NASA Procedural Requirements] 7120.8, “NASA Research and Technology Program and Project Management Requirements.” (That document is still in draft form, but the definitions in it will supersede the previous TRL definitions.)

TABLE D.1 Technology Readiness Levels (TRLs)

TRL	Definition	Hardware Description	Software Description	Exit Criteria
1	Basic principles observed and reported.	Scientific knowledge generated underpinning hardware technology concepts/applications.	Scientific knowledge generated underpinning basic properties of software architecture and mathematical formulation.	Peer reviewed publication of research underlying the proposed concept/application.
2	Technology concept and/or application formulated.	Invention begins, practical application is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture.	Practical application is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture. Basic properties of algorithms, representations and concepts defined. Basic principles coded. Experiments performed with synthetic data.	Documented description of the application/concept that addresses feasibility and benefit.
3	Analytical and experimental critical function and/or characteristic proof of concept.	Analytical studies place the technology in an appropriate context and laboratory demonstrations, modeling and simulation validate analytical prediction.	Development of limited functionality to validate critical properties and predictions using non-integrated software components.	Documented analytical/experimental results validating predictions of key parameters.

continued

TABLE D.1 Continued

TRL	Definition	Hardware Description	Software Description	Exit Criteria
4	Component and/or breadboard validation in laboratory environment.	A low fidelity system/ component breadboard is built and operated to demonstrate basic functionality and critical test environments, and associated performance predictions are defined relative to the final operating environment.	Key, functionally critical, software components are integrated, and functionally validated, to establish interoperability and begin architecture development. Relevant environments defined and performance in this environment predicted.	Documented test performance demonstrating agreement with analytical predictions. Documented definition of relevant environment.
5	Component and/or breadboard validation in relevant environment.	A medium fidelity system/ component brassboard is built and operated to demonstrate overall performance in a simulated operational environment with realistic support elements that demonstrates overall performance in critical areas. Performance predictions are made for subsequent development phases.	End-to-end software elements implemented and interfaced with existing systems/ simulations conforming to target environment. End-to-end software system, tested in relevant environment, meeting predicted performance. Operational environment performance predicted. Prototype implementations developed.	Documented test performance demonstrating agreement with analytical predictions. Documented definition of scaling requirements.
6	System/ subsystem model or prototype demonstration in an operation environment.	A high-fidelity system/ component prototype that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate operations under critical environmental conditions.	Prototype implementations of the software demonstrated on full-scale realistic problems. Partially integrate with existing hardware/software systems. Limited documentation available. Engineering feasibility fully demonstrated.	Documented test performance demonstrating agreement with analytical predictions.
7	System prototype demonstration in an operational environment.	A high fidelity engineering unit that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate performance in the actual operational environment and platform (ground, airborne, or space).	Prototype software exists having all key functionality available for demonstration and test. Well integrated with operational hardware/software systems demonstrating operational feasibility. Most software bugs removed. Limited documentation available.	Documented test performance demonstrating agreement with analytical predictions.
8	Actual system completed and “flight qualified” through test and demonstration.	The final product in its final configuration is successfully demonstrated through test and analysis for its intended operational environment and platform (ground, airborne, or space).	All software has been thoroughly debugged and fully integrated with all operational hardware and software systems. All user documentation, training documentation, and maintenance documentation completed. All functionality successfully demonstrated in simulated operational scenarios. Verification and Validation (V&V) completed.	Documented test performance verifying analytical predictions.

continued

TABLE D.1 Continued

TRL	Definition	Hardware Description	Software Description	Exit Criteria
9	Actual system flight proven through successful mission operations.	The final product is successfully operated in an actual mission.	All software has been thoroughly debugged and fully integrated with all operational hardware/software systems. All documentation has been completed. Sustaining software engineering support is in place. System has been successfully operated in the operational environment.	Documented mission operational results.

NOTE: Generic TRL descriptions are found in NASA, *NASA Systems Engineering Processes and Requirements,* NPR 7123.1, Table G-19.

Appendix E

Acronyms

A4O	Autonomy for Operations
Al-Li	aluminum-lithium
ALHAT	Autonomous Landing and Hazard Avoidance Technology
ARC	Ames Research Center
AR&D	Automated Rendezvous and Docking
AR&DST	Automated Rendezvous and Docking Sensor Technology
AVGS	Advanced Video Guidance Sensor
CELSS	Controlled Ecological Life Support System
CEV	Crew Exploration Vehicle
CFM	Cryogenic Fluid Management
CONOPS	concept of operations
CSPE	Colorimetric Solid Phase Extraction
DARPA	Defense Advanced Research Projects Agency
DOD	Department of Defense
DOE	Department of Energy
DTM	Development Test Model
ELS	Exploration Life Support
EM	Engineering Model
ENose	Electronic Nose
ESMD	Exploration Systems Mission Directorate
ETDP	Exploration Technology Development Program
EVA	extravehicular activity
FDR	Final Design Review
FPDS	Fire Prevention, Detection, and Suppression
FSP	Fission Surface Power

FY	fiscal year
GRC	Glenn Research Center
GSFC	Goddard Space Flight Center
HRP	Human Research Program
ISD	Intelligent Software Design
ISHM	Integrated Systems Health Management
ISRU	In Situ Resource Utilization
ISS	International Space Station
JIMO	Jupiter Icy Moons Orbiter
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
KSC	Kennedy Space Center
LANL	Los Alamos National Laboratory
LaRC	Langley Research Center
LCROSS	Lunar Crater Observation and Sensing Satellite
lidar	Light Detection and Ranging
LLPO	Lunar Lander Projects Office
LOCAD	Lab-on-a-Chip Application Development
LOX/CH_4	liquid oxygen/methane
LOX/LH_2	liquid oxygen/liquid hydrogen
LRO	Lunar Reconnaissance Orbiter
MER	Mars Exploration Rover
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NERVA	Nuclear Engine for Rocket Vehicle Applications
NFIR	Natural Feature Image Recognition
NGAVGS	Next Generation Advanced Video Guidance Sensor
NRC	National Research Council
NTO/MMH	nitrogen tetroxide/monomethyl hydrazine
NTP	nuclear thermal propulsion
NTR	nuclear thermal rocket
PCAD	Propulsion and Cryogenics Advanced Development
PCAI	Power, Communications, Avionics, and Informatics
PDR	Preliminary Design Review
PLSS	Portable Life Support System
R&D	research and development
RAT	research and technology
RCS	reaction control system
RFP	request for proposal
RHESE	Radiation-Hardened Electronics for Space Environments

RMAT	Risk Mitigation Analysis Tool
SAME	Smoke and Aerosol Measurement Experiment
SBIR	Small Business Innovation Research
SiGe	silicon germanium
STTR	Small Business Technology Transfer
TCS	Thermal Control Systems
TPS	thermal protection system
TRL	technology readiness level
V&V	validation and verification
VCAM	Vehicle Cabin Atmosphere Monitor
VNS	Vision Navigation Sensor
VPU	Vegetable Production Unit
VSE	Vision for Space Exploration
ZBOT	Zero Boil Off Tank (Experiment)

Appendix F

The Constellation Program

NASA's Constellation Program is currently composed of the four development programs described below: Orion, Altair, Ares I, and Ares V.

- *Orion*—According to NASA, "Orion will be capable of carrying crew and cargo to the space station. It will be able to rendezvous with a lunar landing module and an Earth departure stage in low-Earth orbit to carry crews to the moon and, one day, to Mars-bound vehicles assembled in low-Earth orbit. Orion will be the Earth entry vehicle for lunar and Mars returns. Orion's design will borrow its shape from the capsules of the past, but takes advantage of 21st century technology in computers, electronics, life support, propulsion and heat protection systems."[1]
- *Altair*—According to NASA, "Altair will be capable of landing four astronauts on the moon, providing life support and a base for weeklong initial surface exploration missions, and returning the crew to the Orion spacecraft that will bring them home to Earth. Altair will launch aboard an Ares V rocket into low Earth orbit, where it will rendezvous with the Orion crew vehicle."[2]
- *Ares I*—According to NASA, "Future astronauts will ride to orbit on Ares I, which uses a single five-segment solid rocket booster, a derivative of the space shuttle's solid rocket booster, for the first stage. A liquid oxygen/liquid hydrogen J-2X engine derived from the J-2 engine used on Apollo's second stage will power the crew exploration vehicle's second stage. The Ares I can lift more than 55,000 pounds to low Earth orbit."[3]
- *Ares V*—According to NASA, "Ares V, a heavy lift launch vehicle, will use five RS-68 liquid oxygen/liquid hydrogen engines mounted below a larger version of the space shuttle's external tank, and two five-segment solid propellant rocket boosters for the first stage. The upper stage will use the same J-2X engine as the Ares I. The Ares V can lift more than 286,000 pounds to low Earth orbit and stands approximately 360 feet tall. This versatile system will be used to carry cargo and the components into orbit needed to go to the moon and later to Mars."[4]

---

[1] See http://www.nasa.gov/mission_pages/constellation/orion/index.html. Accessed May 18, 2008.

[2] See http://www.nasa.gov/mission_pages/constellation/altair/index.html. Accessed May 18, 2008.

[3] See http://www.nasa.gov/mission_pages/constellation/ares/index.html. Accessed May 18, 2008.

[4] See http://www.nasa.gov/mission_pages/constellation/ares/index.html. Accessed May 18, 2008.

Appendix G

Mapping of Bioastronautics Roadmap Risks to Relevant Projects of the Exploration Technology Development Program

TABLE G.1 Mapping Between Bioastronautics Roadmap Risks and Relevant ETDP Projects

Selected ETDP Projects, by Number and Name	Bioastronautics Roadmap Risks (BRM), by Number	Other Reference Documents
03 Lunar Dust Mitigation	Risk #33: Monitor External Environment, Lack of remedial action poses of crew health risk for chemical composition of dust, particulate size Risk #37: Provide Space Suits and Portable Life Support Systems “Lunar and Mars and dust contamination leading to suit failure”	Risk of Adverse Health Affects from Lunar Dust Exposure. It is clear that prolonged exposure to rock dust is harmful, but it is not clear if exposure to regolith dust is more or less harmful than terrestrial rock dust. Research into this area may determine if exposure limits need to be changed, and/or if additional medical treatment capability is required. (1,2)
10 Autonomy for Operations	Risk #26: Mismatch Between Crew Cognitive Capabilities and Task Demands Risk #45: Poorly Integrated Ground, Crew, and Automation Functions	Risk of Impaired Ability to Maintain Control of Vehicles and Other Complex Systems: It has been shown that long duration spaceflight alters sensimotor functions which manifests as changes in locomotion, gaze control, dynamic visual acuity, and perception. (1,2)
12 Autonomous Landing and Hazard Avoidance Technology	Risk #26: Mismatch Between Crew Cognitive Capabilities and Task Demands	Risk of Impaired Ability to Maintain Control of Vehicles and Other Complex Systems: It has been shown that long duration spaceflight alters sensimotor functions which manifests as changes in locomotion, gaze control, dynamic visual acuity, and perception. (1,2)
13 Automated Rendezvous and Docking Sensors	Risk #26: Mismatch Between Crew Cognitive Capabilities and Task Demands	Risk of Impaired Ability to Maintain Control of Vehicles and Other Complex Systems: It has been shown that long duration spaceflight alters sensimotor functions which manifests as changes in locomotion, gaze control, dynamic visual acuity, and perception.

continued

TABLE G.1 Continued

Selected ETDP Projects, by Number and Name	Bioastronautics Roadmap Risks (BRM), by Number	Other Reference Documents
14 Exploration Life Support		HRP [Human Research Program] requirements are derived from the Exploration Architecture Requirements Document-Section TBD, ESMD Implementation Plan-Page 18, (NP-2006-11-448-HQ), NASA Space Flight Human Systems Standards [SFHSS], Vol. I: Crew Health (SFHSS Vol. 1) and NASA Space Flight Human Systems Standards, Vol. II: Habitability and Environmental Health (SFHSS Vol. 2) (1,2)
15 Advanced Environmental Monitoring and Control		HRP requirements are derived from the Exploration Architecture Requirements Document-Section TBD, ESMD Implementation Plan-Page 18, (NP-2006-11-448-HQ), NASA Space Flight Human Systems Standards, Vol. I: Crew Health (SFHSS Vol. 1) and NASA Space Flight Human Systems Standards, Vol. II: Habitability and Environmental Health (SFHSS Vol. 2)
17 Extravehicular Activity Technologies	Risk #26: Mismatch Between Crew Cognitive Capabilities and Task Demands	HHC Risk of Compromised EVA [Extravehicular Activity] Performance and crew Health Due to Inadequate EVA Suit Systems: Improperly designed EVA suits can result in the inability of the crew to perform as expected, and can cause mechanical and decompression injury. Suit developers must fully understand the impact of the suit design on crew performance and health to ensure properly designed mobility, pressures, nutrition, life support, etc. (1,2)
	Risk #1: Accelerated Bone Loss and Fracture Risk Risk #2: Impaired Fracture Healing Risk #3: Injury to Joints and Intervertebral Structures Risk #6: Diminished Cardiac and Vascular Function Risk #11: Reduced Muscle Mass, Strength, and Endurance Risk #12: Increased Susceptibility to Muscle Damage Risk #30: Chronic and Degenerative Tissue Risks (due to Radiation Exposure) Risk #31: Acute Radiation Risks Risk #37: Provide Space Suits and Portable Life Support Systems	Risk of Adverse Health Affects from Lunar Dust Exposure: It is clear that prolonged exposure to rock dust is harmful, but it is not clear if exposure to regolith dust is more or less harmful than terrestrial rock dust. Research into this area may determine if exposure limits need to be changed, and/or if additional medical treatment capability is required.

continued

TABLE G.1 Continued

Selected ETDP Projects, by Number and Name	Bioastronautics Roadmap Risks (BRM), by Number	Other Reference Documents
21 Supportability	Risk #26: Mismatch Between Crew Cognitive Capabilities and Task Demands	Risk of Impaired Ability to Maintain Control of Vehicles and Other Complex Systems: It has been shown that long duration spaceflight alters sensimotor functions which manifests as changes in locomotion, gaze control, dynamic visual acuity, and perception. (1,2)
22 Human-Robotic Systems/Analogs	Risk #26: Mismatch Between Crew Cognitive Capabilities and Task Demands	Risk of Impaired Ability to Maintain Control of Vehicles and Other Complex Systems: It has been shown that long duration spaceflight alters sensimotor functions which manifests as changes in locomotion, gaze control, dynamic visual acuity, and perception (1,2)

1. HRP-47052, Revision A. The Human Research Program [HRP] Requirements Document, Human Research Program, which was baselined in July, 2007, established the flow down of requirements from the Exploration Systems Mission Directorate (ESMD) and the Office of Chief Health Medical Officer (OCHMO) to the HRP Program Elements to ensure delivery of countermeasures and technologies that satisfy ESMD's and OCHMO's exploration mission requirements.
2. RMAT reviews medical risks in terms of probability, impact and proposals for mitigating the risks, and reviews each risk in terms of multiple mission architectures (short duration Earth orbital, ISS [International Space Station] 6 month, ISS 12 month, short duration Lunar sortie, long duration Lunar Mission and Mars Mission). The results are embodied in HRP-47052.
3. NP-2006-11-448-HQ.
4. NASA Space Flight Human Systems Standards, Vol. I: Crew Health (SFHSS Vol. 1).
5. NASA Space Flight Human Systems Standards, Vol. II: Habitability and Environmental Health (SFHSS Vol. 2).

Appendix H

Description of the Exploration Technology Development Program

A presentation, “Exploration Technology Development Program (ETDP) Overview,” from Frank Peri, Program Manager, Exploration Technology Development Program, NASA, to the Exploration Technology Development Program on October 10-11, 2007, in Washington D.C., is reprinted in its entirety, as received, in this appendix.

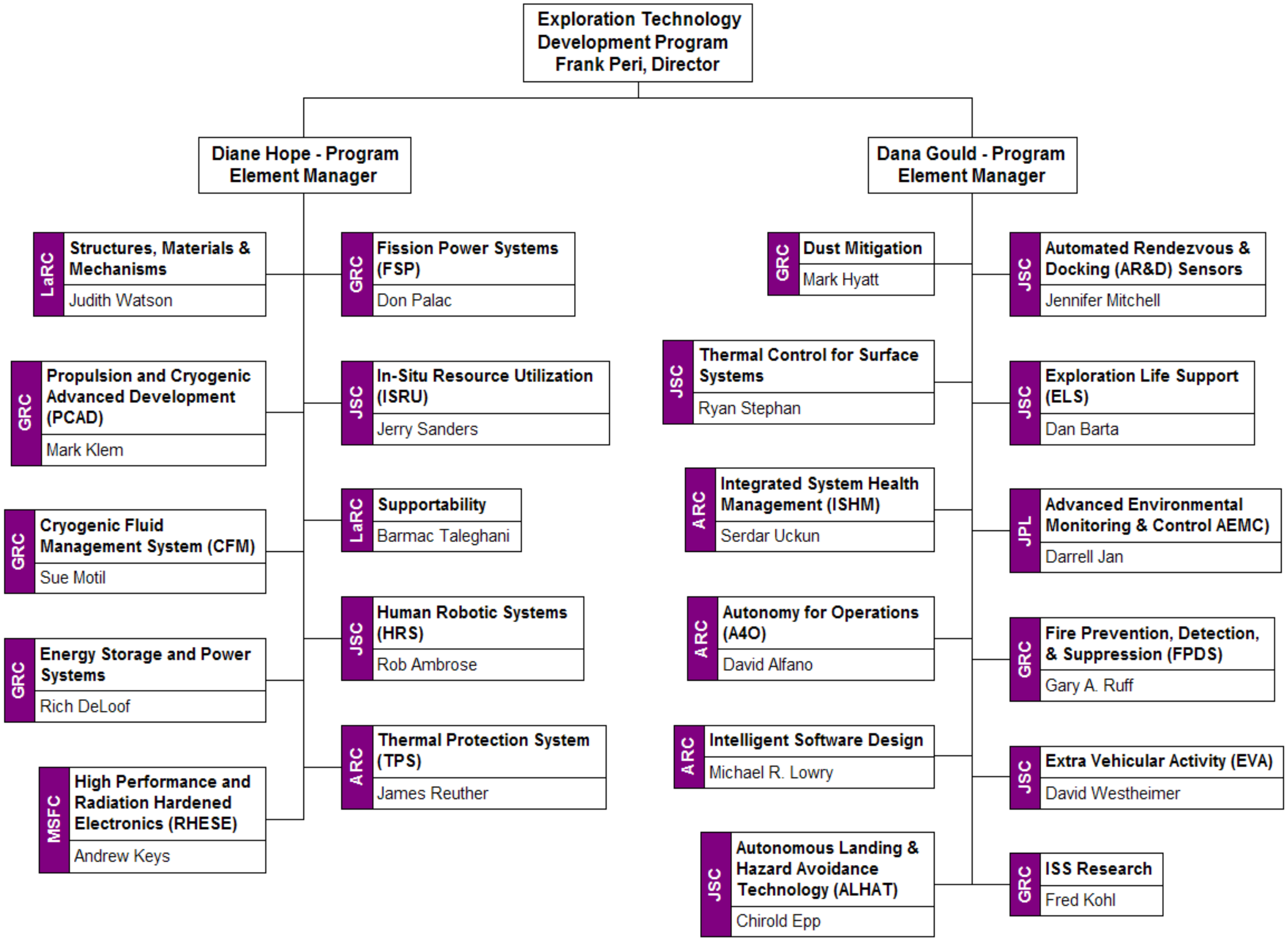
Exploration Technology Development Program (ETDP) Overview

11 October 2007

Frank Peri

Program Manager

ETDP Projects



Exploration Technology Development Program
Frank Peri, Director

Diane Hope - Program Element Manager

- LaRC — **Structures, Materials & Mechanisms** — Judith Watson
- GRC — **Propulsion and Cryogenic Advanced Development (PCAD)** — Mark Klem
- GRC — **Cryogenic Fluid Management System (CFM)** — Sue Motil
- GRC — **Energy Storage and Power Systems** — Rich DeLoof
- MSFC — **High Performance and Radiation Hardened Electronics (RHESE)** — Andrew Keys
- GRC — **Fission Power Systems (FSP)** — Don Palac
- JSC — **In-Situ Resource Utilization (ISRU)** — Jerry Sanders
- LaRC — **Supportability** — Barmac Taleghani
- JSC — **Human Robotic Systems (HRS)** — Rob Ambrose
- ARC — **Thermal Protection System (TPS)** — James Reuther

Dana Gould - Program Element Manager

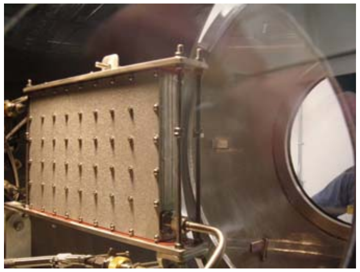
- GRC — **Dust Mitigation** — Mark Hyatt
- JSC — **Thermal Control for Surface Systems** — Ryan Stephan
- ARC — **Integrated System Health Management (ISHM)** — Serdar Uckun
- ARC — **Autonomy for Operations (A4O)** — David Alfano
- ARC — **Intelligent Software Design** — Michael R. Lowry
- JSC — **Autonomous Landing & Hazard Avoidance Technology (ALHAT)** — Chirold Epp
- JSC — **Automated Rendezvous & Docking (AR&D) Sensors** — Jennifer Mitchell
- JSC — **Exploration Life Support (ELS)** — Dan Barta
- JPL — **Advanced Environmental Monitoring & Control AEMC)** — Darrell Jan
- GRC — **Fire Prevention, Detection, & Suppression (FPDS)** — Gary A. Ruff
- JSC — **Extra Vehicular Activity (EVA)** — David Westheimer
- GRC — **ISS Research** — Fred Kohl

97

Technology Development for Orion

AR&D Sensors: Characterizing optical and laser sensors that measure the range and orientation of a target vehicle during autonomous rendezvous and docking.

Structures & Materials: Developing lightweight, high-strength parachute materials.



Thermal Control: Developing prototype flash evaporator, sublimator, and composite radiator for thermal control during different phases of mission.

Ablative TPS: Qualifying thermal protection system materials in arcjet tests and developing a prototype heat shield.

Exploration Life Support: Developing a prototype carbon dioxide and moisture removal system.

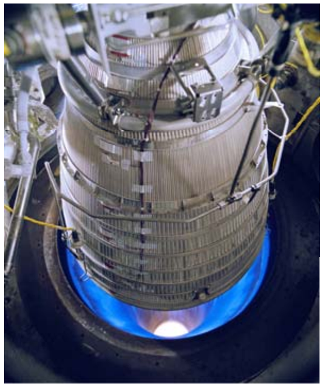
Technology Development for Ares

Structures & Materials: Developing friction stir welding and spin forming manufacturing processes for Ares I Upper Stage propellant tanks.

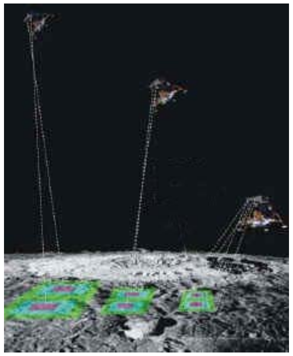
Integrated Systems Health Monitoring: Developing health monitoring system for Solid Rocket Motor.

Technology Development for the Lunar Lander

Propulsion & Cryogenics: Prototype LOX-Methane engine for ascent stage



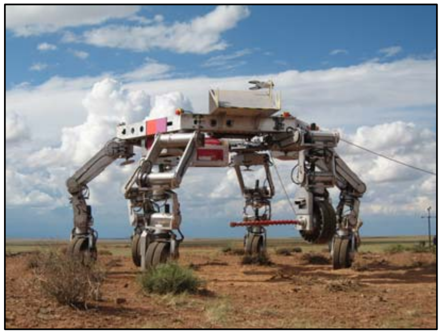
Propulsion & Cryogenics: Prototype deep throttling RL-10 engine for descent stage



Autonomous Precision Landing: Guidance algorithms and lidar sensors to enable precision landing and hazard avoidance.

Propulsion & Cryogenics: Zero boil off cryogenic propellant storage to enable long duration missions

Technology Development for the Lunar Outpost



Human Robotic Systems: Developing surface mobility systems to transport crew and large payloads across lunar surface.

Energy Storage: Developing lithium-ion batteries and regenerative fuel cells to power lunar surface systems.

Fission Surface Power: Developing concepts and technologies for affordable nuclear power systems.

Structures & Materials: Developing structural concepts for lunar surface habitats.

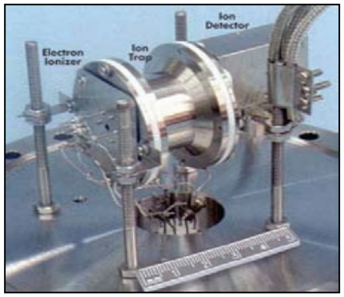
In-Situ Resource Utilization: Developing systems to produce oxygen from lunar regolith

Dust Mitigation: Characterizing effects of lunar dust on surface systems and developing technologies to prevent dust accumulation.

Technology Development for ISS

LOCAD-PTS

Advanced Environmental Monitoring & Control: Developing ENose and Vehicle Cabin Air Monitor (VCAM) instruments to detect atmospheric contaminants, and LOCAD-PTS instrument to detect harmful bacteria.

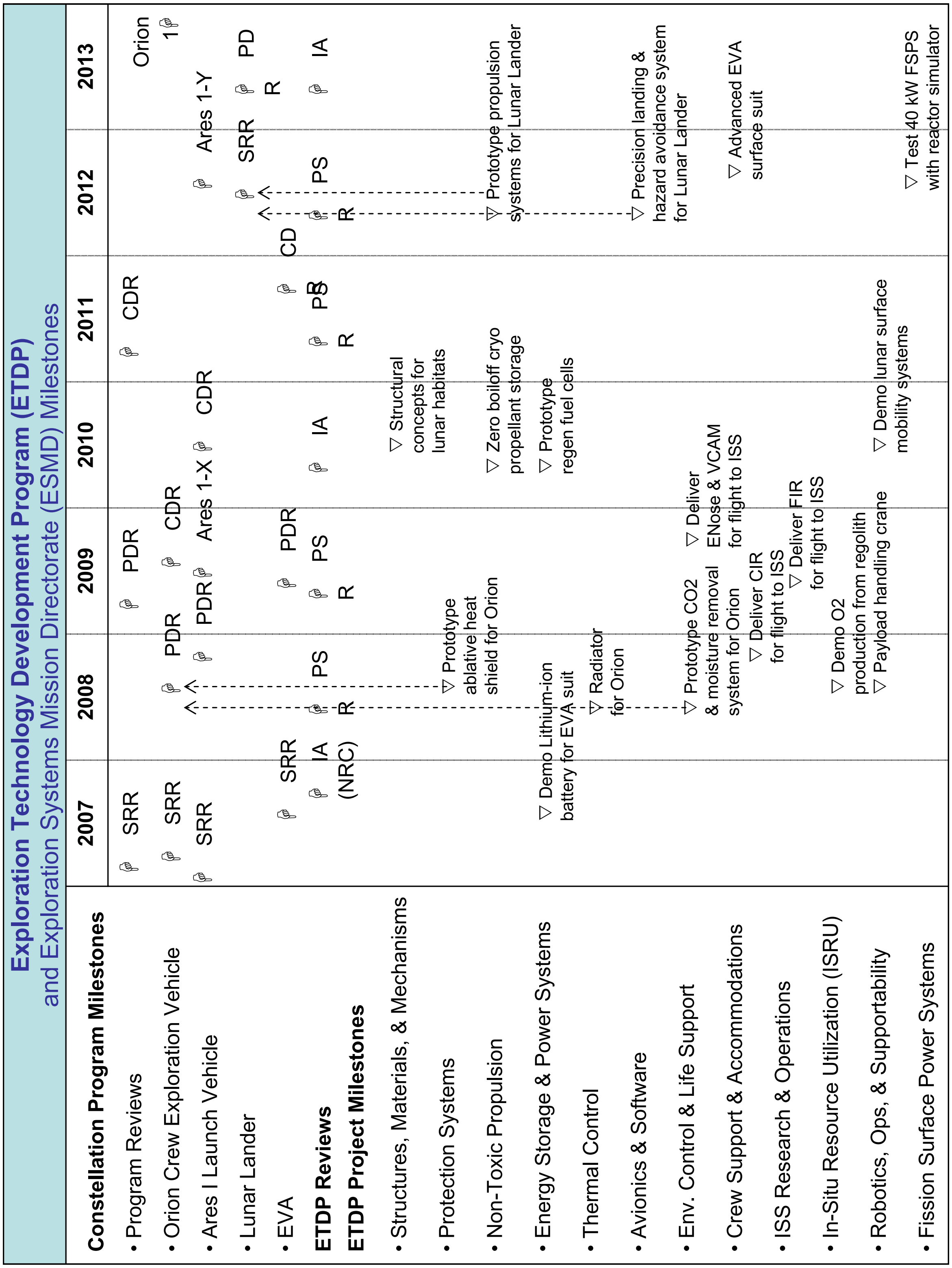


VCAM

CIR

ISS Research: Developing Combustion Integrated Rack (CIR) and Fluids Integrated Rack (FIR) to conduct basic microgravity research on combustion and fluid physics

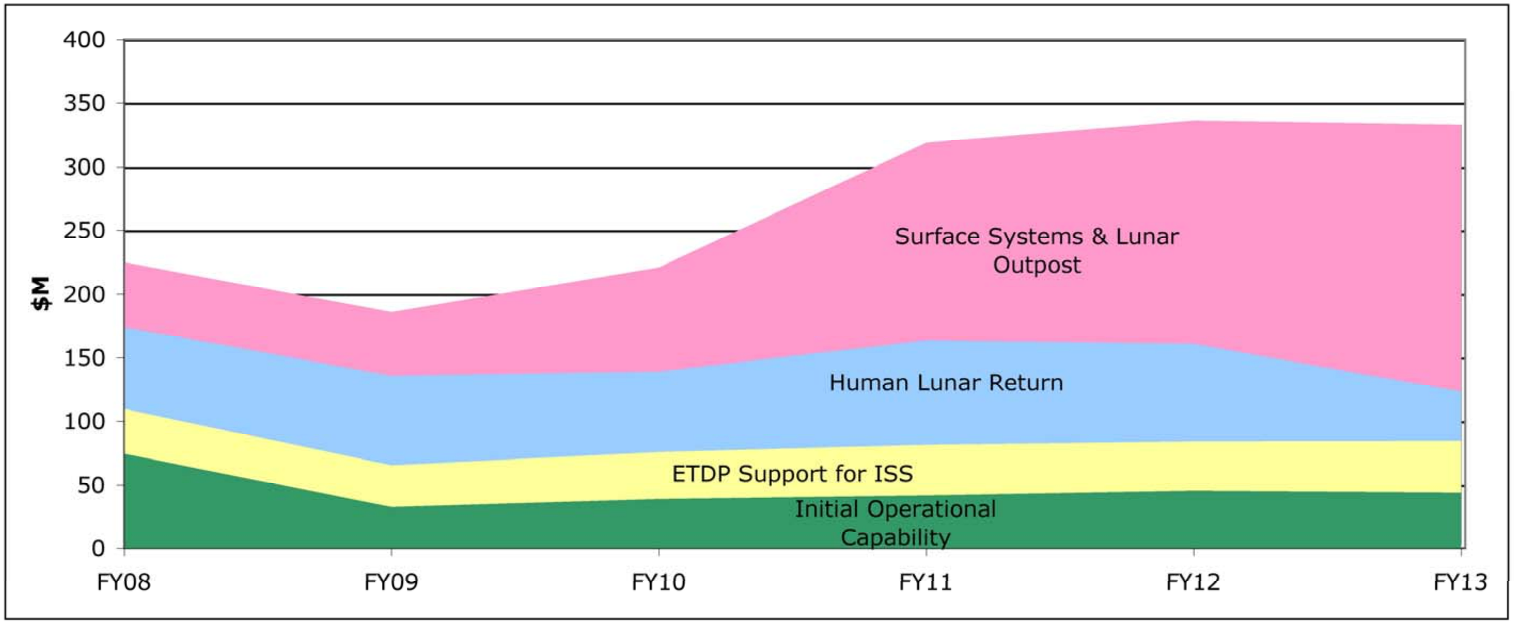
FIR


Exploration Technology Development Program (ETDP)
and Exploration Systems Mission Directorate (ESMD) Milestones
2007
2008
2009
2010
2011
2012
2013
Constellation Program Milestones
• Program Reviews
• Orion Crew Exploration Vehicle
• Ares I Launch Vehicle
• Lunar Lander
• EVA
ETDP Reviews
ETDP Project Milestones
• Structures, Materials, & Mechanisms
• Protection Systems
• Non-Toxic Propulsion
• Energy Storage & Power Systems
• Thermal Control
• Avionics & Software
• Env. Control & Life Support
• Crew Support & Accommodations
• ISS Research & Operations
• In-Situ Resource Utilization (ISRU)
• Robotics, Ops, & Supportability
• Fission Surface Power Systems
SRR
PDR
CDR
Orion 1
SRR
PDR
CDR
SRR
PDR
Ares 1-X
CDR
Ares 1-Y
SRR
PDR
SRR
PDR
CDR
IA (NRC)
PS
PS
IA
PS
PS
IA
R
R
R
R
▽ Structural concepts for lunar habitats
▽ Prototype ablative heat shield for Orion
▽ Zero boiloff cryo propellant storage
▽ Prototype propulsion systems for Lunar Lander
▽ Demo Lithium-ion battery for EVA suit
▽ Prototype regen fuel cells
▽ Radiator for Orion
▽ Precision landing & hazard avoidance system for Lunar Lander
▽ Prototype CO2 & moisture removal system for Orion
▽ Deliver ENose & VCAM for flight to ISS
▽ Advanced EVA surface suit
▽ Deliver CIR for flight to ISS
▽ Deliver FIR for flight to ISS
▽ Demo O2 production from regolith
▽ Payload handling crane
▽ Demo lunar surface mobility systems
▽ Test 40 kW FSPS with reactor simulator

Project Partnerships - examples

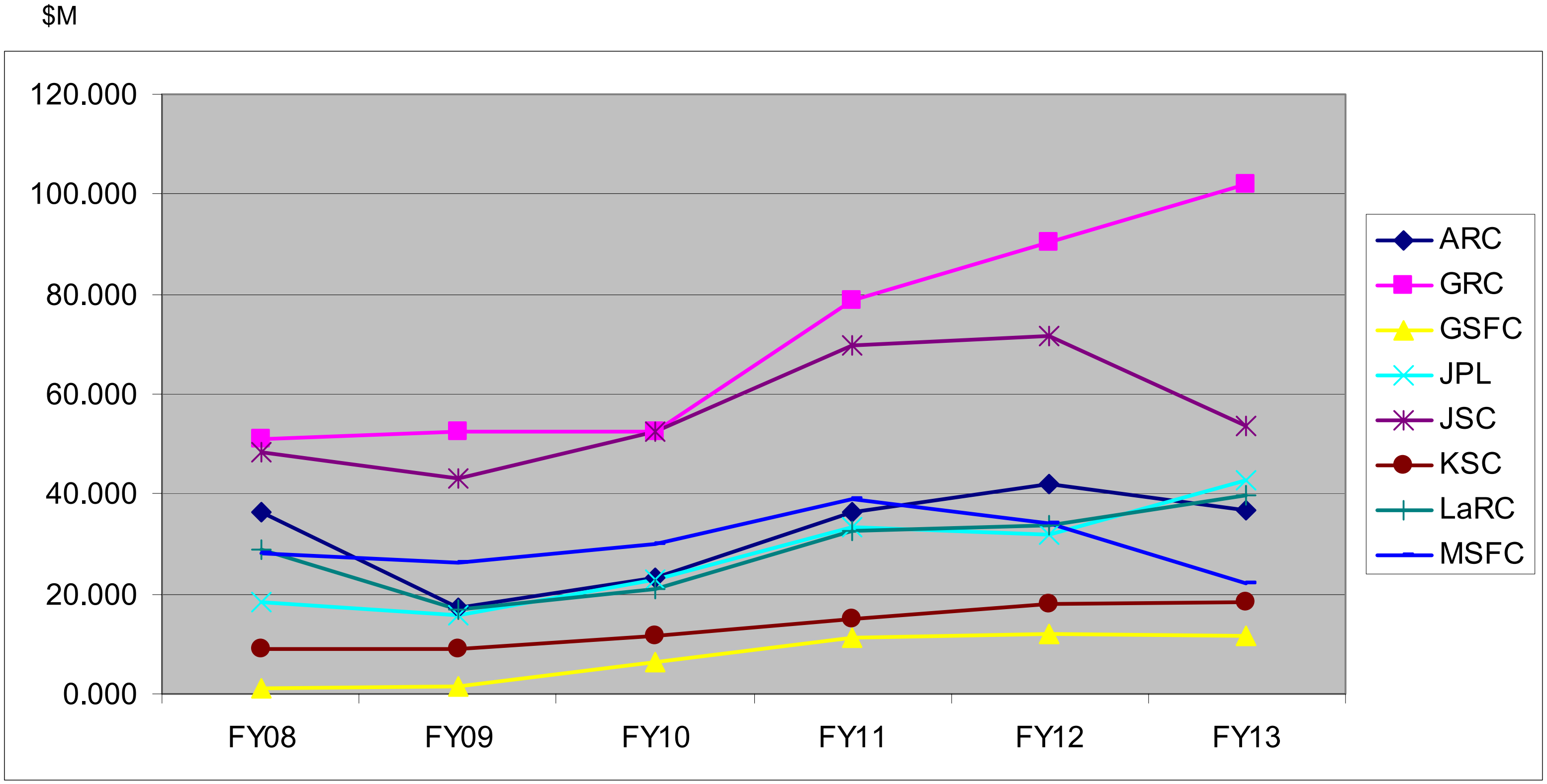
DOE - Fission Surface Power - architecture studies
Georgia Tech - systems analysis, low-temp avionics
NORCAT - ISRU drill
AFRL - autonomy sw, SIRF avionics
Draper, APL, Lincoln Labs - GN&C algorithms
Caterpillar - mobility system supervisor
Michelin - mobility Tweel development (Segway)
Hamilton Sundstrand - environmental systems
Lockheed-Martin Denver (LMA)/Orbitec - Oxygen production from regolith
PWR, NGST, Aerojet - propulsion systems

ETDP Supports Multiple Mission Needs

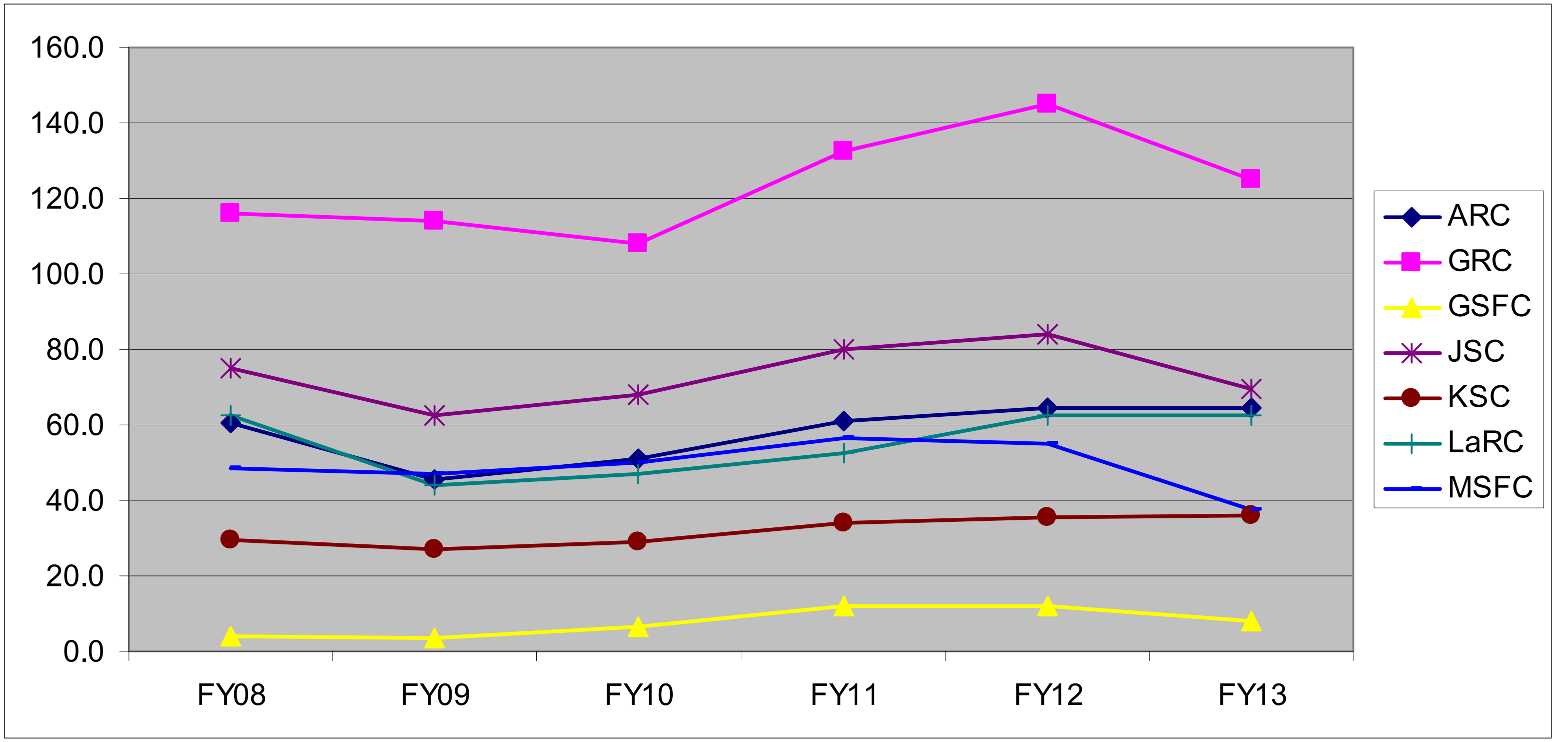


- IOC is support for Orion, Ares I
- Human Lunar Return is support for Ares V and Lunar Lander
- Chart excludes ESMD Program Support, Program Office Operations, and Integration

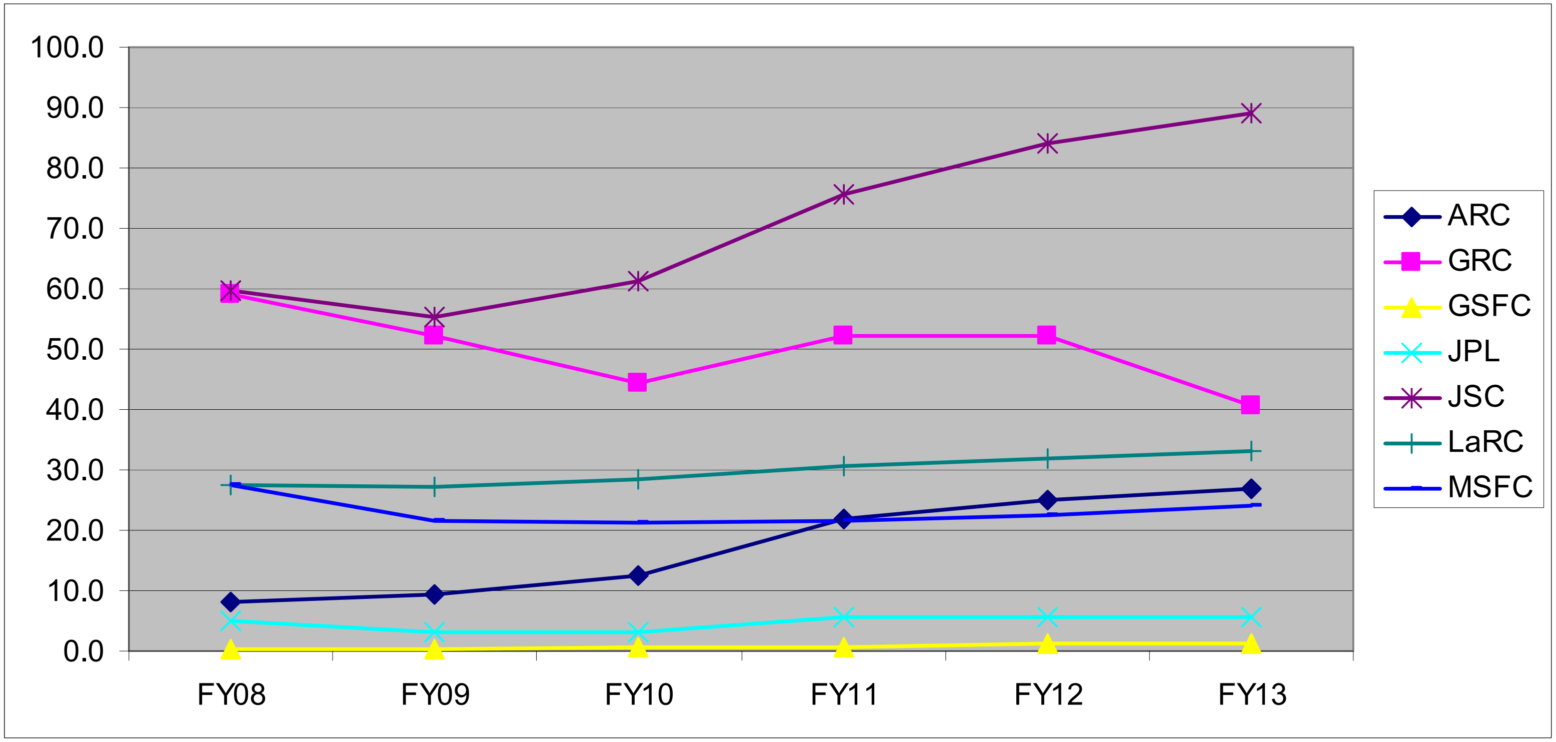
FY08-13 Dollars by Center



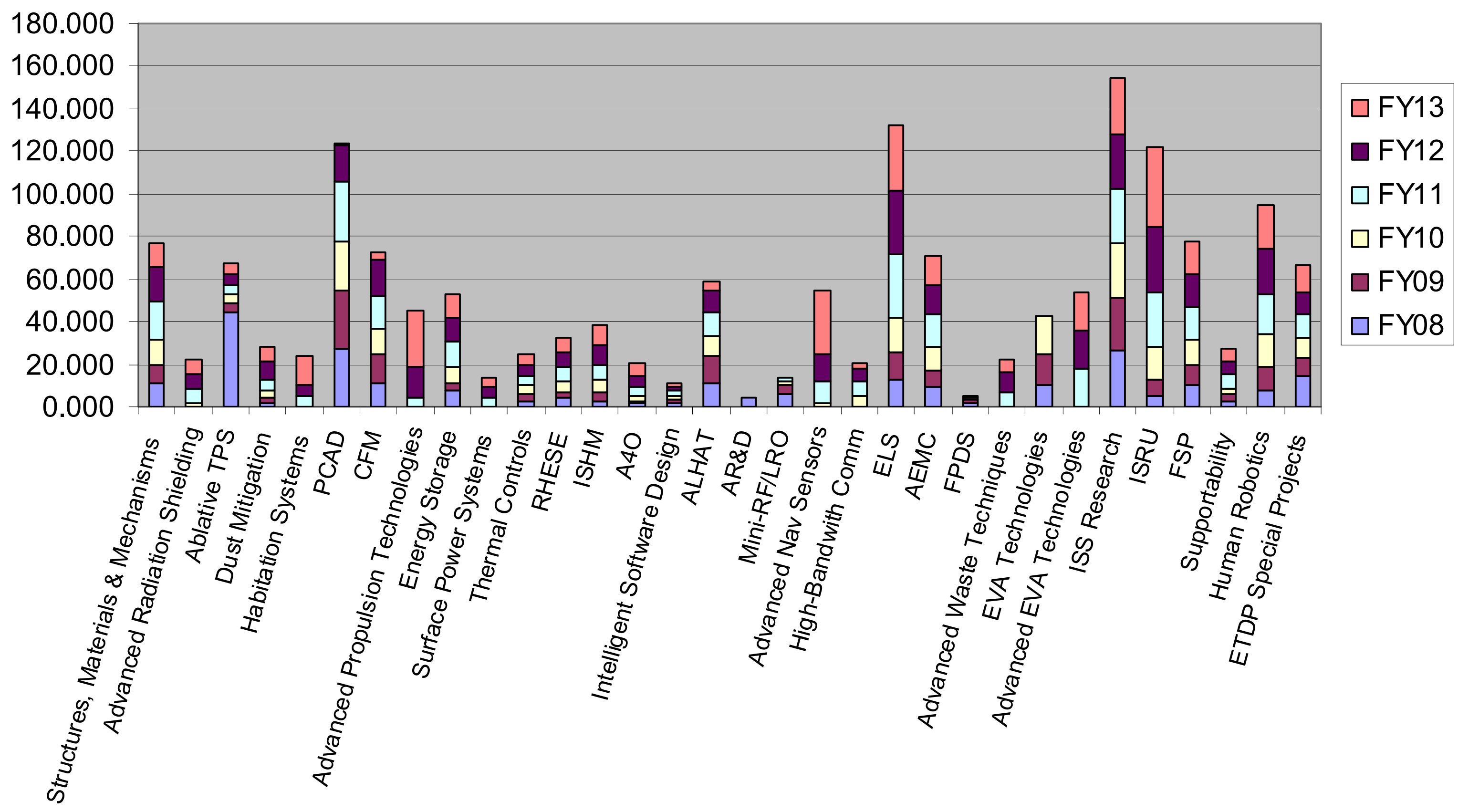
FY08-13 FTE’s by Center



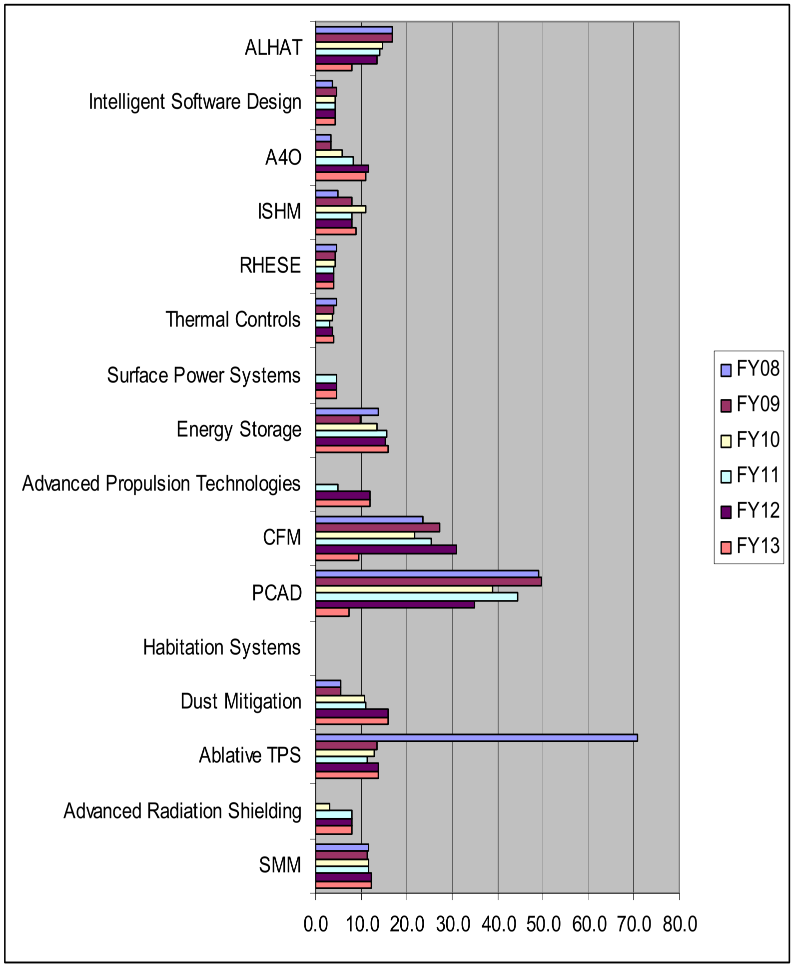
FY08-13 WYE's by Center

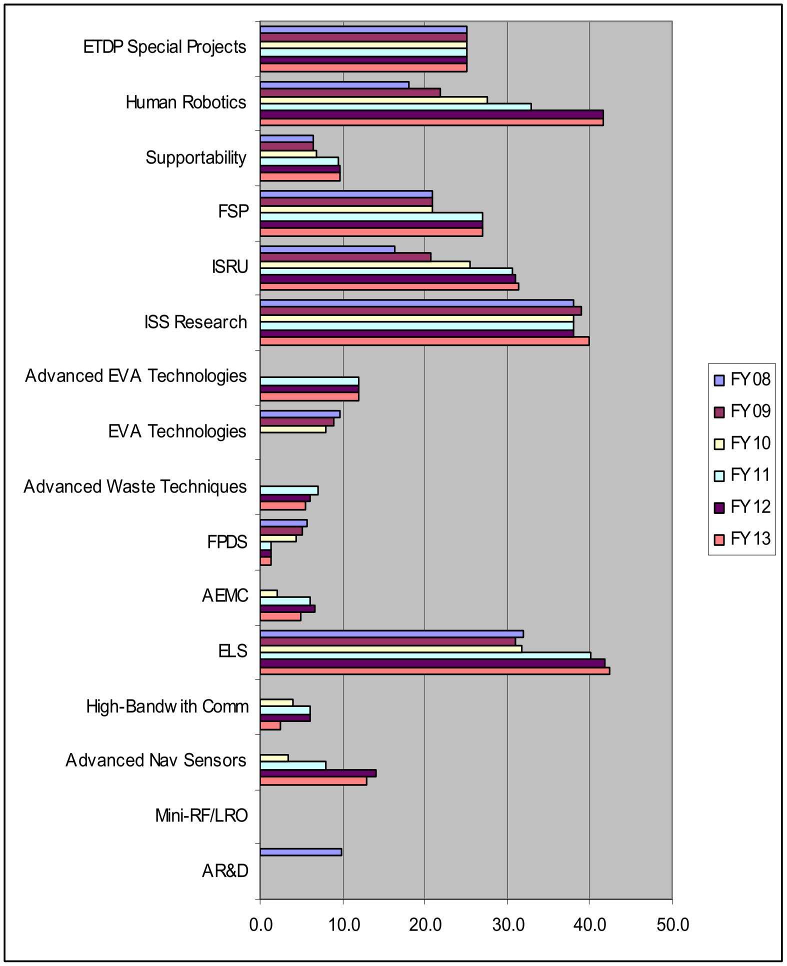


FY08-13 Funding by Project



FY08-13 FTEs by Project





Project Overviews

Candidate KPP's

ETDP Project	Technical Performance Commitment	Goal
Structures, Materials, and Mechanisms	**Develop and test lightweight structural concepts for lunar surface habitats.**	**10 – 20% reduction in mass**
Protection Systems	**Deliver a prototype lunar return capable ablative heat shield for the Orion crew exploration vehicle.**	**Peak heating rate > 750 W/cm^2**
Non-Toxic Propulsion	**Develop a deep throttling LOX-hydrogen rocket engine for the Lunar Lander descent stage, and a prototype LOX-methane rocket engine for the Lunar Lander ascent stage.**	**10:1 throttling ratio for descent engine; 4000 lbf thrust for ascent engine**
Energy Storage and Power Systems	**Develop a modular regenerative fuel system for energy storage at the lunar outpost.**	**Specific power > 130 W/kg**
Thermal Control for Surface Systems	**Develop and test prototype thermal control system components for the Orion crew exploration vehicle.**	**Radiator mass per area > 1.4 kg/m^2**

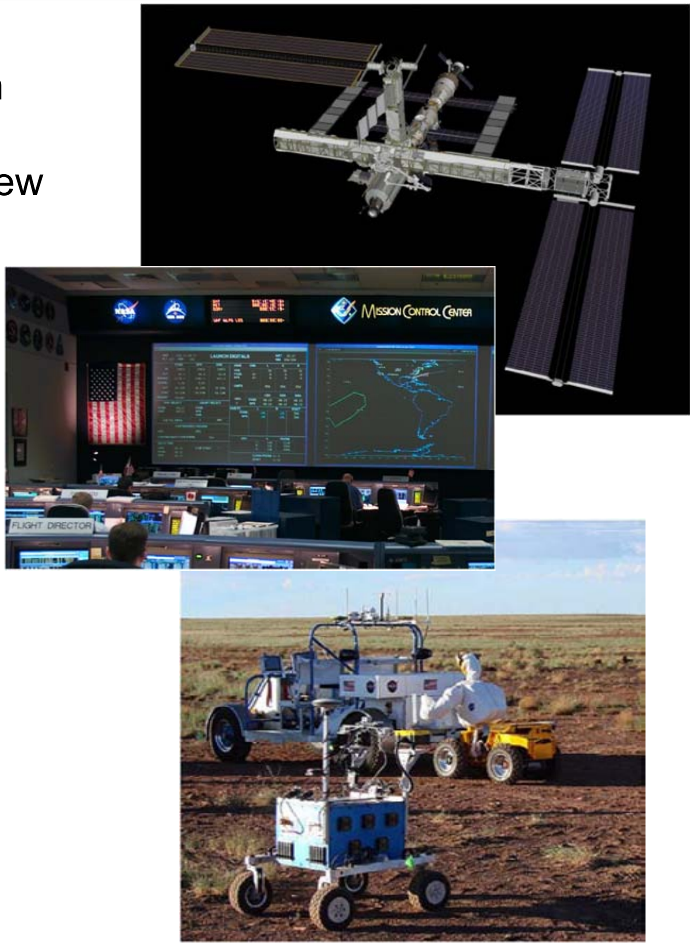
Candidate KPP's

ETDP Project	Technical Performance Commitment	Goal
Avionics and Software	**Develop a prototype autonomous precision landing and hazard avoidance system for the Lunar Lander.**	**Landing precision < 30 m**
Environmental Control and Life Support	**Deliver a prototype carbon dioxide and moisture removal system for the Orion crew exploration vehicle. Deliver the Electronic Nose (E-Nose) and Vehicle Cabin Air Monitor (VCAM) flight hardware for launch to the ISS.**	**Specific energy to remove CO_2 and moisture from air < 0.073 kW-h/kg air**
Crew Support and Accommodations	**Develop component technologies for an advanced EVA surface suit.**	**120 hours survival on lunar surface**
ISS Research and Operations	**Deliver the Fluids Integrated Rack (FIR) and Combustion Integrated Rack (CIR) for launch to the ISS.**	**Conduct 1 experiment every 2 years per rack**

Candidate KPP’s

ETDP Project	Technical Performance Commitment	Goal
In-Situ Resource Utilization	**Demonstrate the production of oxygen from lunar regolith.**	**Production rate = 50 kg/day**
Robotics, Operations, and Supportability	**Demonstrate surface mobility systems for transporting crew and large payloads to support lunar outpost assembly.**	**Range > 100 km; Payload Mass = 5000 kg**
Fission Surface Power Systems	**Test proof-of-concept fission surface power system with reactor simulator.**	**Power = 40 kWe**

Automation for Operations



Objective

- Develop and mature needed automation software capabilities for Constellation mission operations, on-board control, crew assistance and robotics.

Core Capabilities

- Human-in-the-loop Automation
- Monitored Execution
- Decision Support

Products

- Re-usable and evolvable automation software for
  - Mission operations
  - Crewed spacecraft operations
  - Unmanned spacecraft operations
  - Rover and Lunar Asset operations
- Example: Solar Array Constraint Engine

Intelligent Software Design

Objective: **to develop technologies that ensure**

- Software requirements and designs are correct,
- The designs are implemented correctly
- Comprehensive testing of implemented code

Approach

- Model-based development - brings software engineering up to date with other aerospace engineering disciplines. Models and prototypes are not just visual aides to understanding aspects of a software system, but executable artifacts.
- Automatic code generation from models, autocode verification.
- Testing - tools for ensuring coverage of requirements, models, and code throughout all testing phases. Automation for test case generation and test log analysis.
- COTS - Integration Analysis and Testing to ensure reliable use commercial off the shelf software in safety-critical applications.
- Safety and Security Cases - Formalization and quantification of Safety and Security Cases

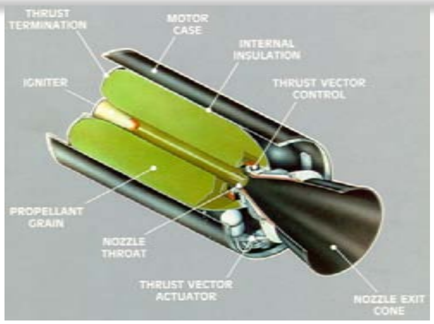
Integrated Systems Health Management

Solid Rocket Motor Health Management

- Early detection of SRM anomalies that may lead to crew abort during CLV launch and ascent operations.
- Develop high-fidelity physics-based models (developed by AFRL) to estimate parameters of low-order models that can be tracked online for failure detection and prediction; verify and validate models through simulation and flight experiments.

Integrated Ground System Diagnostics

- Integrated GSE ground diagnostics workstation at KSC certified for use for CxP ground operations
- Develop, certify, and deploy health management systems for GSE at KSC in support of Cx ground operations; technology assessment of products for wire and harness integrity testing



Ablative Thermal Protection System

Objective: **to develop a single heat-shield design that meets both Lunar Return-Direct and Low Earth Orbit (LEO) reentry requirements**

To minimize risk, the project will develop two heat-shield preliminary design concepts

- Lunar direct return capable
- LEO only return capable TPS as a backup

The effort includes

- TPS material
- Carrier structure
- Interface structures and attachments.

The two heat-shield concept definitions to the Orion Project Office at the TPS Preliminary Design Review (PDR)

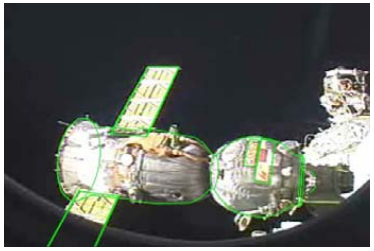
Arcjet testing of TPS material

Prototype 5 m diameter heat shield

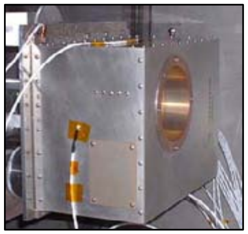
Automated Rendezvous and Docking

Objective: **Reduce risk associated with relative navigation sensors for proximity operations and docking through testing and simulation.**

- **Natural Feature Image Recognition (NFIR)**
- **Flash LIDAR**
- **Next Generation Advanced Video Guidance Sensor (NG AVGS)**
- **Simulation and Testing**. Test relative navigation sensors with prototype software and simulations



NFIR



AVGS

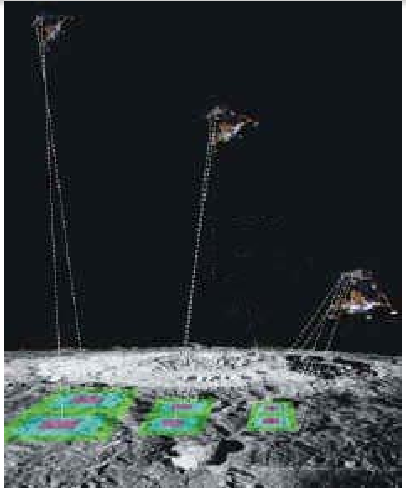
MSFC's Flight Robotics Laboratory (FRL)

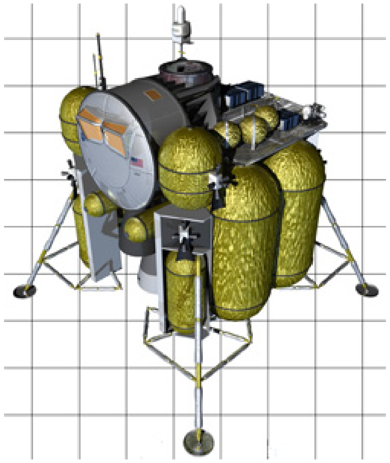
Autonomous Landing and Hazard Avoidance Technology

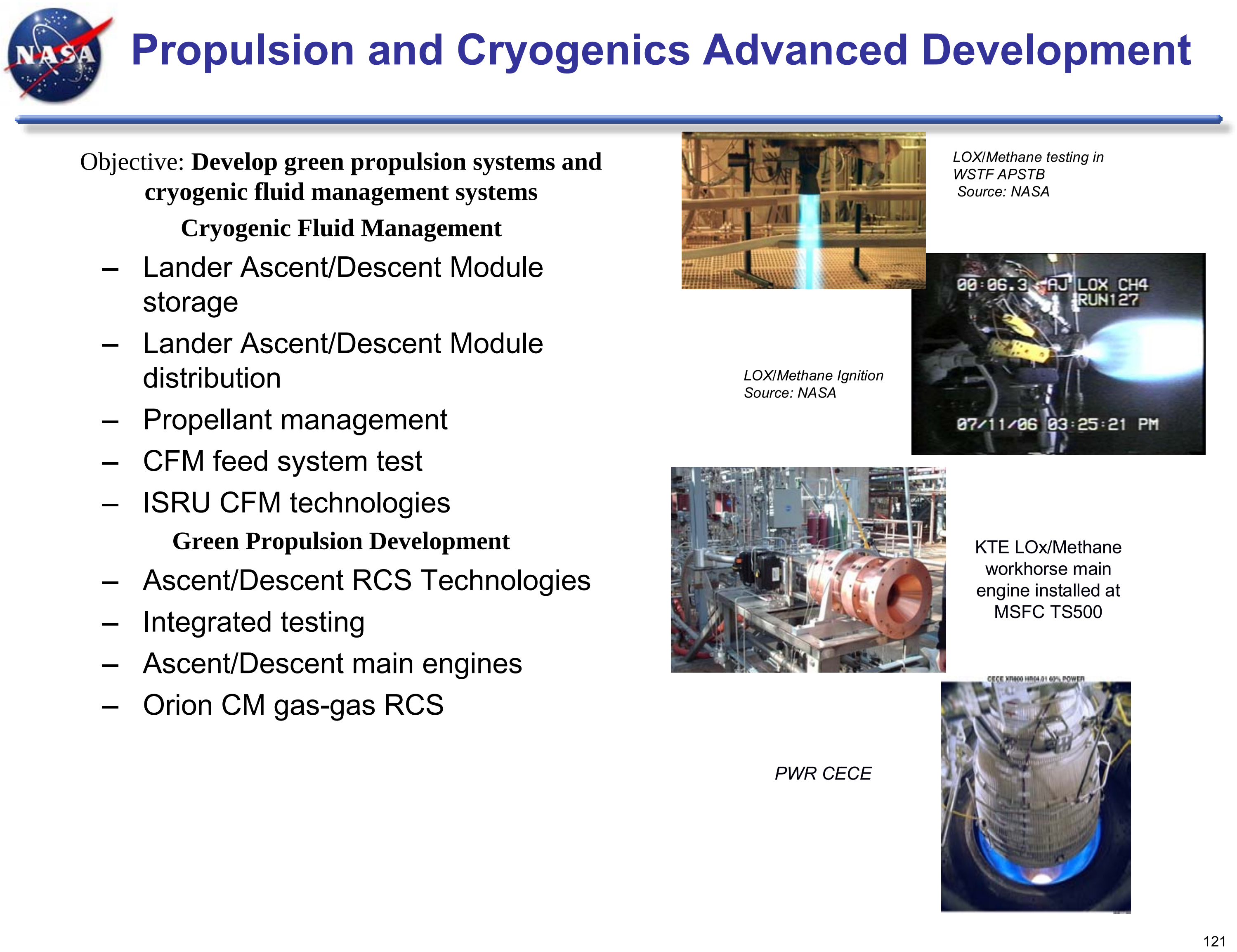
Objective: **to develop and mature to TRL 6 an autonomous lunar landing GN&C and sensing system for crewed, cargo, and robotic lunar descent vehicles. The system will be capable of identifying and avoiding surface hazards to enable a safe precision landing to within tens of meters of certified and designated landing sites anywhere on the Moon under any lighting conditions.**

Tasks:

- Evaluate available sensor technology
- Integrate achievable sensor capabilities with appropriate trajectory development
- Implement HDA sensor development procurement followed by TRN sensor development procurement
- Perform analysis, simulations and sensor testing to define the required capabilities of an integrated system







Propulsion and Cryogenics Advanced Development

Objective: **Develop green propulsion systems and cryogenic fluid management systems**

Cryogenic Fluid Management

- Lander Ascent/Descent Module storage
- Lander Ascent/Descent Module distribution
- Propellant management
- CFM feed system test
- ISRU CFM technologies

Green Propulsion Development

- Ascent/Descent RCS Technologies
- Integrated testing
- Ascent/Descent main engines
- Orion CM gas-gas RCS

LOX/Methane testing in WSTF APSTB
Source: NASA

LOX/Methane Ignition
Source: NASA

KTE LOx/Methane workhorse main engine installed at MSFC TS500

PWR CECE

Human Robotic Systems

Surface Mobility

- Crew Transport
- Payload Transport
- Component Technologies

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

Surface Handling

- Large scale handling/offloading
- Fine handling/connecting

Human-Systems Interaction

- Machine – to EVA
- Machine – to IV
- Machine – to Ground

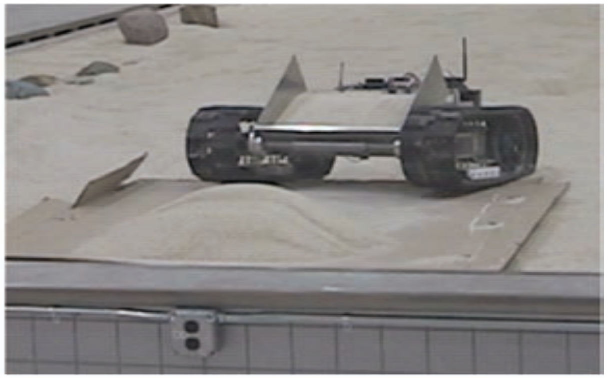
In-Situ Resource Utilization (ISRU)

Technical Development Areas

- Regolith Excavation & Material Handling
- Oxygen Production from Regolith
- Volatile/Water Extraction & Production and Resource Prospecting
- Site preparation, construction, consumable storage and distribution

System Engineering, Environments, Integration, & Testing

- System & Element Modeling
- Lunar Simulant Development
- ISRU Simulation Capability Development
- ISRU Interfaces & Integrated Demonstrations



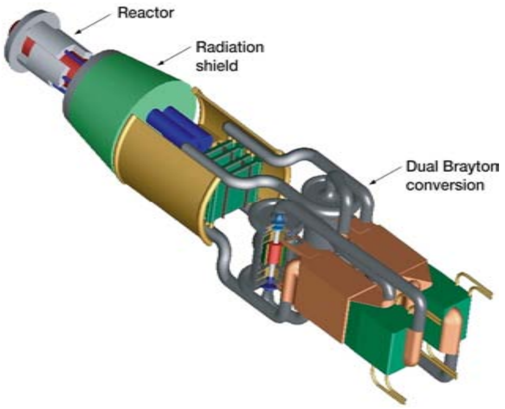
Advanced Fission Based Power Systems

Fission Surface Power System Concept Definition

- Provides performance data and characteristics to planners, basis for cost estimation and guides component and system technology development

Fission Surface Power System Risk Reduction

- Provides test data for critical subsystems and components. A technology demonstration unit validates subsystems and component performance and characteristics are preserved when integrated into a test-bed power system.



Dual 100kW Brayton Conversion System with liquid metal cooled reactor

Energy Storage

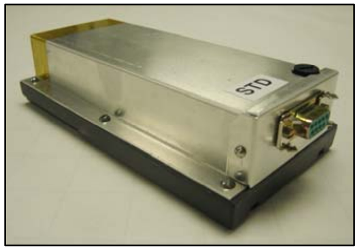
Advance battery and fuel cell technology to meet critical energy storage needs

Lithium-ion (Li-ion) battery development objectives

- Develop and demonstrate advanced lithium-ion battery technology for human-rated systems having increased:
  - Safety, specific energy, energy density, and temperature tolerance
- Deliver a prototype common battery module at TRL 6 by FY11 for infusion into Lander PDR

Fuel cell development objectives

- Advance FlowThru Proton Exchange Membrane Fuel Cell (PEMFC) systems by replacing active balance-of-plant components with passive components
- Advance Non-FlowThru PEMFC systems by eliminating most balance-of-plant components altogether
  - Potential significant reduction in weight and complexity, and increased reliability and life – both for primary fuel cell systems and Regenerative Fuel Cell (RFC) energy storage systems
- Develop three classes of fuel cells for Exploration missions:
  - 1-kW max - advanced EVA portable life support systems
  - 8-kW class - unpressurized rovers
  - 25-kW class - RFC surface power plants and pressurized rovers



Lithium-ion battery for spacesuit

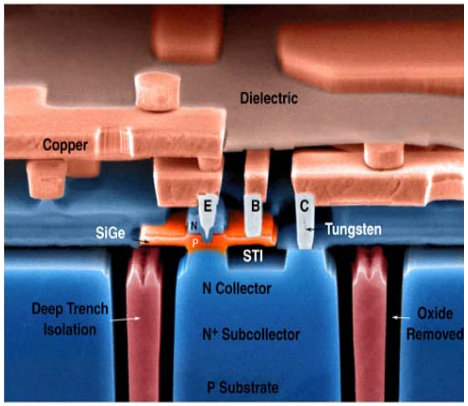
Regenerative fuel cell

High Performance & Radiation Hardened Electronics

Objective: **to advance the state-of-the-art in high-performance, radiation-hardened electronics that enable long-term, reliable vehicle operation in the extreme radiation and temperature environment of space and the lunar surface.**

Tasks:

- SiGe Integrated Electronics for Extreme Environments - Develop modular mission-critical electronic components to operate reliably in the space environment on spacecraft extremities.
- Radiation Effects on Electronics Modeling - Develop model to diagnose the causes of Single Event Effects (SEEs) and web-based tool to support real-time prediction of component reliability.



- High Performance Processors (HPP) – Improve high-performance radiation-hardened processors’ capabilities for demanding processing in natural environments.
- Reconfigurable Computers (RC) - Provide reconfigurable computing capability, resulting in reduction of flight spares and provision for circuit life-time limitation.

Supportability

- **Objective:** to enhance the sustainability of exploration systems through logistics and maintenance related technology development
  - Diagnostics
    - Compact electronic component diagnostic equipment
    - Self-healing and lightweight materials to complement internal health management
  - Servicing
    - Mobile consumable replacement in no/low g environments
  - Repair technologies
    - Manual and semi-automated electronic circuit repair

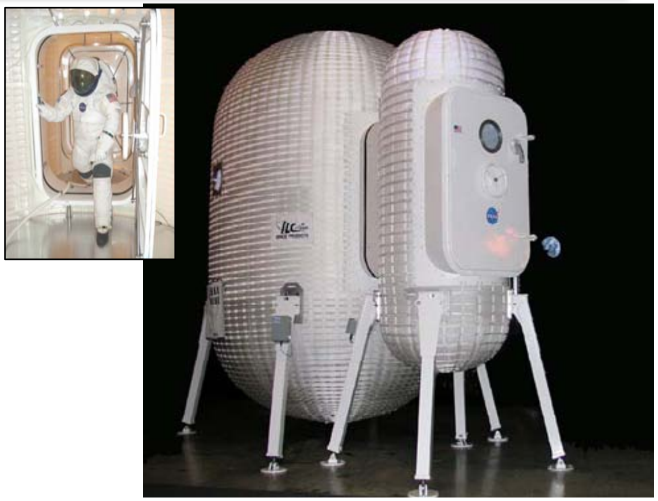
Structures/Mechanisms/Materials

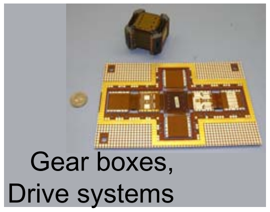
Objectives:

- Develop lightweight primary structures for the pressurized elements of the Lunar Lander and surface habitats with relevant technology made available to the Orion and Ares.
- Develop low-temperature mechanisms to allow operation in temperatures below -200 C for missions to the lunar polar regions for lunar surface rovers, robotics, and mechanized operations

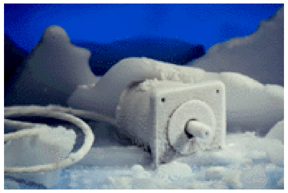
Tasks:

- Al-Li Manufacturing (spun form domes)
- Advanced Composite Structures
- Expandable Structures
- Flexible Reconfigurable Radiation Shielding Kit
- Low Temperature Mechanisms
- NESC Composite Crew Module
- CEV Parachute

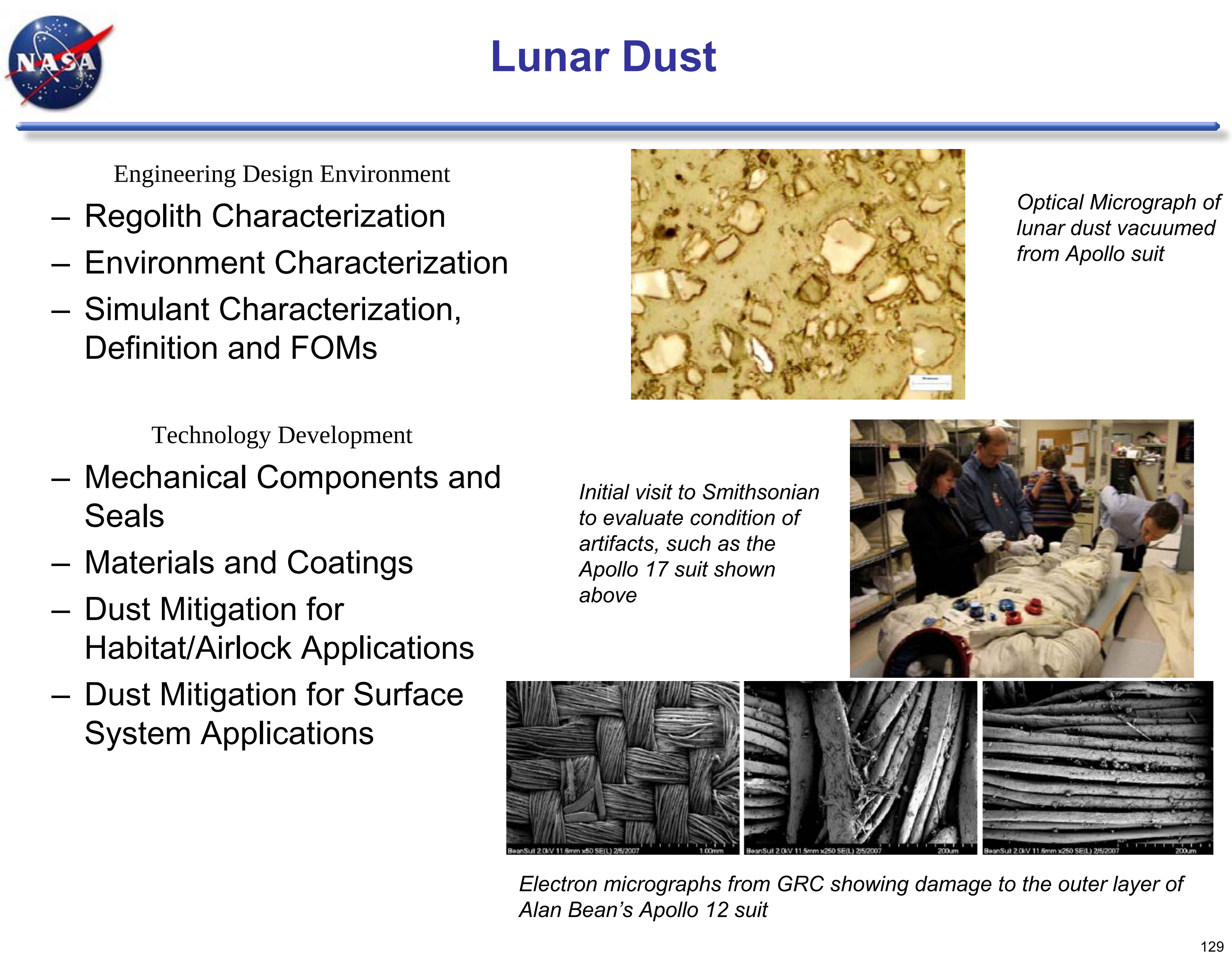




Gear boxes, Drive systems



NESC Composite CM



Lunar Dust

Engineering Design Environment

- Regolith Characterization
- Environment Characterization
- Simulant Characterization, Definition and FOMs

Technology Development

- Mechanical Components and Seals
- Materials and Coatings
- Dust Mitigation for Habitat/Airlock Applications
- Dust Mitigation for Surface System Applications

Optical Micrograph of lunar dust vacuumed from Apollo suit

Initial visit to Smithsonian to evaluate condition of artifacts, such as the Apollo 17 suit shown above

Electron micrographs from GRC showing damage to the outer layer of Alan Bean's Apollo 12 suit

129

Extra-Vehicular Activity Suit

Life Support Subsystem (LSS)

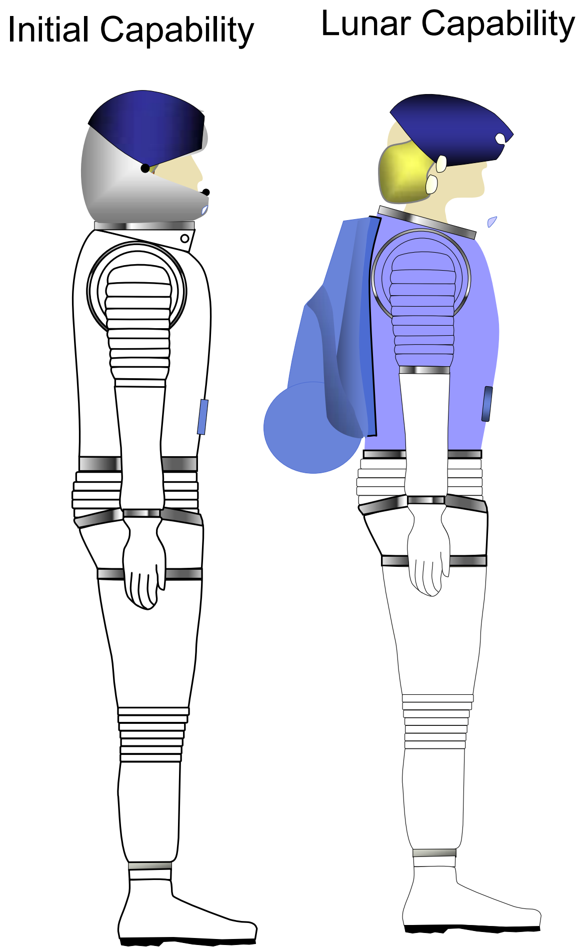
- Architecture
- Thermal Systems
- Ventilation Systems
- Oxygen Supply

Communication / Avionics / Informatics (CAI) Subsystem

- CAI / LSS Integration
- Software and Information Systems
- Radio, Communications and Navigation

Power Subsystem

- Power / LSS Integration
- Battery Development

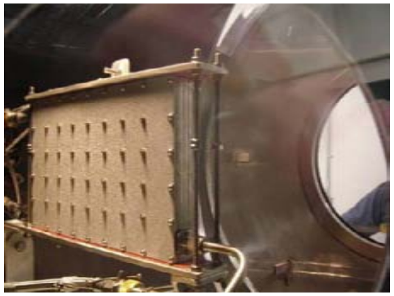


Thermal Control System Development

Objective: **the development of advanced thermal control systems designed for use on lunar surface missions**

Tasks:

- Fluids - long duration thermal control fluid stability data for lunar outpost
- Heat Acquisition - reduced mass heat exchangers using composites and innovative designs
- Heat Pump - lower mass thermal control systems for missions in hot lunar environments
- Evaporative Heat Sinks - required for future vehicles and space suit apps
- Radiator - unique design drivers include limited vehicle surface area, effects of dust, surface radiation environment, and extreme day/night cycle environment variations
- System Design and Testing



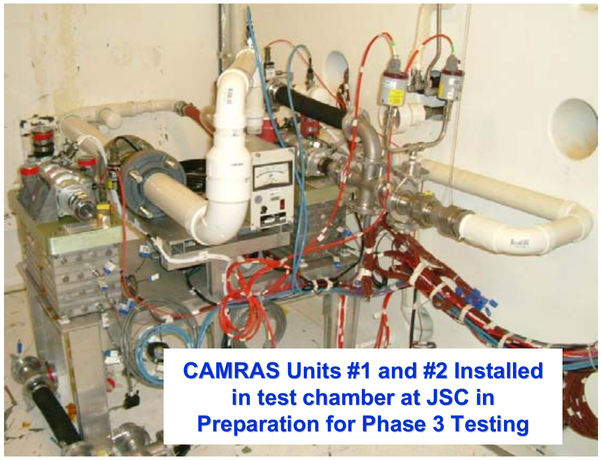
CIS Engineering Unit Test

TCS Fluids Test Bed

Exploration Life Support

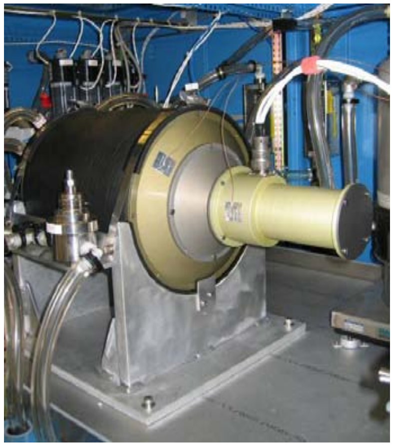
Objective: **Identify, develop and mature a suite of environmental control and life support system technologies. Major areas of investment include**

- Air Revitalization
- Water Recovery
- Waste Management
- Systems Integration Modeling and Analysis
- Integrated Testing
- Flight Experiments
- Habitation Engineering



CAMRAS Units #1 and #2 Installed in test chamber at JSC in Preparation for Phase 3 Testing

Honeywell's Cascade Distillation Subsystem (CDS) test stand

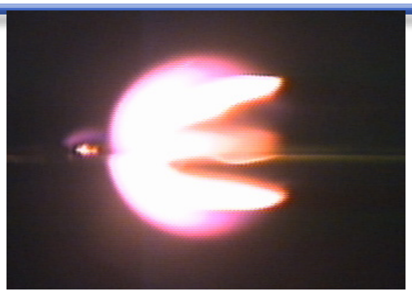


The Cascade Distiller, the central processing component of the Cascade Distillation Subsystem. The Cascade Distiller contains five rotating distillation surfaces used for wastewater recovery.

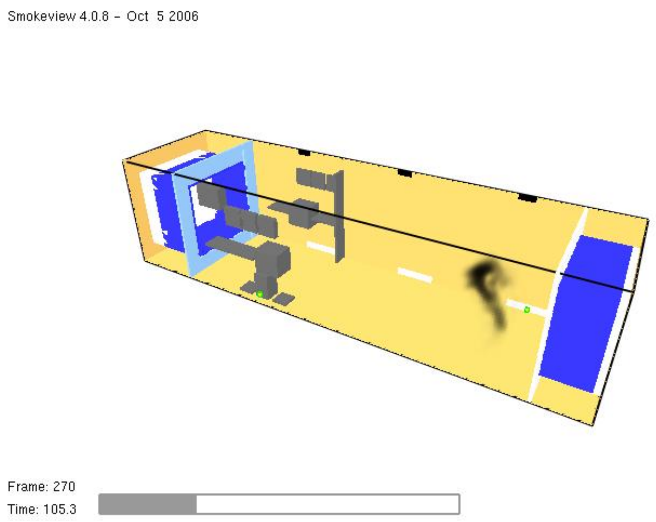
Fire Protection, Detection, and Suppression

Objective: **to develop technologies to ensure fire safety on exploration vehicles and habitats. This includes:**

- providing material flammability screening tests relevant to exploration conditions
- providing reliable fire detection in all exploration environments
- equipping the crew with assured fire suppression capability



Concurrent low-g flame on a paper sample at 34% O_2 and 10.2 psia to assess flow quality.



Low-g suppression tests on PMMA cylinder

Advanced Environmental Monitoring & Control

- **Goals:**
  - – Miniaturize & customize
  - – Gain operational experience
  - – Improve reliability
- **Approach:** work with a current space platform, ISS to demonstrate and validate monitoring technology
  - – Lab-On-a-Chip Application Development Portable Test System (LOCAD PTS)
    - Microbial monitor
  - – Vehicle Cabin Atmosphere Monitor (VCAM)
  - – Electronic Nose (ENose)
    - Event monitor
  - – Colorimetric Solid Phase Extraction (CSPE)
    - Biocide monitor

ISS014E18818

ISS Exploration and Non-Exploration Research

Goals: **To provide ground-based and space flight hardware that will support the generation of research data for science and technology experiments**

Objectives:

- Exploration: To utilize the ISS as a test bed for technology development, demonstration, and problem resolution in the areas of life support, fire safety, power, propulsion, thermal management, etc.
- Non-Exploration: To support ground-based, free-flyer, and ISS life and microgravity science research that is not directly related to supporting the human exploration program.

Tasks/Experiments

- Physical Sciences
- Life Sciences

Combustion Integrated Rack

EVA attachment of MISSE 1 on ISS

ISS Research Experiments

Streptococcus Pneumoniae Expression of Genes In Space (SPEGIS)
Effect of Spaceflight on Microbial Gene Expression and Virulence in S. typhimurium, P. aeruginosa, C. albicans (Microbe)
Fungal Pathogenesis, Tumerogenesis, and Effects on Host Immunity in Space (FIT)
Role of the interleukin-2 receptor in signal transduction (Leukin)
European Modular Cultivation System - Gravitropism (EMCS-TROPI)
Foton-M2 (Plasmid-F2, Regeneration-F2, Gecko-F2, Receptor-F2)
Foton-M3 (Plasmid-F2, Regeneration-F2, Gecko-F2, Receptor-F2)
MicroSat Multi-Center Integrated Free Flyers
Ground Animal Research (not HRP)
Combustion Integrated Rack (CIR)
Fluids Integrated Rack (FIR)
FCF Sustaining Engineering
ISS Operations: Integration & Operations (I&O) and Telescience Support Center (TSC)
Mission Integration & Planning (MIP)
Multi-User Droplet Combustion Apparatus (MDCA)/ Flame Extinguishment Experiment (FLEX)
Light Microscopy Module (LMM)/ Constrained Vapor Bubble (CVB)
Boiling Experiment Facility (BXF)
Smoke Aerosol Measurement Experiment (SAME)/ Dust and Aerosol measurement Feasibility Test (DAFT)

ISS Research Experiments - cont’d

Capillary Flow Experiments (CFE)
Space Acceleration Measurement Systems (SAMS)/ Microgravity Acceleration Measurement System (MAMS)
Binary Colloidal Alloy Test (BCAT-3+ / BCAT-4)
Coarsening in Solid-Liquid Mixtures-2 (CSLM-2)
Investigating the Structures of Paramagnetic Aggregates (InSPACE-2)
Multi-User Droplet Combustion Apparatus (MDCA)/ Flame Extinguishment Experiment (FLEX-2)
Capillary Channel Flow (CCF)
Shear History Extensional Rheology Experiment (SHERE)
Smoke Point in Coflow Experiment (SPICE)
Zero Boil-Off Tank Experiment (ZBOT)
Gradient Driven Fluctuations Experiment (GRADFLEX)
Boiling and Two Phase Laboratory Grant (2ϕ Flow)
Space Life Sciences Lab
Exploration Lighting Technologies
VOC Control (Non-Methane) with COTS Polymeric Adsorbents Sensor Validation
Sensor Validation in Variable Pressure Environments
Payload Processing and Development/ Passive Observatories for Experimental Microbial Systems (POEMS)
HQ Support/ International Advanced Life Support Working Group (IALSWG) Executive Secretary
Materials Science Research Rack (MSRR)
Microgravity Science Glovebox (MSG)

MISSE

Provides a proven, economical means for in-space evaluations to mitigate risk for Exploration spacecraft

NASA funding to MISSE is leveraged by DOD & industry investments

MISSE 6A & 6 B:

- Environmental effects CEV TPS
- Elastomer seal and O-ring materials for CEV Advanced Docking and Berthing System.
- Effects of surface bias on charge enhanced contamination.
- New approaches to exposure effects experiments on the Lunar and Martian surfaces.
- Ballute materials for entry braking and aero-capture in exploration missions.

MISSE 1

MISSE 5

EVA attachment of MISSE 1 on ISS

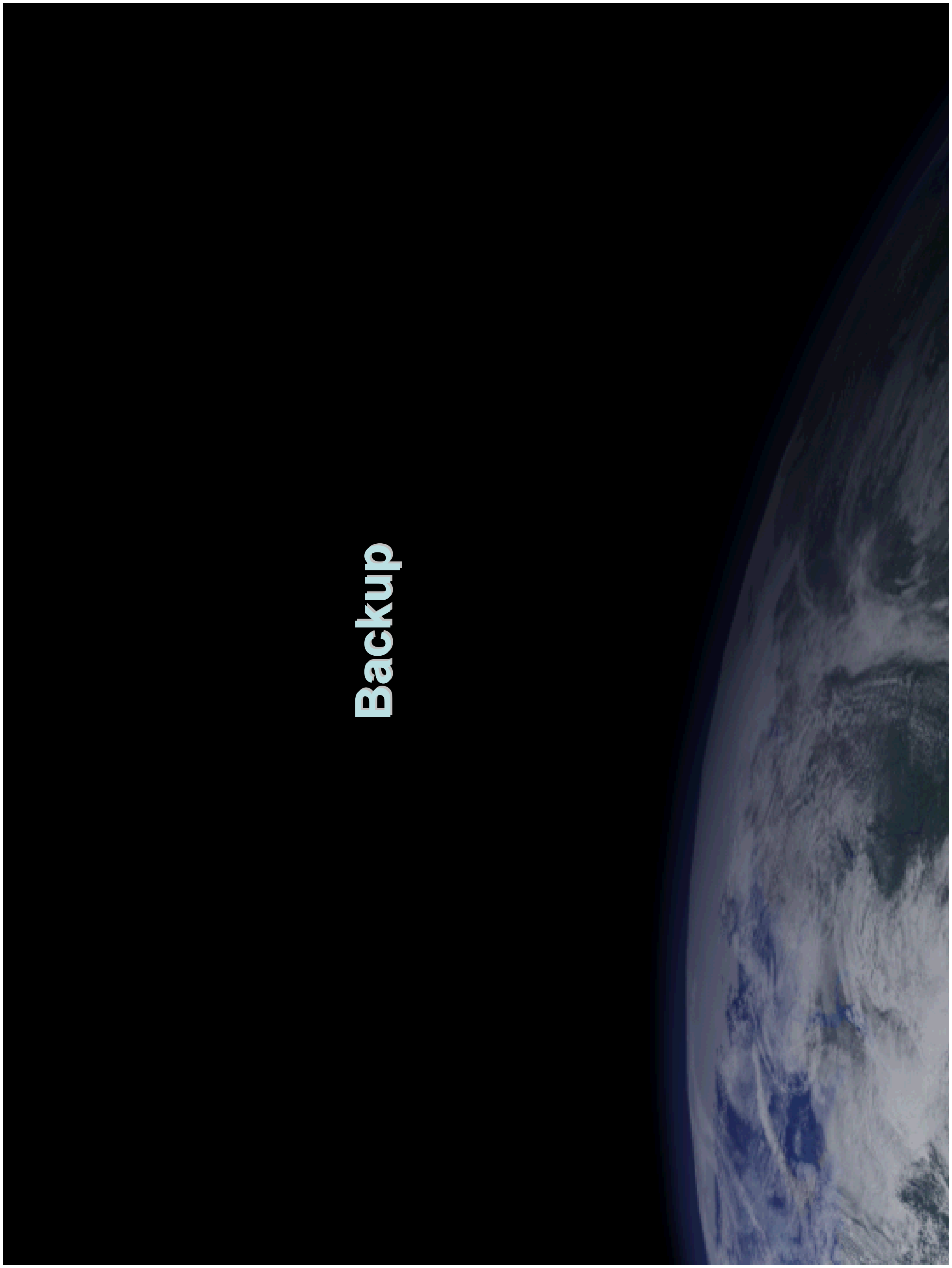
Summary

Exploration Technology Development Program has a broad portfolio

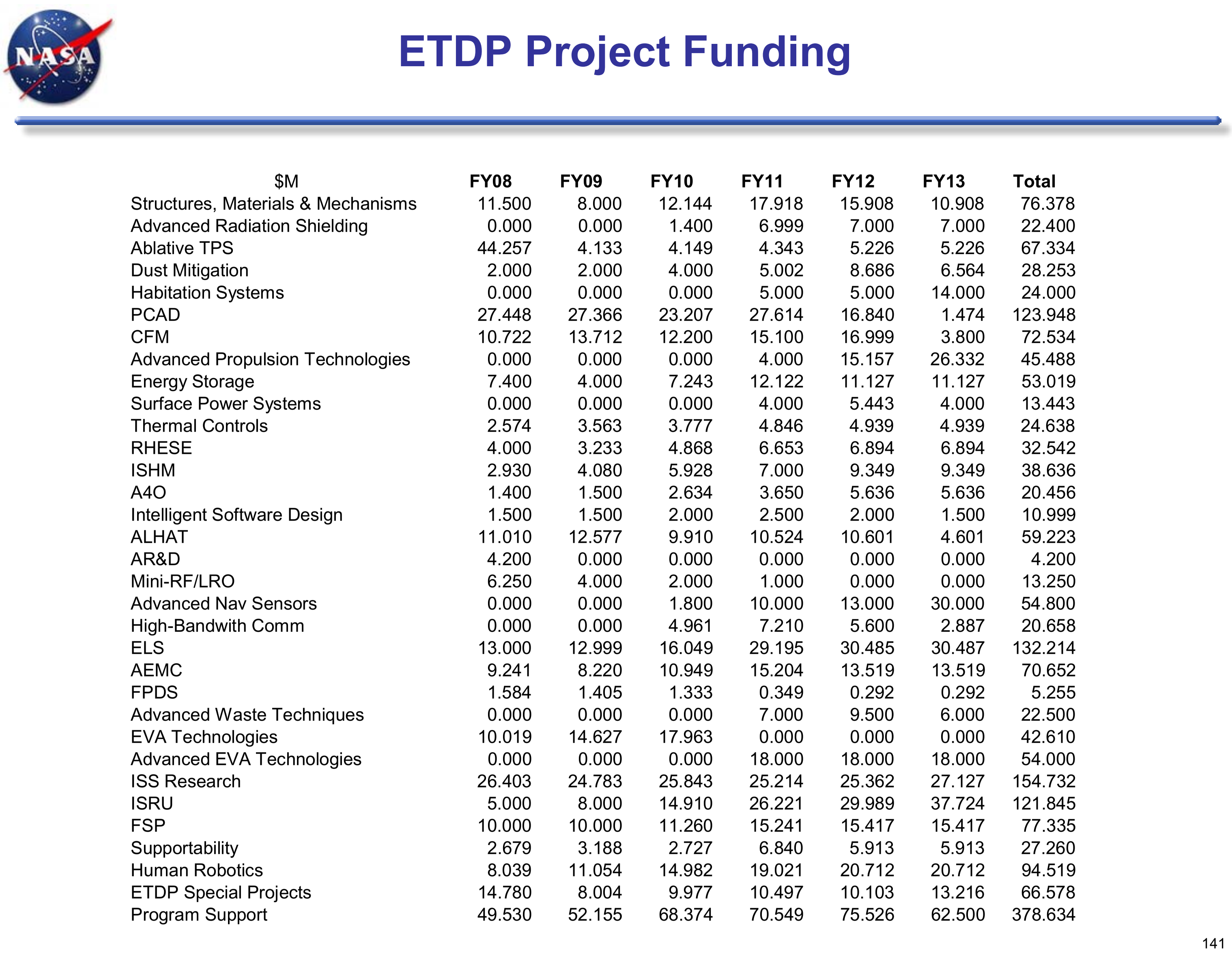
The portfolio is focused on our customer's needs <u>as defined by them:</u>

- *Orion*
- *Ares*
- *ISS*
- *EVA*
- *Mission Operations*
- *Ground Operations*
- *Lunar Lander*
- *Lunar Surface Systems*

Our success will be measured by our ability to infuse technologies into flight elements



Backup



ETDP Project Funding

$M	FY08	FY09	FY10	FY11	FY12	FY13	Total
Structures, Materials & Mechanisms	11.500	8.000	12.144	17.918	15.908	10.908	76.378
Advanced Radiation Shielding	0.000	0.000	1.400	6.999	7.000	7.000	22.400
Ablative TPS	44.257	4.133	4.149	4.343	5.226	5.226	67.334
Dust Mitigation	2.000	2.000	4.000	5.002	8.686	6.564	28.253
Habitation Systems	0.000	0.000	0.000	5.000	5.000	14.000	24.000
PCAD	27.448	27.366	23.207	27.614	16.840	1.474	123.948
CFM	10.722	13.712	12.200	15.100	16.999	3.800	72.534
Advanced Propulsion Technologies	0.000	0.000	0.000	4.000	15.157	26.332	45.488
Energy Storage	7.400	4.000	7.243	12.122	11.127	11.127	53.019
Surface Power Systems	0.000	0.000	0.000	4.000	5.443	4.000	13.443
Thermal Controls	2.574	3.563	3.777	4.846	4.939	4.939	24.638
RHESE	4.000	3.233	4.868	6.653	6.894	6.894	32.542
ISHM	2.930	4.080	5.928	7.000	9.349	9.349	38.636
A4O	1.400	1.500	2.634	3.650	5.636	5.636	20.456
Intelligent Software Design	1.500	1.500	2.000	2.500	2.000	1.500	10.999
ALHAT	11.010	12.577	9.910	10.524	10.601	4.601	59.223
AR&D	4.200	0.000	0.000	0.000	0.000	0.000	4.200
Mini-RF/LRO	6.250	4.000	2.000	1.000	0.000	0.000	13.250
Advanced Nav Sensors	0.000	0.000	1.800	10.000	13.000	30.000	54.800
High-Bandwith Comm	0.000	0.000	4.961	7.210	5.600	2.887	20.658
ELS	13.000	12.999	16.049	29.195	30.485	30.487	132.214
AEMC	9.241	8.220	10.949	15.204	13.519	13.519	70.652
FPDS	1.584	1.405	1.333	0.349	0.292	0.292	5.255
Advanced Waste Techniques	0.000	0.000	0.000	7.000	9.500	6.000	22.500
EVA Technologies	10.019	14.627	17.963	0.000	0.000	0.000	42.610
Advanced EVA Technologies	0.000	0.000	0.000	18.000	18.000	18.000	54.000
ISS Research	26.403	24.783	25.843	25.214	25.362	27.127	154.732
ISRU	5.000	8.000	14.910	26.221	29.989	37.724	121.845
FSP	10.000	10.000	11.260	15.241	15.417	15.417	77.335
Supportability	2.679	3.188	2.727	6.840	5.913	5.913	27.260
Human Robotics	8.039	11.054	14.982	19.021	20.712	20.712	94.519
ETDP Special Projects	14.780	8.004	9.977	10.497	10.103	13.216	66.578
Program Support	49.530	52.155	68.374	70.549	75.526	62.500	378.634

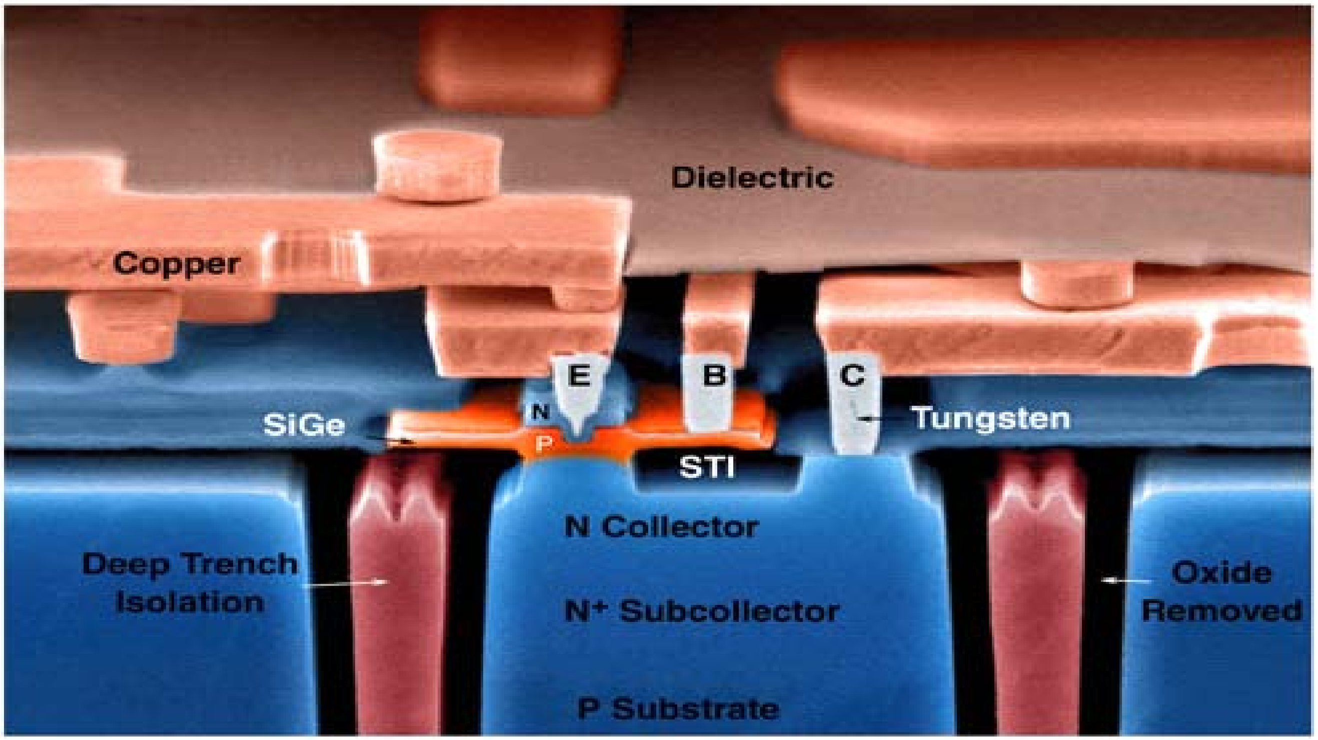
ETDP Civil Service FTEs

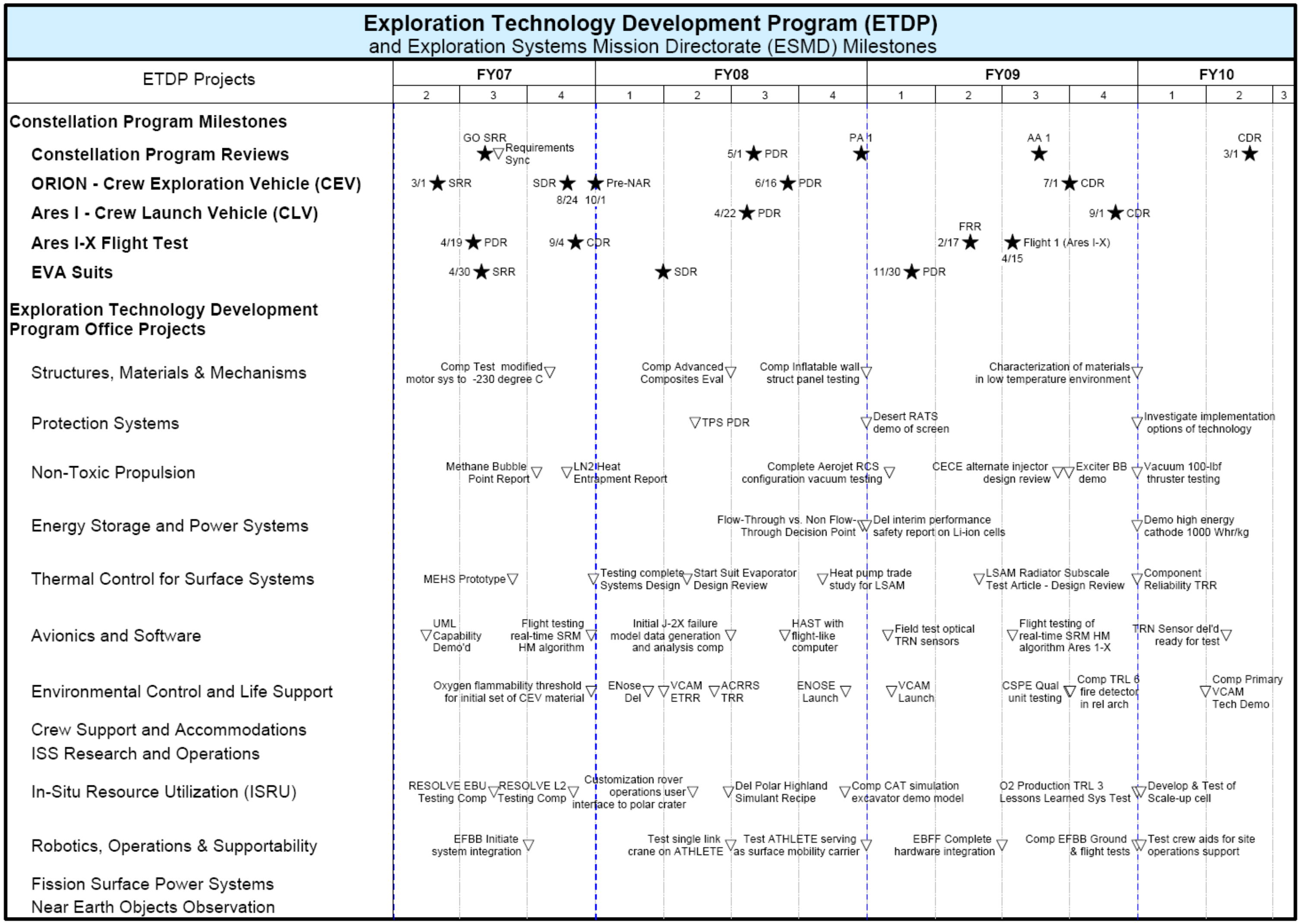
Civil Service FTEs	**FY08**	**FY09**	**FY10**	**FY11**	**FY12**	**FY13**
SMM	11.8	11.3	11.8	11.8	12.3	12.3
Advanced Radiation Shielding	0.0	0.0	3.0	8.0	8.0	8.0
Ablative TPS	70.9	13.5	12.8	11.3	13.8	13.8
Dust Mitigation	5.5	5.4	10.7	10.9	15.9	16.0
Habitation Systems	0.0	0.0	0.0	0.0	0.0	0.0
PCAD	49.1	49.8	38.8	44.6	35.1	7.3
CFM	23.8	27.3	21.9	25.4	31.0	9.6
Advanced Propulsion Technologies	0.0	0.0	0.0	5.0	12.0	12.0
Energy Storage	13.9	9.9	13.6	15.7	15.2	15.9
Surface Power Systems	0.0	0.0	0.0	4.5	4.5	4.5
Thermal Controls	4.6	4.0	3.7	3.2	3.8	4.0
RHESE	4.5	4.2	4.2	4.1	4.1	4.1
ISHM	5.0	8.0	11.0	8.0	8.0	9.0
A4O	3.4	3.4	5.9	8.2	11.7	11.2
Intelligent Software Design	3.7	4.5	4.3	4.3	4.3	4.3
ALHAT	16.8	16.9	14.7	14.2	13.5	8.0
AR&D	9.8	0.0	0.0	0.0	0.0	0.0
Mini-RF/LRO	0.0	0.0	0.0	0.0	0.0	0.0
Advanced Nav Sensors	0.0	0.0	3.5	8.0	14.0	13.0
High-Bandwith Comm	0.0	0.0	4.0	6.0	6.0	2.5
ELS	31.9	31.0	31.8	40.2	41.9	42.4
AEMC	0.0	0.0	2.0	6.1	6.7	4.9
FPDS	5.7	5.1	4.4	1.3	1.3	1.3
Advanced Waste Techniques	0.0	0.0	0.0	7.0	6.0	5.5
EVA Technologies	9.8	8.9	8.0	0.0	0.0	0.0
Advanced EVA Technologies	0.0	0.0	0.0	12.0	12.0	12.0
ISS Research	38.0	39.0	38.0	38.0	38.0	40.0
ISRU	16.3	20.7	25.4	30.6	31.0	31.3
FSP	21.0	21.0	21.0	27.0	27.0	27.0
Supportability	6.4	6.4	6.8	9.5	9.7	9.7
Human Robotics	18.1	21.9	27.5	32.8	41.7	41.7
ETDP Special Projects	25.1	25.1	25.1	25.1	25.1	25.1
Program Support	2.0	6.0	6.0	6.0	6.0	7.0

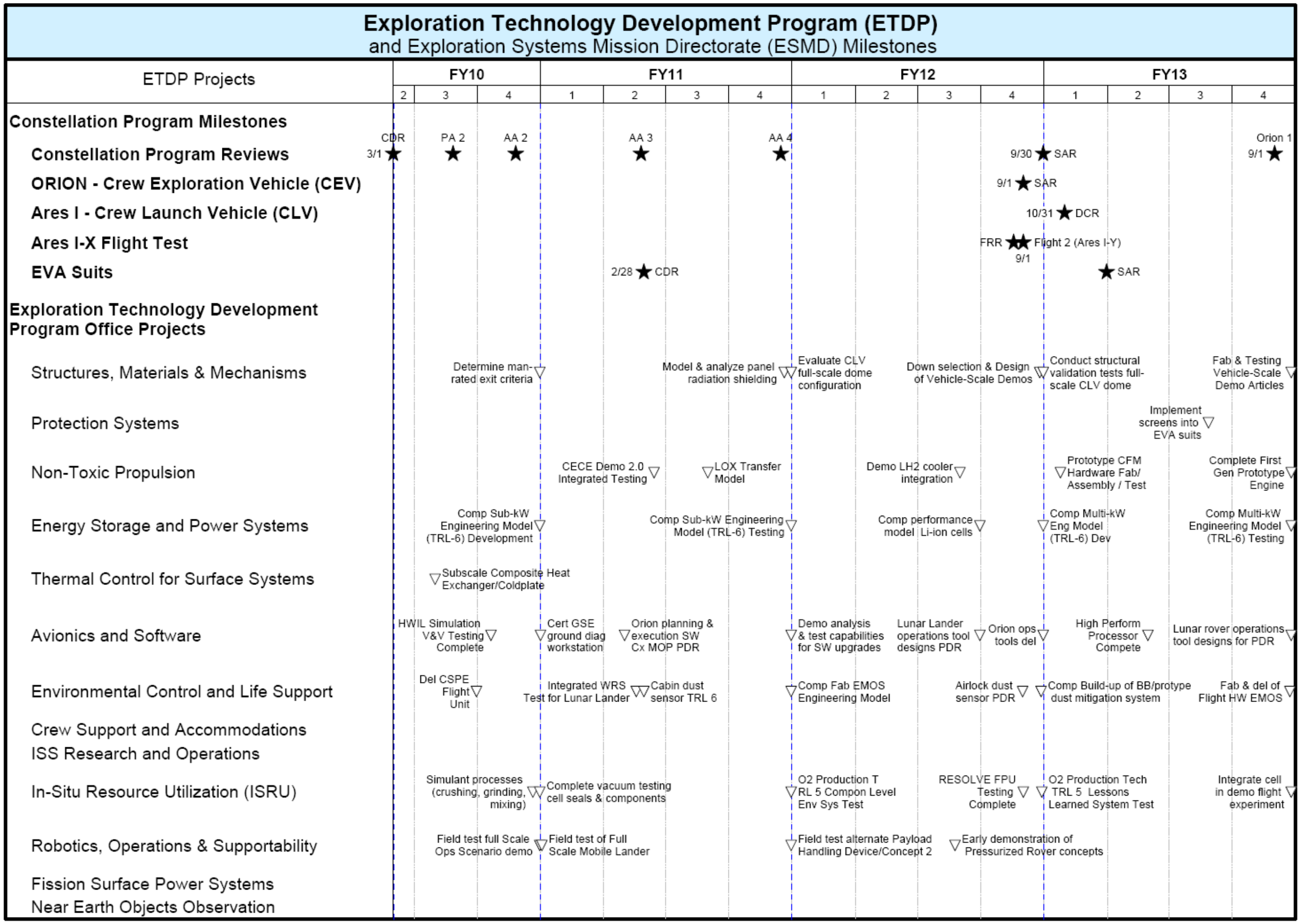
ETDP WYEs

WYEs	FY08	FY09	FY10	FY11	FY12	FY13
SMM	6.0	4.9	5.4	5.4	5.9	5.9
Advanced Radiation Shielding	0.0	0.0	0.0	0.0	0.0	0.0
Ablative TPS	33.5	5.8	3.8	3.8	7.8	7.8
Dust Mitigation	3.6	3.5	7.3	8.9	12.0	8.8
Habitation Systems	0.0	0.0	0.0	0.0	0.0	0.0
PCAD	35.0	27.5	13.5	18.0	14.0	2.0
CFM	16.3	20.0	18.7	18.9	21.8	5.1
Advanced Propulsion Technologies	0.0	0.0	0.0	0.0	0.0	0.0
Energy Storage	14.3	8.5	12.1	16.8	16.3	16.6
Surface Power Systems	0.0	0.0	0.0	0.0	0.0	0.0
Thermal Controls	0.5	0.5	0.0	0.0	0.0	0.0
RHESE	4.0	4.0	3.0	3.0	3.0	3.0
ISHM	6.0	8.0	10.0	21.5	22.5	25.5
A4O	4.1	4.1	7.1	11.9	16.4	16.9
Intelligent Software Design	3.7	3.0	1.9	1.9	1.9	1.9
ALHAT	13.5	14.1	14.3	10.3	9.7	7.3
AR&D	8.4	0.0	0.0	0.0	0.0	0.0
Mini-RF/LRO	0.0	0.0	0.0	0.0	0.0	0.0
Advanced Nav Sensors	0.0	0.0	0.2	3.0	5.0	10.0
High-Bandwith Comm	0.0	0.0	4.0	6.0	6.0	2.5
ELS	23.5	21.9	24.8	30.5	33.4	33.7
AEMC	29.1	35.5	35.9	32.7	28.1	30.1
FPDS	1.5	1.3	1.3	0.4	0.3	0.3
Advanced Waste Techniques	0.0	0.0	0.0	0.0	0.0	0.0
EVA Technologies	21.3	29.5	32.2	0.0	0.0	0.0
Advanced EVA Technologies	0.0	0.0	0.0	0.0	0.0	0.0
ISS Research	33.0	30.0	31.0	30.0	30.0	31.0
ISRU	5.1	5.7	9.6	11.7	13.9	13.9
FSP	9.0	9.0	9.0	9.0	9.0	9.0
Supportability	6.8	7.8	8.0	11.5	11.7	11.7
Human Robotics	16.8	21.9	27.4	35.8	54.4	54.3
ETDP Special Projects	4.7	4.8	4.8	4.8	4.8	4.8
Program Support	9.0	8.0	8.0	8.0	8.0	9.0

ETDP Project Managers




Exploration Technology Development Program (ETDP)
and Exploration Systems Mission Directorate (ESMD) Milestones
ETDP Projects
FY07
FY08
FY09
FY10
2
3
4
1
2
3
4
1
2
3
4
1
2
3
Constellation Program Milestones
Constellation Program Reviews
ORION - Crew Exploration Vehicle (CEV)
Ares I - Crew Launch Vehicle (CLV)
Ares I-X Flight Test
EVA Suits
Exploration Technology Development Program Office Projects
Structures, Materials & Mechanisms
Protection Systems
Non-Toxic Propulsion
Energy Storage and Power Systems
Thermal Control for Surface Systems
Avionics and Software
Environmental Control and Life Support
Crew Support and Accommodations
ISS Research and Operations
In-Situ Resource Utilization (ISRU)
Robotics, Operations & Supportability
Fission Surface Power Systems
Near Earth Objects Observation
GO SRR
Requirements Sync
5/1 PDR
PA 1
AA 1
CDR
3/1
3/1 SRR
SDR
8/24
Pre-NAR
10/1
6/16 PDR
7/1 CDR
4/22 PDR
9/1 CDR
FRR
2/17
4/19 PDR
9/4 CDR
Flight 1 (Ares I-X)
4/15
4/30 SRR
SDR
11/30 PDR
Comp Test modified motor sys to -230 degree C
Comp Advanced Composites Eval
Comp Inflatable wall struct panel testing
Characterization of materials in low temperature environment
TPS PDR
Desert RATS demo of screen
Investigate implementation options of technology
Methane Bubble Point Report
LN2 Heat Entrapment Report
Complete Aerojet RCS configuration vacuum testing
CECE alternate injector design review
Exciter BB demo
Vacuum 100-lbf thruster testing
Flow-Through vs. Non Flow-Through Decision Point
Del interim performance safety report on Li-ion cells
Demo high energy cathode 1000 Whr/kg
MEHS Prototype
Testing complete Systems Design
Start Suit Evaporator Design Review
Heat pump trade study for LSAM
LSAM Radiator Subscale Test Article - Design Review
Component Reliability TRR
UML Capability Demo'd
Flight testing real-time SRM HM algorithm
Initial J-2X failure model data generation and analysis comp
HAST with flight-like computer
Field test optical TRN sensors
Flight testing of real-time SRM HM algorithm Ares 1-X
TRN Sensor del'd ready for test
Oxygen flammability threshold for initial set of CEV material
ENose Del
VCAM ETRR
ACRRS TRR
ENOSE Launch
VCAM Launch
CSPE Qual unit testing
Comp TRL 6 fire detector in rel arch
Comp Primary VCAM Tech Demo
RESOLVE EBU Testing Comp
RESOLVE L2 Testing Comp
Customization rover operations user interface to polar crater
Del Polar Highland Simulant Recipe
Comp CAT simulation excavator demo model
O2 Production TRL 3 Lessons Learned Sys Test
Develop & Test of Scale-up cell
EFBB Initiate system integration
Test single link crane on ATHLETE
Test ATHLETE serving as surface mobility carrier
EBFF Complete hardware integration
Comp EFBB Ground & flight tests
Test crew aids for site operations support



Exploration Technology Development Program (ETDP)
and Exploration Systems Mission Directorate (ESMD) Milestones