

**Report
on
Project Management in NASA**

*by the
Mars Climate Orbiter
Mishap Investigation Board*

March 13, 2000

Table of Contents

	Page
Signature Page (Board Members)	3
Consultants	4
Acknowledgements	5
Executive Summary	6
1. Introduction	10
2. The Mars Climate Orbiter Mission: Observations and Lessons Learned	15
3. A New Vision for NASA Programs and Projects	24
4. NASA's Current Program/Project Management Environment	33
5. Recommendations and Metrics	36
6. Checklist for Project Management and Review Boards	44
7. Concluding Remarks	47

Appendices

- A. Letter Establishing the Mars Climate Orbiter Mishap Investigation Board
- B. Mars Climate Orbiter Mishap Investigation Board Phase I Report (dated Nov. 10, 1999)
- C. Letter Providing Revised Charter for the Mars Climate Orbiter Mishap Investigation Board
- D. List of Existing Processes and Requirements Applicable to Programs/Projects
- E. List of Additional Projects Reviewed by the Mars Climate Orbiter Mishap Investigation Board
- F. Recurring Themes From Failure Investigations and Studies

Signature Page

/s/
Arthur G. Stephenson, Chairman
Director, George C. Marshall
Space Flight Center

/s/
Dr. Daniel R. Mulville
Associate Deputy Administrator
NASA Headquarters

/s/
Frank H. Bauer
Chief, Guidance,
Navigation and Control Center
Goddard Space Flight Center

/s/
Greg A. Dukeman
Guidance and Navigation Specialist
Vehicle Flight Mechanics Group
George C. Marshall Space Flight Center

/s/
Dr. Peter Norvig
Chief, Computational Sciences Division
Ames Research Center

/s/
Approved
Dr. Edward J. Weiler
Associate Administrator
Office of Space Science

/s/
Lia S. LaPiana, Executive Secretary
Program Executive
Office of Space Science
NASA Headquarters

/s/
Dr. Peter J. Rutledge (ex-officio)
Director, Enterprise Safety and
Mission Assurance Division
NASA Headquarters

/s/
David Folta
System Engineer, Guidance,
Navigation and Control Center
Goddard Space Flight Center

/s/
Robert Sackheim
Assistant Director for Space
Propulsion Systems
George C. Marshall Space Flight Center

/s/
Approved
Frederick D. Gregory
Associate Administrator
Office of Safety & Mission Assurance

Advisors:

Office of Chief Counsel: MSFC/Louis Durnya
Office of Public Affairs: HQ/Donald Savage

Consultants

Ann Merwarth

NASA/GSFC-retired
Expert in ground operations & flight
software development

Moshe F. Rubinstein

Prof. Emeritus,
University of California, Los Angeles
Civil and Environmental Engineering

John Mari

Vice-President of Product Assurance
Lockheed Martin Astronautics

Peter Sharer

Senior Professional Staff
Mission Concepts and Analysis Group
The Johns Hopkins University
Applied Physics Laboratory

Craig Staresinich

Chandra X-ray Observatory Program
Manager, TRW

Dr. Michael G. Hauser

Deputy Director
Space Telescope Science Institute

Tim Crumbley

Deputy Group Lead
Flight Software Group
Avionics Department
George C. Marshall Space Flight Center

Don Pearson

Assistant for Advanced Mission Design
Flight Design and Dynamics Division
Mission Operations Directorate
Johnson Space Center

Acknowledgements

The Mars Climate Orbiter Mishap Investigation Board wishes to thank the technical teams from Jet Propulsion Laboratory and Lockheed Martin Astronautics for their cooperation, which was essential in our review of the Mars Climate Orbiter project.

In addition, the Board wishes to thank the presenters and members of other review boards and projects listed in Appendix E, who shared their thoughts on project management.

Finally, the Board wishes to thank Jerry Berg and Rick Smith, of the Marshall Space Flight Center's Media Relations Department, for their editorial assistance on this report; and Drew Smith, of the Marshall Center, for his invaluable support to the Board.

Executive Summary

This second report, prepared by the Mars Climate Orbiter Mishap Investigation Board, presents a vision and recommendations to maximize the probability of success for future space missions. The Mars Climate Orbiter Phase I Report, released Nov. 10, 1999, identified the root cause and factors contributing to the Mars Climate Orbiter failure. The charter for this second report is to derive lessons learned from that failure and from other failed missions — as well as some successful ones — and from them create a formula for future mission success.

The Mars Climate Orbiter mission was conducted under NASA's "Faster, Better, Cheaper" philosophy, developed in recent years to enhance innovation, productivity and cost-effectiveness of America's space program. The "Faster, Better, Cheaper" paradigm has successfully challenged project teams to infuse new technologies and processes that allow NASA to do more with less. The success of "Faster, Better, Cheaper" is tempered by the fact that some projects and programs have put too much emphasis on cost and schedule reduction (the "Faster" and "Cheaper" elements of the paradigm). At the same time, they have failed to instill sufficient rigor in risk management throughout the mission lifecycle. These actions have increased risk to an unacceptable level on these projects.

The Mishap Investigation Board conducted a series of meetings over several months with the Jet Propulsion Laboratory and Lockheed Martin Astronautics to better understand the issues that led to the failure of the Mars Climate Orbiter. The Board found that the Mars Surveyor Program, agreed to significant cuts in monetary and personnel resources available to support the Mars Climate Orbiter mission, as compared to previous projects. More importantly, the project failed to introduce sufficient discipline in the processes used to develop, validate and operate the spacecraft; nor did it adequately instill a mission success culture that would shore up the risk introduced by these cuts. These process and project leadership deficiencies introduced sufficient risk to compromise mission success to the point of mission failure.

It should be noted that despite these deficiencies, the spacecraft operated as commanded and the mission was categorized as extremely successful until right before Mars orbit insertion. This is a testament to the hard work and dedication of the entire Mars Climate Orbiter team. The Board recognizes that mistakes and deficiencies occur on all spacecraft projects. It is imperative that all spacecraft projects have sufficient processes in place to catch mistakes before they become detrimental to mission success. Unfortunately for the Mars Climate Orbiter, the processes in place did not catch the root cause and contributing navigational factors that ultimately led to mission failure.

Building upon the lessons learned from the Mars Climate Orbiter and a review of seven other failure investigation board results, this second report puts forth a new vision for NASA programs and projects — one that will improve mission success within the

context of the “Faster, Better, Cheaper” paradigm. This vision, **Mission Success First**, entails a new NASA culture and new methods of managing projects. To proceed with this culture shift, mission success must become the highest priority at all levels of the program/project and the institutional organization. All individuals should feel ownership and accountability, not only for their own work, but for the success of the entire mission.

Examining the current state of NASA’s program and project management environment, the Board found that a significant infrastructure of processes and requirements already is in place to enable robust program and project management. However, these processes are not being adequately implemented within the context of “Faster, Better, Cheaper.” To move toward the ideal vision of **Mission Success First**, the Board makes a series of observations and recommendations that are grouped into four categories, providing a guide by which to measure progress.

1) People

The Board recognizes that one of the most important assets to a program and project is its people. Success means starting with top-notch people and creating the right cultural environment in which they can excel. Thus, **Mission Success First** demands that every individual on the program/project team continuously employ solid engineering and scientific discipline, take personal ownership for their product development efforts and continuously manage risk in order to design, develop and deliver robust systems capable of supporting all mission scenarios.

Teamwork is critical for mission success. Good communication between all project elements — government and contractor, engineer and scientist — is essential to maintaining an effective team. To ensure good teamwork, the project manager must guarantee an appropriate level of staffing, and all roles and responsibilities must be clearly defined.

2) Process

Even the best people with the best motivation and teamwork need a set of guidelines to ensure mission success. In most cases NASA has very good processes in place, but there are a few areas for improvement.

A concise set of mission success criteria should be developed and frozen early in the project life cycle.

During the mission formulation process, the program office and the project should perform the system trades necessary to scope out the expected costs for mission success. This should be accomplished independently of any predefined dollar cap. If necessary, consider mission scope changes to drive the costs to a level that the program can afford. Scope should never be decreased below a minimum threshold for science and for technical achievement as defined by the mission success criteria.

Both the project and the program should hold adequate contingency reserves, to ensure that mission success is achievable. Projects and programs that wind up with inadequate funding should obtain more funds or consider cancellation before proceeding with inadequate funds.

Close attention should be paid from project outset to the plan for transition between development and operations. Adequate systems engineering staffing, particularly a mission systems engineer, should be in place to provide a bridge during the transition between development and operations, and also to support risk management trade studies.

Greater attention needs to be paid to risk identification and management. Risk management should be employed throughout the life cycle of the project, much the way cost, schedule and content are managed. Risk, therefore, becomes the “fourth dimension” of project management — treated equally as important as cost and schedule.

Project managers should copy the checklist located in the back of this report, putting it to constant use and adding to it in order to benchmark the performance of their project team. Moreover, this checklist should be distributed to all members of the project team as a 360-degree benchmark tool, to identify and reduce potential risk areas.

3) Execution

Most mission failures and serious errors can be traced to a breakdown in existing communication channels, or failure to follow existing processes — in other words, a failure in execution. To successfully shift to the **Mission Success First** culture, it is necessary for the institutional line management to become more engaged in the execution of a project. As such, line managers at the field centers need to be held accountable for the success of all missions at their centers.

Let us be clear that this role of institutional line management accountability should not be construed as a return to the old management formula, wherein NASA civil servants provided oversight for every task performed by the contractor or team. Instead, we recommend that NASA conduct more rigorous, in-depth reviews of the contractor’s and the team’s work — something that was lacking on the Mars Climate Orbiter.

To accomplish this, line management should be held accountable for asking the right questions at meetings and reviews, and getting the right people to those reviews to uncover mission-critical issues and concerns early in the program. Institutional management also must be accountable for ensuring that concerns raised in their area of responsibility are pursued, adequately addressed and closed out.

Line organizations at the field centers also must be responsible for providing robust mechanisms for training, mentoring, coaching and overseeing their employees, project managers and other project team leaders. An aggressive mentoring and certification

program should be employed as the first step toward nurturing competent project managers, systems engineers and mission assurance engineers for future programs.

Line organizations, in conjunction with the projects, also must instill a culture that encourages all internal and external team members to forcefully and vigorously elevate concerns as far as necessary to get attention within the organization. Only then will **Mission Success First** become a reality.

4) Technology

Technological innovation is a key aspect in making the “Faster, Better, Cheaper” approach a reality. Through such innovation, smaller, lighter, cheaper, and better-performing systems can be developed. In addition, innovative processes enable quicker development cycles. To enable this vision, NASA requires adequately funded technology development, specifically aimed at Agency needs. Programs and projects must conduct long-range planning for and champion technology infusions resulting in delivery of low-risk products for project incorporation.

Mechanisms which minimize technology infusion risk, such as the New Millennium Program, should be employed to flight-validate high risk technologies prior to their use on science missions.

Agenda for the Future

The Mars Climate Orbiter Mishap Investigation Board perceives its recommendations as the first step in an agenda that will be revisited and adjusted on an ongoing basis. The aim is to make **Mission Success First** a way of life — a concern and responsibility for everyone involved in NASA programs.

The recommendations of this report must trigger the first wave of changes in processes and work habits that will make **Mission Success First** a reality. To implement this agenda with a sense of urgency and propagate it throughout the Agency, NASA Headquarters and the NASA centers must address the recommendations presented in this report. NASA must further assign responsibility to an organization (such as the Office of the Chief Engineer) for including the recommendations in Agency policy and in training courses for program and project management.

These actions will ensure that **Mission Success First** serves as a beacon to guide NASA as the future unfolds.

1. Introduction

Background

In 1993, NASA started the Mars Surveyor Program, with the objective of conducting a series of missions to explore Mars. A Mars Program Office was established and given the responsibility of defining objectives for sending two missions to Mars at each biennial launch opportunity, culminating in return of a sample of Martian material to Earth.

For each launch opportunity, the Jet Propulsion Laboratory established a project office to manage development of specific spacecraft and mission operations. In 1995, the Mars Program Office identified two missions for launch in late 1998/early 1999: the Mars Climate Orbiter and the Mars Polar Lander. The Jet Propulsion Laboratory created the Mars Surveyor Project '98 Office, which was responsible for designing the missions, developing both spacecraft and all payload elements, and integrating, testing and launching both flight systems. In March of 1996, subsequent to the formation of the project office, the Mars Surveyor Program established the Mars Surveyor Operations Project, which was tasked to perform operations of all Mars Surveyor Program missions.

The Mars Climate Orbiter was launched Dec. 11, 1998, atop a Delta II launch vehicle from Cape Canaveral Air Force Station, Florida. Nine and a half months after launch, in September 1999, the spacecraft was to fire its main engine to achieve an elliptical orbit around Mars. It then was to skim through Mars' upper atmosphere for several weeks, in a technique called aerobraking, to move into a low circular orbit. Friction against the spacecraft's single, 5.5-meter solar array was to have lowered the altitude of the spacecraft as it dipped into the atmosphere, reducing its orbital period from more than 14 hours to 2 hours.

On Sept. 23, 1999 the Mars Climate Orbiter mission was lost when it entered the Martian atmosphere on a lower than expected trajectory.

On Oct. 15, 1999, the NASA Office of Space Science established the Mars Climate Orbiter Mission Failure Mishap Investigation Board — hereafter referred to as "the Board" — and appointed Arthur G. Stephenson, Director of the Marshall Space Flight Center, as chairman of the Board. A copy of the letter establishing the Board is contained in Appendix A.

On Nov. 10, 1999, the Board's Phase I Report was released in response to the letter of October 15. That report focused on identifying the root cause and contributing factors of the Mars Climate Orbiter failure and made observations related to the Mars Polar Lander's entry, descent and landing activities, which were planned for Dec. 3, 1999. A copy of the Phase I Report is contained in Appendix B.

On Jan. 3, 2000, the Office of Space Science revised the Board's charter (*see Appendix C*) to broaden the area of investigation beyond the Mars Climate Orbiter failure in order to derive lessons learned and develop recommendations to benefit future NASA missions. To learn from other failure experiences, the Board looked at the additional projects listed in Appendix E.

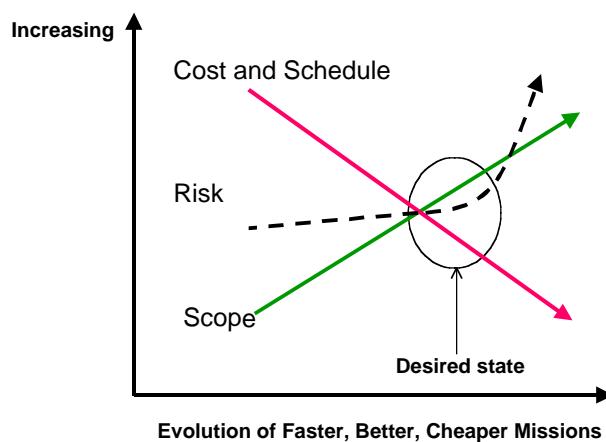
This report responds to the revised charter by first presenting findings related to the failure of the Mars Climate Orbiter — going beyond those developed in Phase I. The report accomplishes the following actions:

- Summarizes lessons learned from the Mars Climate Orbiter,
- Provides an idealized vision of project management,
- Describes how NASA is currently performing project management,
- Identifies common themes contributing to recent mission failures, and
- Makes recommendations for improving the likelihood of mission success in future NASA missions.

The “Faster, Better, Cheaper” Paradigm

The aim of the “Faster, Better, Cheaper” philosophy is to encourage doing more with less. This is accomplished by enhancing innovation and productivity, while enabling new safe, cost-effective approaches to achieving mission success. The initiative in recent years has led to significant restructuring of programs and a number of successful missions. Costs were reduced and program scope — including both content and the infusion of new technology — increased at the same time.

As implementation of this strategy evolved, however, the focus on cost and schedule reduction increased risk beyond acceptable levels on some NASA projects. Even now, NASA may be operating on the edge of high, unacceptable risk on some projects. These trends of increasing scope, decreasing cost and eventual, significant increase in risk are notionally illustrated in the figure below.



The desired state, as indicated in the figure, is the region where cost is well matched to the desired scope and risk is not significantly affected by changes in cost, schedule and scope. Ideally, cost should not be reduced — nor content increased — beyond the point where risk rises rapidly.

The Board finds that implementation of the “Faster, Better, Cheaper” philosophy must be refined at this stage in a new context: **Mission Success First**. For the purposes of this report, a proper emphasis on mission success encompasses the following principles:

- Emphasis on definition of a minimum set of mission success criteria and rigorous requirements derived therefrom,
- Sufficient analysis and verification prior to launch, ensuring a high probability of satisfying the mission success criteria,
- Assurance of sufficient robustness in the design of the mission to maintain the health and safety of the flight systems until the mission science and/or technology objectives are achieved, even in the event of off-nominal conditions, and
- Ensuring that we will be able to learn from mission failure or abnormalities, by being able to obtain sufficient engineering data to understand what happened and thereby design future missions to avoid a repeat occurrence.

The “Faster, Better, Cheaper” paradigm has enabled NASA to respond to the national mandate to do more with less. In order for this paradigm to succeed in the future, we face two key challenges: the timely development and infusion of new technology into our missions, and the fostering of the **Mission Success First** mentality throughout the workforce, ensuring safe, cost-effective mission accomplishment.

Mission Success First is the over-arching focus of this report.

The Changing Environment

Significant change has taken place in the environment for NASA projects over the past five to seven years. The “Faster, Better, Cheaper” paradigm has been extremely successful in producing a greater number of smaller missions, with significantly shortened development cycles. Many of these missions are selected on the basis of proposals from principal investigators, who become responsible for managing all aspects of the mission through a NASA center. With freedom to operate outside traditional, NASA-specified management approaches, managers may use smaller teams and a strict “design-to-cost” philosophy in implementing projects.

One of the consequences of this approach has been increased partnering between NASA, industry, academia and other government agencies, necessitating increased and improved communications. New and innovative teaming arrangements and contracting approaches have been employed in the procurement processes. These changes have shifted accountability and required the various participants to learn new roles.

During the same period, the size, experience and focus of the NASA workforce and industry have also undergone significant change. The workforce has been reduced, resulting in a loss of experienced personnel in all skill categories. The primary focus of in-house work is shifting from spacecraft development and operations to new technology development. NASA management of out-of-house missions has changed from “oversight” to “insight” — with far fewer resources devoted to contract monitoring.

NASA projects have placed increased emphasis on public education and outreach. In addition, the public is more engaged in NASA missions because there are more of them. While this has delivered the desired results — heightening public interest in our missions and increasing public understanding of our scientific advances — it has also made NASA’s failures more visible, along with our successes.

Perpetuating the Legacy

NASA is a national resource. It enjoys a legacy of excellence established by many successes that inspired the nation and the world. Policies that contributed to this legacy must now be assessed because of changes that have occurred in response to the new environment — one characterized by the need to “do more with less.”

Policies must be examined, current processes adjusted and behaviors modified to preserve NASA as a national resource and perpetuate its legacy of success in innovative scientific and technological undertakings.

Outline of the Report

This report is organized as follows. Section 2 addresses the Mars Climate Orbiter mission. In the Phase I Report by this Board (*see Appendix B*), the focus was on items deemed particularly important to the Mars Polar Lander mission, then cruising toward Mars. Section 2 describes the lessons learned from the Mars Climate Orbiter mission in general. In Section 3, we offer a vision of an improved NASA culture and the characteristics of an ideal project process aimed at **Mission Success First**. In Section 4, we present observations of the current project management environment, based upon documented processes (*see Appendix D*) and our review of a number of projects (*see Appendix E*). We identify some common causes of project problems. In Section 5, we provide specific recommendations for bridging the gap between where we are now and where we would like to be, and suggest some metrics for measuring our progress toward the desired **Mission Success First** environment. A checklist for project management is also provided in Section 5.

The report addresses broad issues that are important to all parties involved in the NASA program. It is intended to be widely disseminated to NASA employees, contractors and those in academic or other institutions participating in the implementation of NASA projects.

Agenda for the Future

The Mars Climate Orbiter Mishap Investigation Board perceives its recommendations as the first step in an agenda that will be revisited and adjusted on an ongoing basis in the future. The aim of the agenda is to make **Mission Success First** a way of life — a concern and responsibility for everyone involved in NASA programs.

The recommendations of this report must trigger the first wave of changes in processes and work habits that will make **Mission Success First** a reality. To implement this agenda with a sense of urgency and propagate it throughout the Agency, NASA Headquarters and the NASA Centers should make plans to address the recommendations presented in this report, as well as other investigative reports (i.e., Spear, McDonald, Young) soon to be released. NASA must further assign an organization (such as the Office of the Chief Engineer) responsibility for including the recommendations in Agency guidance and in training courses for program and project management.

These actions will ensure that **Mission Success First** serves as a beacon to guide NASA decisions as the future unfolds.

2. The Mars Climate Orbiter Mission: Observations and Lessons Learned

To better understand the issues that led to the failure of the Mars Climate Orbiter, the Mishap Investigation Board conducted a series of meetings over several months with the Jet Propulsion Laboratory and Lockheed Martin Astronautics. As part of its investigation, the Board uncovered several mistakes and deficiencies in the overall Mars Surveyor Program. Despite these deficiencies, the spacecraft operated as commanded and the mission was categorized as extremely successful until just before Mars orbit insertion. This is a testament to the hard work and dedication of the entire Mars Climate Orbiter team.

The Board recognizes that mistakes and deficiencies occur on all spacecraft projects. It is imperative for all spacecraft projects to have sufficient processes in place to catch mistakes and deficiencies before they become detrimental to mission success. Unfortunately for the Mars Climate Orbiter, the processes in place did not catch the root problem and contributing navigational factors that ultimately led to mission failure.

As part of its Phase I activity, the Board identified one root cause, eight contributing causes and 10 observations. These are described in the Phase I report (*see Appendix B*). Subsequent Board investigations and meetings have uncovered additional observations. These observations — as well as the issues identified in the Phase I report — were compiled and consolidated into five primary issue areas:

- **Systems Engineering**
- **Project Management**
- **Institutional Involvement**
- **Communication Among Project Elements**
- **Mission Assurance**

A top-level description of the observations made during the investigation follows, along with some lessons learned.

Systems Engineering

A necessary condition for mission success in all spaceflight programs is a robust, experienced systems engineering team and well thought-out systems engineering processes. The systems engineering team performs critical trade studies that help optimize the mission in terms of performance, cost, schedule and risk. Throughout mission formulation, design, development and operations, this team leads the subsystem-discipline teams in the identification of mission risks. The systems engineers work with the project manager and the discipline engineering teams to mitigate these risks.

The Board saw strong evidence that the systems engineering team and the systems processes were inadequate on the Mars Climate Orbiter project. Some specific observations demonstrating that a robust systems engineering team and processes were not in place included:

- Absence of a mission systems engineer during the operations phase to provide the bridge between the spacecraft system, the instrument system and the ground/operations system.
- Lack of identification of acceptable risk by the operations team in the context of the “Faster, Better, Cheaper” philosophy.
- Navigation requirements set at too high a management level, insufficient flowdown of requirements and inadequate validation of these requirements.
- Several significant system and subsystem design and development issues, uncovered after the launch of the Mars Climate Orbiter (the star camera glint issue and the inability of the navigation team to receive telemetry from the ground system for almost six months, for example).
- Inadequate independent verification and validation of Mars Climate Orbiter ground software (end-to-end testing to validate the small forces ground software performance and its applicability to the software interface specification did not appear to be accomplished).
- Failure to complete — or completion with insufficient rigor — of the interface control process, as well as verification of specific ground system interfaces.
- Absence of a process, such as a fault tree analysis, for determining “what could go wrong” during the mission.
- Inadequate identification of mission-critical elements throughout the mission (the mission criticality of specific elements of the ground software that impacted navigation trajectory was not identified, for example).
- Inadequate attention, within the system engineering process, to the transition from development to operations.
- Inadequate criteria for mission contingency planning (without the development of a fault tree up front, there was no basis for adequate contingency planning).
- Insufficient autonomy and contingency planning to execute Trajectory Correction Maneuver 5 and other mission-critical operations scenarios.
- A navigation strategy that was totally reliant on Earth-based, Deep Space Network tracking of the Mars Climate Orbiter as a single vehicle traveling in interplanetary space. Mission plans for the Mars Polar Lander included alternative methods of processing this data — including using “Near Simultaneous Tracking” of a Mars-orbiting spacecraft. These alternatives were not implemented nor were operational at the time of the Mars Climate Orbiter’s encounter with Mars. The Board found that reliance on single-vehicle, Deep Space Network tracking to support planetary orbit insertion involved considerable systems risk, due to the possible accumulation of unobserved perturbations to the long interplanetary trajectory.

Lessons Learned

- Establish and fully staff a comprehensive systems engineering team at the start of each project. Ensure that the systems engineering team possesses the skills to fully engage the subsystem engineers so that a healthy communication flow is present up and down the project elements.
- Engage operations personnel early in the project, preferably during the mission formulation phase.
- Define program architecture at the beginning of a program by means of a thorough mission formulation process.
- Develop a comprehensive set of mission requirements early in the formulation phase. Perform a thorough flowdown of these requirements to the subsystem level.
- Continually perform system analyses necessary to explicitly identify mission risks and communicate these risks to all segments of the project team and institutional management. Vigorously work with this team to make trade-off decisions that mitigate these risks in order to maximize the likelihood of mission success. Regularly communicate the progress of the risk mitigation plans and tradeoffs to project, program and institutional management.
- Develop and deploy alternative navigational schemes to single-vehicle, Deep Space Network tracking for future planetary missions. For example, utilizing “relative navigation” when in the vicinity of another planet is promising.
- Give consideration to technology developments addressing optical tracking, relative state ranging and in-situ autonomous spacecraft orbit determination. Such determination should be based on nearby planetary features or Global Positioning System-type tracking.

Project Management

In order to accomplish the very aggressive Mars mission, the Mars Surveyor Program agreed to significant cuts in the monetary and personnel resources available to support the Mars Climate Orbiter mission, as compared to previous projects. More importantly, the program failed to introduce sufficient discipline in the processes used to develop, validate and operate the spacecraft, and did not adequately instill a mission-success culture that would shore up the risk introduced by these cuts. These process and project leadership deficiencies introduced sufficient risk to compromise mission success to the point of mission failure. The following are specific issues that may have contributed to that failure.

Roles and responsibilities of some individuals on the Mars Climate Orbiter and Mars Surveyor Operations Project teams were not clearly specified by project management.

To exacerbate this situation, the mission was understaffed, with virtually no Jet Propulsion Laboratory oversight of Lockheed Martin Astronautics' subsystem developments. Thus, as the mission workforce was reduced and focus shifted from spacecraft development to operations, several mission critical functions — such as navigation and software validation — received insufficient management oversight.

Authority and accountability appeared to be a significant issue here. Recurring questions in the Board's investigation included "Who's in charge?" and "Who is the mission manager?" The Board perceived hesitancy and wavering on the part of people attempting to answer the latter question. One interviewee answered that the flight operations manager was acting like a mission manager, but is not actually designated as such.

The Board found that the overall project plan did not provide for a careful handover from the development project to the very busy operations project. Transition from development to operations — as two separate teams — disrupted continuity and unity of shared purpose.

Training of some new, inexperienced development team members was inadequate. Team membership was not balanced by the inclusion of experienced specialists who could serve as mentors. This team's inexperience was a key factor in the root cause of the mission failure (the failure to use metric units in the coding of the "Small Forces" ground software used in trajectory modeling). This problem might have been uncovered with proper training. In addition, the operations navigation team was not intimately familiar with the attitude operations of the spacecraft, especially with regard to the attitude control system and related subsystem parameters. These functions and their ramifications for Mars Climate Orbiter navigation were fully understood by neither the operations navigation team nor the spacecraft team, due to inexperience and miscommunication.

The Board found that the project management team appeared more focused on meeting mission cost and schedule objectives and did not adequately focus on mission risk.

A critical deficiency in Mars Climate Orbiter project management was the lack of discipline in reporting problems and insufficient follow-up. The primary, structured problem-reporting procedure used by the Jet Propulsion Laboratory — the Incident, Surprise, Anomaly process — was not embraced by the whole team. Project leadership did not instill the necessary sense of authority and responsibility in workers that would have spurred them to broadcast problems they detected so those problems might be articulated, interpreted and elevated to the highest appropriate level, until resolved.

This error was at the heart of the mission's navigation mishap. If discipline in the problem reporting and follow-up process had been in place, the operations navigation team or the spacecraft team may have identified the navigation discrepancies, using the Incident, Surprise, Anomaly process, and the team would have made sure those discrepancies were resolved. Furthermore, flight-critical decisions did not adequately involve the mission scientists who had the most knowledge of Mars, the instruments and the mission science objectives. This was particularly apparent in the decision not to perform the fifth Trajectory Correction Maneuver prior to Mars orbit insertion.

In summary, the Mars Surveyor Program increased the scope of the operations project and reduced personnel and funding resources. These actions went unchallenged by the project, causing it to operate beyond the edge of acceptable risk. In short, they went beyond the boundaries of **Mission Success First**.

Lessons Learned

- Roles, responsibilities and accountabilities must be made explicit and clear for all partners on a project, and a visible leader appointed over the entire operation.
- A cohesive team must be developed and involved in the project from inception to completion.
- Training and mentoring using experienced personnel should be institutionalized as a process to preserve and perpetuate the wisdom of institutional memory as well as to reduce mission risk.
- Steps must be taken to aggressively mitigate unresolved problems by creating a structured process of problem reporting and resolution. Workers should be trained to detect, broadcast, interpret and elevate problems to the highest level necessary until resolved.
- Lessons learned from such problems must be articulated, documented and made part of institutional and Agency memory (see “Lessons Learned Information System” on the World Wide Web at <http://llis.gsfc.nasa.gov>).
- Acceptable risk must be defined and quantified, wherever possible, and disseminated throughout the team and the organization to guide all activities in the context of **Mission Success First**.

Institutional Involvement

All successful spacecraft projects require strong engagement and participation of the project management team, the spacecraft discipline team, the systems engineering team, the operations team, the science team and the organization’s institutional management. For the Mars Climate Orbiter and the Mars Polar Lander, there clearly appeared to be little or no ownership of these missions within the Jet Propulsion Laboratory’s institutional organization until after the Mars Climate Orbiter mission failure occurred.

In an effort to reduce costs, the project management team elected not to fully involve the Jet Propulsion Laboratory’s technical divisions in spacecraft design and development activities. They also did not appear to properly engage the safety and mission assurance group during the operations phase. Unfortunately, key oversight in a few critical discipline areas — propulsion, attitude control, navigation, flight software and systems — could have identified problems and brought issues to the attention of institutional management at the Jet Propulsion Laboratory as well as to project management. Because the Jet Propulsion Laboratory’s technical divisions were disengaged from the Mars

Climate Orbiter mission, there was little or no ownership of the mission beyond the flight project and a few organizational managers.

The lack of institutional involvement resulted in a project team culture that was isolated from institutional experts at the Jet Propulsion Laboratory. The project team did not adequately engage these experts when problems arose, they did not elevate concerns to the highest levels within the contractor and they did not receive the proper coaching and mentoring during the project life cycle to ensure mission success.

In short, there was lack of institutional involvement to help bridge the transition as old, proven ways of project management were discontinued and new, unproven ways were implemented.

Lessons Learned

- In the era of “Faster, Better, Cheaper,” projects and line organizations need to be extremely vigilant to ensure that a **Mission Success First** attitude propagates through all levels of the organization. A proper balance of contractor and project oversight by technical divisions at NASA field centers is required to ensure mission success and to develop a sense of ownership of the project by the institution.
- The Agency, field centers and projects need to convey to project team members and line organizations that they are responsible for the success of each mission. NASA needs to instill a culture that encourages all internal and external team members to forcefully and vigorously elevate concerns as far as necessary to get attention — either vertically or horizontally within the organization.
- Organizations should provide robust mechanisms for training, mentoring and oversight of project managers and other leaders of project teams. An aggressive mentoring and certification program should be instituted to nurture competent project managers, systems engineers and mission assurance engineers to support future programs.
- Line managers at the field centers should be held accountable for all missions at their centers. As such, they should be held accountable for getting the right people to reviews and ensuring the right questions are asked at meetings and reviews to uncover mission-critical issues and concerns. They also must be accountable to ensure adequate answers are provided in response to their questions. This factor was missing on the Mars Climate Orbiter project. Let us be clear that we do not advocate returning to the old approach, wherein NASA civil servants performed oversight on every task performed by the system contractor. The need, rather, is for NASA to conduct rigorous reviews of the

contractor's and the team's work — something that was not done on Mars Climate Orbiter.

Communications Among Project Elements

The Mars Climate Orbiter project exhibited inadequate communications between project elements during its development and operations phases. This was identified as a contributing cause to the mission failure in the Board's Phase I report (*see Appendix B*).

A summary of specific inadequacies follows:

- Inadequate communications between project elements led to a lack of cross-discipline knowledge among team members. Example: the operations navigation team's lack of knowledge regarding the designed spacecraft's characteristics, such as the impact of solar pressure on torque.
- There was a lack of early and constant involvement of all project elements throughout the project life cycle. Example: inadequate communications between the development and operations teams.
- Project management did not develop an environment of open communications within the operations team. Example: inadequate communications between operations navigation staff and the rest of the Mars Surveyor Operations team supporting the Mars Climate Orbiter.
- There was inadequate communication between the project system elements and the institutional technical line divisions at the Jet Propulsion Laboratory. Example: lack of knowledge by the Jet Propulsion Laboratory's navigation section regarding analyses and assumptions made by Mars Climate Orbiter operations navigators.

Lessons Learned

A successful project is a result of many factors: a good design, a good implementation strategy, a good understanding of how the project will function during the operations phase and project members with good technical skills. A project can have all these elements and still fail, however, because of a lack of good communications within the project team.

Good communications within a project — including the contractors and science team elements — is fostered when the following environment is put into place by project management at the beginning of project formulation and maintained until the end of the mission:

- Project managers lead by example. They must be constant communicators, proactively promoting and creating opportunities for communication.
- Communications meetings must be regular and frequent, and attendance must be open to the entire project team, including

contractors and science elements — thus ensuring ample opportunity for anyone to speak up. During critical periods, daily meetings should be held to facilitate dissemination of fast-breaking news and rapid problem solving.

- An open atmosphere must be created, where anyone can raise an issue or voice an opinion without being rejected out of hand. There must also be a constant and routine flow of information up, down and sideways, through formal and informal channels, making information available to all parties.
- If an issue is raised — no matter by whom — resolution must be pursued in an open fashion with all involved parties.
- Government, industry and academia must work together as a cohesive team to resolve issues. A project philosophy must be established to communicate any problem or concern raised by these participants to the NASA project office. That is, there must be no filtering of concerns or issues. This allows proper resources to be applied quickly for effective issue resolution. It requires an environment of trust to be created between the government, industry and academic components involved in the mission.
- Key project team members must be co-located during critical periods, such as project design trade studies and critical problem solving. Co-location makes it easier for communication to occur across systems and organizations.

Mission Assurance

The Mars Climate Orbiter program did not incorporate a project-level mission assurance function during the operations phase. The Board observed lapses in the mission assurance function, such as the absence of an Incident, Surprise, Anomaly submittal documenting anomalies impacting the Angular Momentum Desaturation module. The root cause of the mission failure may have been eliminated had there been a rigorous approach to the definition of mission-critical software — thereby allowing the aforementioned module to receive the appropriate level of review.

In addition, software verification and validation at the module level and of the navigation algorithms at the subsequent system level did not detect the error, though there was evidence of the anomaly. A rigorous application of internal and external discipline engineering support in the review cycle, with participation from knowledgeable independent reviewers, also might have uncovered the discrepancy.

Lessons Learned

- A strong mission assurance function should be present in all project phases. In addition to advising and assisting projects in implementing lower level, detailed mission assurance activities such as system safety and reliability analyses, it should also take

on the higher level, oversight function of ensuring that robust assurance processes are at work in the project. Example: mission assurance should ensure the proper and effective functioning of a problem-reporting process such as the Incident, Surprise, Anomaly process that failed to work effectively in the operational phase of the Mars Climate Orbiter mission.

- Rigorous discipline must be enforced in the review process. Key reviews should have the proper skill mix of personnel for all disciplines involved in the subject matter under review. Independent reviewers or peers with significant relevant knowledge and experience are mandatory participants.
- From the simplest component or module to the most complex system, end-to-end verification and validation conducted via simulation or testing of hardware/software must be structured to permit traceability and compliance with mission and derived requirements. Integrated hardware/software testing is a must to validate the system in a flight-like environment. Independent verification and validation of software is essential, particularly for mission-critical software functions.
- Final end-to-end verification and validation of all mission-critical operational procedures (Trajectory Correction Maneuver 5, for example) must be performed.
- The definition of mission-critical software for both ground and flight must be rigorous to allow the software development process to provide a check-and-balance system.

3. A New Vision for NASA Programs and Projects

In the future, NASA's culture must be one driven by improved mission success within the context of a continued adherence to the "Faster, Better, Cheaper" paradigm. We propose to establish **Mission Success First** as the highest priority within all levels of NASA. To do so, NASA's culture — and current techniques for program and project management — must evolve.

This new vision relies on implementing specific recommendations to improve mission success in the future. Reflecting on recent mishaps, a return to long, expensive projects is simply not warranted. However, the "Faster, Better, Cheaper" mantra cannot become an excuse for reduced attention to quality or to mission success.

In this section, a vision of NASA's new culture and suggested methods of managing its projects are described.

Cultural Vision

NASA's culture in the 21st century reemphasizes the need for overall mission success. At all levels in the organization, mission success is the highest priority. Every person in the Agency and its contractor organizations is focused on providing quality products and services. This includes searching for errors and potential failure modes and correcting them as early in the process as possible. Their confidence in their own individual capabilities is tempered with plenty of healthy skepticism. They are invigorated by the basic scientific method of thinking. They review and test, and ask others to independently review and test. They realize their jobs require scrupulous attention to details.

All individuals feel ownership and accountability for their work. Mission success and good process discipline are emphasized daily, both in words and in actions. As they develop specific products (hardware components, software components or processes), they maintain their ownership over the full life cycle of that product, understanding how the product is being used, validating the interfaces and verifying that its end use is consistent with its intended use. They develop, understand, manage and communicate their risk assessments.

Keeping a lookout for problems internal and external to their area, these responsible engineers look beyond their product needs and support wider systems engineering efforts to ensure a successful, robust system design. They feel responsible for the overall system in addition to their unique part, allowing more system-level issues to be identified and resolved early in the project. These individuals understand that the only real success is overall mission success.

NASA management at all levels promotes open communications (including bad news) and encourages inter-center cooperation and joint development efforts at the system and subsystem levels. Management provides strong leadership of badgeless teams, with civil servants and contractors alike involved in design, development, testing and early mission operations. Management ensures sufficient resources to promote continuous interaction between all elements of NASA, understanding that the sum is truly greater than the parts.

NASA Project Management

Our vision of an ideal project team builds on the foundation established in NASA Procedures and Guidelines (NPG 7120.5a) and includes some new insight into how projects should be executed.

Mission Success Criteria

In concert with NASA Headquarters and center-level senior management, program managers negotiate multi-mission objectives and associated top-level mission success criteria for the program. Subsequently, at the inception of each project, the project manager works with the program management to flow these needs into the project, thereby establishing specific project-level mission objectives and mission success criteria. This information is then flowed down through the project, resulting in system-level and subsystem-level requirements and associated mission success criteria, which will be baselined at the beginning of the project and managed throughout its life cycle.

The project team strives for quantifiable, measurable mission success criteria whenever possible. Status reports on mission success criteria are delivered to program and senior level management throughout the project life cycle to ensure that mission success is not being eroded. A coordinated understanding of expected mission success levels is communicated throughout the organization and to the American public.

Adequate resources are provided during all phases of the mission to assure that mission success criteria are met. A test of resources versus mission success criteria is constantly made during the development and operational phases. If there is an indication of inadequate resources, a decision is made to reduce the mission success criteria to match resources. If the mission success criteria drops below a minimum acceptable scientific and/or technical level, and no added resources are available, project cancellation is considered.

Technology Needs

Technology is the *better* part of the “Faster, Better, Cheaper” paradigm. Technology advancements can lead to improved spacecraft systems, science components, spacecraft autonomous operations, ground systems or mission operations processes. Some generic spacecraft technology improvements (propulsion and guidance, navigation and control hardware, for example) are continuously in development at various NASA centers, and

serve multiple programs. Other technology improvements are initiated to solve specific mission needs.

In our vision, NASA invests significantly more of its annual budget in both evolutionary and revolutionary technologies to improve future mission success. Evolutionary technologies represent continual improvement in systems design and operations. Revolutionary technologies — sometimes called breakthrough technologies — represent quantum leaps in capability and generally have high development risks, but may result in large payoffs.

Good project definition requires early, detailed program-level engineering. At the program level, a strong, robust strategy spanning multiple missions is developed to achieve program objectives. This work results in the identification of specific technology needs required for individual missions and projects, and becomes a driving factor in the infusion of technology into projects. These technology roadmaps are embraced by Agency personnel and provide strategic direction for technology development.

Proper long-range planning and scheduling is required to begin development of these technologies well in advance of project “need” dates. In our vision, the efforts to develop these technologies are underway in a timeframe such that the technologies can be matured to high technology readiness levels prior to being baselined into a project. Regardless of the development risk, these technologies are matured before project baselining in order that they may result in the lowest possible deployment risks — thereby allowing the projects to reap the benefits without incurring the risks.

Forming the Team: Project Staffing

Project success is strongly correlated to project team dynamics. This requires that projects and institutional elements interact continuously throughout the life cycle of the project. Senior management must define clear roles and responsibilities between projects and other elements of the organization.

To maximize success, senior management assures selection of experienced project managers, based on previous project management training and field experience. Prospective candidates have the ability to select, motivate and lead a close-knit project team. They also possess the ability to interact well across organizational elements (centers, enterprises and contractor/ academic lines). A junior assistant project manager is also assigned to the project to receive mentoring and on-the-job training — thus becoming an investment for future Agency needs.

Project team formation is based on team members with a good track record for technical, cost and schedule performance, along with the ability to take ownership and continually assess risk, as well as manage and communicate status. Team members are committed to the project and provide continuity throughout the life cycle of the project or mission.

One of NASA's greatest assets is its people, many of whom are truly world-class experts. Yet utilization of these people across centers is inadequate due to lack of awareness of individual abilities and performance outside their center or discipline group. In our vision, there is more inter-center participation in these projects, using discipline specialists across the Agency for direct project support and staffing of review teams.

Project Management

In concert with senior management at the centers and NASA Headquarters, program managers establish mission success criteria at the beginning of each project. Project management works with program-level management to develop top-level requirements consistent with these success criteria. The project manages the flowdown of mission success criteria and associated top-level project requirements to all levels of the project, thus ensuring that mission success is not being compromised. Under project management leadership, **Mission Success First** is practiced and preached continually throughout the project.

The project manager removes barriers and disconnects within the project between development and operations groups; between subsystem developers and system integration groups; and between government, contractors and the science community. The project manager further ensures continuity of key personnel throughout the life cycle of the project.

In the proposal stage, project plans are usually defined only in sufficient detail to allow for a reasonable assessment of cost and schedule, permitting contractor selection and overall project establishment. In our vision, to prepare for the subsequent baselining of the project, a thorough review of the project plan is performed. This is the first opportunity to think the project through from start to completion, based on contractor selection and proposed costs and schedule targets. It is also the first opportunity to avoid pitfalls. Adequate cost and schedule reserves are baselined into the project to protect against future delays and overruns. Disciplined planning, organization and staffing of project tasks is reviewed from the top down to ensure a "good start."

When a project plan is baselined, cost, schedule and content plans are traditionally frozen and subsequent project efforts are measured with respect to this baseline. In our vision, at this early stage in the project, risks are identified at all levels as well and controlled in a similar manner, becoming the fourth dimension to the project. These risks are quantified and communicated throughout the project team as well as to senior management, much the way cost, schedule and content are assessed and communicated.

During project evolution, risk management may entail trading risk on a system-by-system basis to ensure overall mission objectives are still being satisfied. Additionally, the baselined project plan contains sufficient flexibility to make adjustments to the plan, based on unanticipated issues that may surface at major design reviews. Without this flexibility, these project "challenges" present additional risks downstream in the project

life cycle. In our vision, project management is prepared to request necessary cost or schedule relief when the situation warrants, thereby controlling risk and satisfying mission success criteria.

Finally, the project manager promotes continuous capture of knowledge throughout the project. Data collection and “document as you go” behavior are typical of routine project execution, allowing for smooth personnel transitions within the project and development of lessons-learned for possible use in later phases of the project and in future projects Agency-wide.

Science as an Integral Part of the Team

The ultimate objective of most NASA missions is to accomplish scientific and/or technical research (e.g., the New Millennium Program) and study. True mission success requires that scientists be intimately involved in the entire mission — from project initiation through mission completion. As part of mission definition/concept teams, scientists define science requirements, develop an understanding of expected spacecraft capabilities and limitations, conduct trade studies and influence spacecraft design to ensure adequate science return within project limitations.

Scientists participate in project-level decisions, in systems engineering studies, in spacecraft development and in mission planning and operations. Participating throughout the project life cycle, scientists recognize and concur on the proper balance between engineering needs and science needs, in order to maximize the ability of the mission to accomplish the desired scientific objectives. For example, in a planetary mission involving landing, safely landing on the planet must take precedence over science when spacecraft resources are allocated.

Systems Engineering

Systems engineering ensures that all top-level project requirements are directly derived from the identified and controlled mission success criteria, and that these top-level project requirements and mission success criteria are appropriately flowed down to lower levels. Configuration management of these requirements — and development of a traceability matrix linking requirements to implementation — occurs within systems engineering. Requirements are baselined early. Disciplined, documented change control processes are used to manage changes. Validation and verification plans are developed to ensure current work plans address and implement all ground and onboard requirements. This linking of mission success criteria, requirements, implementation and verification plans is reviewed at all major project design reviews and flight readiness reviews.

Systems engineering ties the systems together and validates end-to-end supportability. Resource allocations between systems (power and telemetry, for example) are performed and controlled. All interfaces are tested and verified within and across subsystems. Systems engineers engage all disciplines to support integrated mission analyses using nominal and dispersed conditions. “Out of family,” or anomalous, scenarios are also

identified, analyzed and simulated to determine mission robustness. Results of these studies include identification of disconnects and weak links, and validation of mission risk assessments.

Trade studies are conducted throughout the project to continuously address risk. These studies are performed repetitively as spacecraft systems and mission operations plans evolve during the development phase. During the operational phase, systems engineering continues in this role, assessing mission risks and behavior under actual conditions.

Attention to integrated risk management on the project is a key responsibility of systems engineering. For all mission phases, projects use Fault Tree Analyses, Failure Modes and Effects Analyses and Probabilistic Risk Assessments to identify what could go wrong. Each risk has an associated “risk owner,” who is responsible for managing that risk. Like other “earned value” concepts in project management, risk is continuously addressed throughout the project. The traditional “earned value” approach enables management to objectively measure how much work has been accomplished on a project and compare that statistic with planned-work objectives determined at project startup. The process requires the project manager to plan, budget and schedule the work in the baseline plan, which contained the “planned value.” As work is accomplished, it becomes “earned” and is reflected as a completed task in the project. We envision something analogous for documenting and mitigating risks.

Finally, risks are reported and risk mitigation techniques are rebaselined at all major project reviews, thereby ensuring mission success is not compromised.

Mission Assurance

The mission assurance function advises and assists projects in implementing a variety of lower-level, detailed, technical mission assurance activities, such as system safety and reliability analysis. It also conducts a higher-level oversight function, guaranteeing that robust assurance processes — such as the problem reporting and corrective action process — are at work in the project.

On one hand, mission assurance works shoulder-to-shoulder with the project. On the other, it maintains its independence, serving as a separate set of eyes that continuously oversee project developmental and operational efforts to ensure that mission success is not compromised. Mission assurance works with and reports to project management, yet maintains a separate reporting chain to center and even Agency senior management, should such measures become necessary to assure safety or mission success.

System and Subsystem Development Teams

At the core of the project are the development engineers, who are responsible for designing ground and flight system and subsystem components, including hardware, software or procedures. At the beginning of the project, the development teams learn how their product fits into the bigger picture and how end users intend to use their

product. They understand requirements and develop robust components that meet or exceed customer expectations. During development, they identify and manage risks. They take ownership. They understand, document and communicate limitations of their system, and they advocate solid reviews — internally, externally and continuously.

Catching errors early and correcting them is a high priority for these teams. During project planning, they advocate development of prototype versions and early testing to uncover design errors, especially for higher-risk components. They perform comprehensive unit testing and are intimately involved with systems integration testing. Their philosophy is, “Test, test and test some more.” Their motto is:

*“Know what you build.
Test what you build.
Test what you fly.
Test like you fly.”*

Whether developing onboard spacecraft components or ground support components, these teams take particular care to identify mission-critical components and handle these with special focus.

When a component is anticipated to be derived from a heritage component (as in the instance of software or hardware reuse), careful evaluation and testing is performed to ensure applicability and reusability within the new mission framework, once again considering robust mission scenarios.

Project Review Teams

In our vision, all review teams are established early in the project. The continuity of these teams is managed over the full life cycle of the project, utilizing key personnel. The review teams make commitments to the project to provide resources as specified in the project plan. Project management makes commitments to the review teams by establishing adequate project scheduling for supporting reviews and by implementing review team recommendations as needed. The specific objectives and scope of each review team are established up front and agreed upon by the project manager and senior management. Establishing proper review teams is a top priority of project management and senior management in the line organization. Participation by the best experts inside and outside the Agency should be sought.

“Peer review teams” are established to provide a second set of eyes to review design, development, testing and operations. These teams are composed of people inside and outside the project who possess significant technical expertise in the relevant field. Peer team membership is balanced between peers on the project, line organizational personnel within the center, and external support from other centers, industry, other government organizations and/or academic institutions. Peer review results are reported to higher-level review boards.

A “red team” is established to study mission scenarios, to ensure operational readiness and to validate risks. Team membership is formed from personnel outside the project and generally external to the lead center. The team is composed of experienced veterans as well as “newer” individuals with fresh, innovative ideas. This team provides an independent, aggressive, almost adversarial — yet helpful — role, addressing all levels of the project from high-level requirements down through subsystem design. Key review items include: ensuring system success and reliability; reviewing overall system design and design decisions; reviewing system safety and reliability analyses and risk assessments; reviewing planned and completed testing; and reviewing operational processes, procedures and team preparation. Red team review results and recommendations are reported to the project manager and the project team, as well as senior level management at the centers.

Mission Operations: Preparation and Execution

The role of the operations personnel in the project begins with the initial formation of the project team. A deputy project manager for operations is assigned and a small team is created to consider mission operations from the outset. Rigorous robust operations scenarios are conceived and assessed as part of formulating system design requirements.

Operations plays an important role in the formulation phase of the project, prior to project approval. The core operations team provides a mechanism for capturing and improving knowledge as systems are developed and tested, and brings additional team members up to speed as launch approaches. Together with a core team of development personnel, operations performs high fidelity, pre-launch, end-to-end simulations to validate procedures, system performance and mission preparedness, as well as to solidify team cohesion. These end-to-end simulations exercise all nominal and contingency procedures under a variety of dispersed initial conditions, using flight plans and procedures already under strict configuration control.

Mission rules are developed using the engineering team’s expertise. These rules are exercised during simulations to train the operations team in real time decision processes and discipline. Use of standardized procedures and forms for anomaly reporting is exercised.

Following launch, the full flight team participates in frequent routine discussions addressing current mission status, upcoming events and plans and near-term decisions to be made. A poll of team members is conducted during these meetings to discuss individual status, anomalies and discrepancies in their areas. For critical events, co-location of personnel is strongly encouraged in order to promote quick, effective decision-making and contingency replanning.

Vision Summary

Our emerging **Mission Success First** vision focuses on mission success by utilizing every individual in the organization to continuously employ solid engineering discipline, to take personal ownership for their product development efforts, and to continuously manage risk in order to design, develop and deliver robust systems capable of supporting nominal and contingency mission scenarios.

Program-level and project-level planning address and champion technology infusion. This requires long-range planning and technology investments, resulting in delivery of low-risk products for project incorporation.

Program and project mission success criteria and requirements are established at the outset to enable early, thorough project staffing and formulation. Systems engineering, flight operations personnel, mission assurance personnel and scientists are integrated into the project throughout its life cycle. Peer reviews and red teams are formed at the beginning of the project. They are knowledgeable of the project's activities without becoming part of the project team itself, in order to maintain their independence. Finally, they support sustained involvement of key personnel.

Spanning the full life cycle of the project, our vision includes testing, testing and more testing, conducted as early as possible in the work plans. Future projects increase attention to early and ongoing systems analysis and integration. Risks are identified early in the project and continuously managed in a quantifiable manner much the way cost, schedule and content are managed. These risk quantities are frequently reported to senior management, and a coordinated understanding of expected mission success levels is communicated throughout the organization and to the American public.

4. NASA's Current Program/Project Management Environment

Existing Processes and Requirements

NASA currently has a significant infrastructure of processes and requirements in place to enable robust program and project management, beginning with the capstone document: NASA Procedures and Guidelines 7120.5. To illustrate the sheer volume of these processes and requirements, a partial listing is provided in Appendix D. Many of these clearly have a direct bearing on mission success.

This Board's review of recent project failures and successes raises questions concerning the implementation and adequacy of existing processes and requirements. If NASA's programs and projects had implemented these processes in a disciplined manner, we might not have had the number of mission failures that have occurred in the recent past.

What We Reviewed

In addition to the Mars Climate Orbiter and the Mars Polar Lander, the Board reviewed or was briefed on a sampling of other projects, investigations and studies (*see Appendix E*). While most of the information received by the Board was derived from project failures, some of it was drawn from successful missions. Information obtained from these briefings and reports was used by the Board to reflect on the current state of project management in NASA to determine where we are now. This information provided the basis for the expanded observations and recommendations presented in Section 5.

What We Found

We found a number of themes that have contributed to the failure of past missions. The occurrence of these themes in specific failure reports, investigations and studies — along with some specific detail on the shortcomings associated with each — is provided in Table 1. The themes are listed in order of diminishing frequency, according to the number of times they appeared in the failure reports, investigations and studies reviewed by the Board. The codes found in the individual table cells refer to additional material to be found in Appendix F. Quotations from the referenced reports, investigations and studies are provided in Appendix F as evidence to support the indicated occurrence of each theme.

The important conclusion to be derived from this table is the realization that there is a high correlation of failures connected with a few themes. As shown in Table 1, inadequate reviews, poor risk management and insufficient testing/verification were each found in six of eight separate mission failure investigations. Inadequate communications

were cited in five of the eight cases. Poor telemetry monitoring during critical operations, inadequate safety/quality culture and insufficient staffing were each cited in three of the eight investigations.

Clearly, more attention to these program/project areas is needed. In addition, as the table shows, the list goes on. The recommendations in Section 5 address the majority of these recurring themes.

Table 1. Recurring Themes from Failure Investigations and Studies

PROJECT THEME	Mars Climate Orbiter (MCO)	Widefield Infrared Explorer	Lewis	Boeing MAR	Faster, Better, Cheaper	Solar Helio-spheric Observatory	LMA IAT on Mission Success	Space Shuttle IA Team	Frequency
Reviews	MCO7	WIRE1	L7	BMAR 3	FBC4			SIAT5	6
Risk Management/Assessment	MCO8		L6	BMAR 7	FBC3	SOHO1		SIAT4	6
Testing, Simulation, Verification/Validation	MCO4	WIRE2		BMAR 4		SOHO3	LMA1	SIAT6	6
Communications	MCO3		L1			SOHO4	LMA5	SIAT2	5
Health Monitoring During Critical Ops	MCO13	WIRE3			FBC5				3
Safety/Quality Culture	MCO9			BMAR 6			LMA4		3
Staffing	MCO2					SHOH5		SIAT1	3
Continuity	MCO10				FBC8				2
Cost/Schedule			L8		FBC2				2
Engineering Discipline			L4	BMAR 2					2
Government/Contractor Roles & Responsibilities			L5					SIAT3	2
Human Error							LMA2	SIAT8	2
Leadership	MCO6				FBC1				2
Mission Assurance	MCO11				FBC9				2
Overconfidence	MCO15							SIAT10	2
Problem Reporting	MCO12							SIAT7	2
Subcontractor, Supplier Oversight				BMAR 5			LMA6		2
Systems Engineering	MCO5			BMAR 1					2
Training	MCO1						LMA3		2
Configuration Control						SOHO2			1
Documentation					FBC7				1
Line Organization Involvement	MCO16								1
Operations	MCO17								1
Procedures									1
Project Team					FBC6				1
Requirements			L3						1
Science Involvement	MCO14								1
Technology Readiness					FBC10				1
Workforce Stress								SIAAT9	1

Safety Nets

Even when a NASA project adequately makes use of well-defined program/project management processes and implements those processes to satisfy mission requirements, the unexpected may still arise. Human and machine errors will occur, but they must be prevented from causing mission failure. Therefore, processes we refer to as “safety nets” must be in place to catch these errors. The Board has observed that some of these processes currently are not being utilized in the proper manner.

Safety nets, which may provide a last line of defense in preventing mission failure, include (in rough chronological order):

- **Risk Management** serves as a safety net in that it predicts what could go wrong early in a project and throughout the life cycle. It provides sufficient lead time to develop mitigation and contingency plans before problems actually occur.
- **Mission Assurance** includes safety-net functions such as inspection, auditing and surveillance.
- **Robust Design** provides a safety net in terms of design features such as redundancy and fault tolerance.
- **Safety Margins** provide a safety-net function should stress levels rise higher than expected.
- **Design Reviews, Peer Reviews and Independent Assessments** provide a “second (and third) set of eyes,” supplying experience and expertise to identify potential problems that may have been missed by others.
- **Project Reserves** provide a safety net for implementing recovery measures when problems are identified.

All these safety nets are part of NASA program/project management processes today.

Conclusions

There can be little question that existing mission success-oriented processes and requirements address the recurring themes we found — but they are either not being implemented on some programs and projects, are inadequate, or both.

Finally, existing safety nets have undoubtedly helped to avoid many failures, but as currently structured and implemented they are not sufficient to provide the degree of success desired in NASA missions. Therefore, based on the most frequent recurring themes presented here, issues derived from the Mars Climate Orbiter mishap investigation, and the requirements of this Board’s charter, specific recommendations for improving the probability of mission success are provided in the next section of this report.

5. Recommendations and Metrics

In its mission investigation, the Mishap Investigation Board found a number of recurring themes, upon which we can base recommendations for improvement. Some are specific to the Mars Program, but most are applicable to other programs throughout NASA.

With each recommendation we suggest possible metrics that may be useful in measuring progress. These should be considered a first attempt; we recommend the Agency establish a team to work out a more comprehensive set of metrics. In some cases, we did not come up with associated metrics, and have marked these “To Be Determined.” We encourage others to develop metrics for these areas.

We group the recommendations into four categories:

- **People** — Mission success depends above all on people. Starting with top-notch people — and creating the right cultural environment in which they can excel and in which open communication is practiced — breeds success.
- **Process** — Even the best people with the best motivation and teamwork need a set of guidelines to ensure mission success. In most cases, NASA has very good processes in place, but there are a few areas for improvement.
- **Execution** — Most mission failures and serious errors can be traced to a failure to follow established procedures. This is what we call execution.
- **Technology** — A key idea behind the “Faster, Better, Cheaper” philosophy is that new technology will provide us with components that are higher in performance, lower in mass, cheaper and easier to deploy. To enable this vision, we need to actively foster the development and deployment of new technology.

We close this section with a checklist to be used by project management and review teams. As a minimum, it is this Board’s hope that program/project managers, their team members and review teams will tear out this checklist, post it on their walls and refer to it often.

People: Recommendations and Metrics

Picking the Right People — The success of a mission often depends on having the right people, starting with the project manager. Proper training and experience of all personnel is essential. We recommend that project managers be selected based on experience gained on prior missions and an ability to lead people (good communication skills, team-building capabilities, etc.). They should then receive additional training through on-the-job mentoring from experienced managers and possibly from recently retired experts, and through a formal certification process in project management training. Certification should not be based on having taken the right courses. It should be based on training, but more importantly, on demonstrated, successful project management experience.

Certification plans also should be considered for other key program roles, such as chief systems engineer and mission assurance engineer. All team members should be chosen for their experience, but should be given a chance to grow on the job, with the proper mentoring and training. The right people should be chosen regardless of which NASA center or contractor pool they are drawn from.

Metrics: *Track the number of people at each stage of the certification process for project managers, systems engineers and mission assurance engineers, to ensure an adequate pool of candidates. Perform upward evaluations to measure team members' perceptions of their managers' performance and mentoring abilities.*

Teamwork — A smoothly working team is essential to mission success. We recommend that teams foster an environment of commitment and ownership, and that team members who don't fit in be replaced.

Metrics: *NASA should utilize tools, such as the Occupational Stress Inventory survey tool, for evaluating the health of its project teams. Center management should monitor these results and take action, as appropriate, to ensure well functioning teams.*

Communication — Good communication between project elements is essential to a smoothly working team. We recommend that project management foster an environment where problems may be raised without fear of reprisal — nor of rejection because “it’s too expensive to consider a change now.” We recommend that NASA maintain full communication with contractors and scientists, not letting institutional barriers or geographical distance inhibit communication.

To promote inter-center cooperation and technology sharing, we recommend increased inter-center participation on future projects at the system and subsystem levels, perhaps focused around “centers of excellence” areas. During mission operations, frequent team tagups should be scheduled to discuss status and plans among the full team. Each controller should report on upcoming events, decision needs and concerns.

Metrics: *It is difficult to quantify communication. Nevertheless, one possibility for improvement is to commission the external review team to identify issues raised in each review and poll selected members of the mission team about their awareness of each issue. Project management thus may track the percentage of people who are aware of issues that affect them. Another suggestion is to have external review team members meet one-on-one with randomly selected members of the project staff to identify issues and concerns not raised at the formal review.*

Adequate Staffing and Oversight — The “Faster, Better, Cheaper” philosophy means operating without a large staff — but the staff must be adequate to provide oversight of — and insight into — the project’s progress. We recommend that the project manager

determine and insist on an appropriate level of staffing in-house and at each contractor. We also recommend that the project manager constantly monitor the effectiveness of each team member and be willing to change out those who do not perform well as part of a team.

Metrics: *The external review board should identify the team members responsible for each role within the project, as tracked throughout the project life cycle by the project manager. The latter also should track the number of unfilled positions and those occupied by team members with too many other responsibilities or inadequate expertise. Tracking also should include the number of days spent waiting for personnel to become available.*

Process: Recommendations and Metrics

Responsibility to a Larger Program — The “Faster, Better, Cheaper” mandate often pressures project managers to make decisions that are good for the project but bad for the overall program. For example, the decision not to transmit engineering telemetry during the entry, descent and landing stage of the Mars Polar Lander’s mission helped that mission meet cost, mass and schedule constraints, but it failed to provide feedback that would have been useful in the design of future landers.

Following a key mission event, team members may forego the documentation of lessons-learned, believing they will remember those lessons for the life of the mission. But the knowledge they gained can be of much benefit to other team members and future missions — if it is properly documented. We recommend that all team members (particularly the mission manager) think in terms of the larger program and of missions yet to come. We also recommend that a representative of the program office periodically review all mission-related decisions.

We recommend sufficient program funding to ensure mission and program success (for example, the Mars Program could have paid for additional entry, descent and landing stage telemetry during the Mars Polar Lander mission). We further recommend that all critical flight phases be fully instrumented to support detailed real-time and post-flight analysis.

Metrics: *Each mission should be reviewed against a checklist of larger program goals.*

Develop Mission Success Criteria Early — Establish a concise set of mission-success criteria early in the project life cycle. Baseline these criteria. Changes to the baseline should be avoided to the maximum extent possible (because all low-level and high-level project requirements ultimately flow down from the mission-success criteria.)

After the prime contractor is selected for a project, we recommend insertion of a new project definition phase, thus allowing for a thorough reassessment of cost, schedule,

content and risk prior to baselining. We expect this effort to reduce or eliminate early project baseline misinterpretation within the project and with external management.

Metrics: *Track the percentage of projects with documented mission success criteria — the goal is 100% of projects that have been approved for implementation.*

Systems Engineering — Assign adequate systems engineers not only at the project level, but also at the overall mission level, where they may assist the project manager in defining project requirements, managing risk, developing verification and validation test procedures and assisting in project documentation configuration control. The systems engineer should maintain a “big-picture” perspective, ensuring project requirements are satisfied throughout the project life cycle. Systems engineering should manage changes through early requirements baselining and oversight of the change control process.

Metrics: *Track the number of systems engineers, correlated against project complexity.*

Verification and Validation — Conduct extensive testing and simulation in conditions as similar to actual flight conditions as possible. Reducing the frequency of testing to cut costs should be avoided. Many recent launch vehicle failures and mission mishaps could have been prevented had testing not been shortchanged. Integrated tests across subsystems should be planned early in the project, using breadboards, development hardware and simulations. Hardware/software integration tests should be performed using preliminary software drops to identify integration issues early in code development.

Metrics: *Develop a test verification matrix for the entire mission life cycle. Ensure that the verification program is completed.*

Risk Assessment — We recommend that each mission maintain a formal record of risk factors to mission success, in the form of a risk list. Each mission also should record all design decisions driven by risk factors. Quantitative risk estimates should be used. To develop this risk list, we recommend projects be rigorous in the use of Failure Mode and Effects Analyses, Fault Trees and Probabilistic Risk Assessment tools. It is crucial for the risk management process to thoroughly address the question of “What could go wrong?” in advance of each project, tracking the overall risk profile over the course of the project. This policy enables the team to identify and control risk from the start of each project — much the way cost, schedule and content are managed. The mission risk profile should become a part of each project plan, and the risk profile should be reviewed at all periodic center and external reviews. We further recommend that a team be formed to refine the implementation of risk profile management techniques.

Metrics: *Track risk as a function of time. Also track the post-hoc accuracy of risk assessments; if every project launches with a risk of less than 5% — but 30% of missions fail — then we know the risk assessments need to be revised in future projects.*

Responsibility of the Line Organization — All centers have some form of institutional line organization that serves as “home base” for personnel and provides in-depth technical expertise in each discipline or area. These line organizations need to work hand-in-hand with projects on a continuous basis to ensure mission success. We recommend that line organization managers and project managers be held equally accountable for the success or failure of a mission, within their appointed area of expertise. This accountability is based on the line managers’ success in getting the right people to reviews, having the correct questions asked and getting the right answers. They are accountable for carrying through to closure of all issues.

Line management must empower the project team to make timely decisions, but must also provide oversight to protect against bad decisions. We are not advocating going back to having line management checking every design detail, but rather making sure the project is addressing and closing the right technical issues.

Metrics: *We recommend that line organization supervisors be held accountable in their performance plans for mission success or failure within their appointed area of expertise.*

Science Involvement — Science representatives must be full members of each project’s management team throughout the life cycle of the mission. In particular, the project scientist should be involved with the project manager in performing trade studies and making project decisions during the definition, design, development, testing and operations phases.

Metrics: *At the end of the mission, obtain assessments from the project manager and project scientist of the extent to which scientists were part of the management process. Have scientists participating in the mission assess the degree to which the Project met realistic scientific objectives.*

Operations — Before every launch, a full operations team should be assembled and trained in both nominal and contingency operational scenarios. This operations team should be assisted by a core group of system developers and systems engineering personnel to develop nominal and contingency procedures, mission rules and operational timelines. Using high-fidelity simulations, the operations team should perform end-to-end simulations to validate all nominal and contingency procedures, assess system performance and demonstrate mission preparedness.

Metrics: *A training and simulation plan should be developed to specify proper execution of all nominal and contingency procedures. Execution of this training plan should be tracked and reported as part of all flight readiness reviews.*

Transitions — Missions should pay more attention to the transition between development and operations. The Board recommends the project manager remain with

the project from the start to operations, in order to provide continuity throughout the project's life cycle. We recommend that a deputy project manager for operations be appointed at the beginning of the project to ensure that trade studies properly consider the development and operations phases of the mission. A core set of operations personnel should be assigned to each project at its start. Likewise, a core set of development personnel should be defined for transition to support operations.

Metrics: *Track the number of operations personnel assigned to the project throughout its life cycle.*

Execution: Recommendations and Metrics

Reviews — NASA has a strong process in place for performing reviews, as defined in NPG 7120.5A. We recommend, however, that choosing the right experts to participate in a review be given high priority. We suggest that the choice should not be left to the project manager alone, but rather should be approved by institutional line management. We also recommend that a review no longer be checked off until the right people have participated. Peer reviews should be held with the proper subsystem experts, and should be performed prior to the formal external reviews. Peer review results should be presented at all external reviews.

Standing external review boards should be appointed for each project, thereby ensuring continuity and greater familiarity with the subject matter. Membership in review teams should be established early in the project and the continuity of these teams maintained over the project life cycle. At the start of the project, cost and schedule allocations should be baselined for funding and executing reviews and implementing recommendations resulting from them. Support from other centers for review teams should be increased as well, and all parties should make use of the project's established problem-reporting system to ensure resolution of all issues raised during reviews.

Metrics: *Track review attendance, continuity of personnel and inter-center participation. Review team membership by asking outside experts whether any important participants have been left out.*

Reporting of Problems — All projects studied by this investigatory body included a formal process for reporting incidents, surprises, anomalies and other issues — but not every project used the process well. We recommend providing tools and training to make this process user-friendly, and encouraging team members to make use of the system.

Metrics: *Track the number of reports opened and closed over each project's duration. Track issues identified by review boards that were previously known to team members but were not entered into the system. Track near-misses (incidents that nearly cause a serious problem) and “diving catches” (incidents that would have caused a serious problem, had they not been caught just in time). This kind of tracking helps keep civil aviation safe.*

Documentation — In order to promote continuous knowledge capture throughout the project, thorough data collection and a “document-as-you-go” philosophy should become part of routine daily project execution. This allows for smooth personnel transitions within the project, and permits development of lessons-learned for use in later phases of the project and in future projects. Project documentation can be a valuable resource, but only if it is actually used. Create user-friendly information systems to make it easy to get the right information at the right time.

Metrics: *Periodic reviews should be conducted to ensure documentation is up to date. Use ISO 9000 processes where appropriate. Track utilization of project documentation, as well as other documentation resources, such as the NASA Lessons Learned database (on the Web at <http://llis.nasa.gov>). Use multiple media: paper or online documentation, pictures and video and live, in-person seminars.*

Technology: Recommendations and Metrics

Technology Pipeline — NASA requires a technology pipeline to support its “Faster, Better, Cheaper” initiatives. We recommend adequate funding for technology development aimed at broad Agency needs. This development of mission-enabling breakthrough technologies must be established by redirecting some of NASA’s currently allocated annual budget away from existing operations and flight programs — even if these programs are delayed as a result.

Furthermore, program management should review specific future mission needs and establish technology requirements early. Technology needs should be expediently funded and met prior to project initiation, and should be developed to high technology readiness levels. By the time a project starts, technology insertion should be low risk.

Metrics: *Track the number of new technology applications developed over time, and track total technology expenditures. Track the savings in mass, power, cost, safety and return on science achieved by using these new technologies. Track the technology readiness level of advanced technologies to ensure they are progressing on schedule.*

Flight Opportunities — Mission managers are understandably reluctant to include unproven technology in their project strategies. We recommend an adequately funded “New Millennium” program, or its equivalent, to provide flight-testing opportunities. We recommend incentives for mission managers to include unproven technologies in non-mission-critical applications, and to include well-tested but as-yet-unflown technologies for all appropriate applications.

Metrics: *Track the number of new technology applications flown over time.*

Intelligent Synthesis Environment — The goal of NASA’s Intelligent Synthesis Environment program is to improve the technology of mission design and development. We recommend taking advantage of useful Intelligent Synthesis Environment capabilities as they become available.

Metrics: *To be determined.*

Specific Technologies — We recommend that missions aggressively integrate leading-edge technology that may contribute to reducing cost and project risk. For example, we recommend:

- Development of enhanced navigation systems supporting navigation in the vicinity of planets;
- Autonomous operations and avionics, which would save operations costs and improve onboard fault detection and recovery;
- Software such as neural networks and other graphical models that learn and adapt to changes in the environment;
- Multifunctional designs that enable cost-cutting measures and improve operating capability; and,
- Dramatic weight-savings technologies such as those afforded by advanced propulsion systems and lightweight, smart structures.

Metrics: *To be determined.*

Checklist for Project Management and Review Boards

The following checklist was composed from recurring themes found to have contributed to the success and failure of past missions. It should be treated not as an all-encompassing set of project management areas, but as a checklist of topics which — when managed properly — correlates highly with mission success. It can help show a project where it is strong and where it needs attention.

Examining the health of a project in these areas may give management and review boards insight into the project’s overall probability of success. People were found to be the primary element of the mission-success equation; hence a new emphasis on people needs to be addressed across NASA programs.

We recommend that the checklist be maintained, expanded, improved upon and shared, possibly through a Web site. We also recommend that every negative response to a checklist question should be tracked from reporting to closure via action items, which have an associated timetable for resolution.

For convenience, the checklist is presented in a form that may be easily removed from this document for copying, dissemination and display.

MISSION SUCCESS FIRST

Checklist for Project Management and Review Boards

PEOPLE

Leadership

- Is an accountable, responsible person in place and in charge with experience and training commensurate with the job?
- Does the leader work well with the team and external interfaces?
- Does the leader spend significant time fostering teamwork?
- Is safety the number-one priority?

Organization/Staffing

- Is the organization sound?
- Is the staffing adequate?
- Are science and mission assurance elements properly represented in the organization?
- Does the organization enable error-free communication?

Communications

- Is “Mission Success First” clearly communicated throughout the organization?
- Is open communications evident, with all parties having an opportunity to be heard?
- Is a “Top 10” reviewed and acted upon weekly?
- Are all team members encouraged to report problems?
- Are line organization/project communications good?
- Do all team members understand that the only real success is mission success?

Project Team

- Is safety the number-one priority?
- Has team chemistry been considered, and personality profiles reviewed?

- Is staffing adequate for project size, and are the right people in place?
- Are people who could not demonstrate teamwork gone?
- Are all key positions filled and committed to a sustained effort over the project’s life cycle?
- During team formation, has the project manager performed an Agency-wide search to identify key technical experts for membership on the team or sustained support to reviews?
- Is the team adequately staffed and trained in the processes?
- Are team members supportive and open with one another, review boards and management?
- Does the team actively encourage peer reviews?
- Are science representatives involved in day-to-day decision-making?
- Does the team understand that arrogance is their number-one enemy?
- Does the team understand that “anyone’s problem is my problem?”
- Does the team have assessment metrics, which are evaluated regularly?

PROCESS & EXECUTION

Systems Engineering

- Are risk trades included in the scope of the system engineering job?
- Have risk trades been performed and are risks being actively managed?
- Have flight/ground trades been performed?
- Is a fault tree(s) in place?
- Are adequate margins identified?
- Does mission architecture provide adequate data for failure investigation?
- Is “Mission Success First” reflected in the trades and systems efforts?

MISSION SUCCESS FIRST

Management/Review Checklist (continued)

Systems Engineering (Cont'd)

- Is there a formal process to incorporate lessons learned from other successful and failed missions?
- Has the team conducted reviews of NASA lessons-learned databases early in the project?
- Is a rigorous change control process in place?

Requirements

- Was mission success criteria established at the start of the mission?
- Is “Mission Success First” reflected in top-level requirements?
- Are mission requirements established, agreed upon by all parties, and stable?
- Is the requirements level sufficiently detailed?
- Is the requirements flowdown complete?

Validation and Verification

- Is the verification matrix complete?
- Are the processes sound?
- Are checks in place to ensure processes are being followed?
- Does every process have an owner?
- Is mission-critical software identified in both the flight and ground systems?
- Are processes developed for validation of system interfaces?
- Are facilities established for simulation, verification and validation?
- Is independent validation and verification planned for flight and ground software?
- Are plans and procedures in place for normal and contingency testing?
- Is time available for contingency testing and training?

- Are tests repeated after configuration changes?
- Are adequate end-to-end tests planned and completed?

Cost/Schedule

- Is cost adequate to accommodate scope?
- Has a “bottoms up” budget and schedule been developed?
- Has the team taken ownership of cost and schedule?
- Are adequate cost reserves and schedule slack available to solve problems?
- Has mission success been compromised as a result of cost or schedule?

Government/Contractor

Roles and Responsibilities

- Are roles and responsibilities well defined?
- Are competent leaders in charge?

Risk Management/Analysis/Test

- Is risk managed as one of four key project elements (cost, schedule, content and risk)?
- Are analysis measures in place (Failure Modes and Effects Analysis, Fault Tree Analysis, Probabilistic Risk Assessment)?
- Have single-point failures been identified and justified?
- Has special attention been given to proper reuse of hardware and software?
- Has extensive testing been done in the flight configuration?
- Have potential failure scenarios been identified and modeled?
- Is there a culture that never stops looking for possible failure modes?

MISSION SUCCESS FIRST

Management/Review Checklist (continued)

Independent/Peer Review

- Are all reviews/boards defined and planned?
- Is the discipline in place to hold peer reviews with “the right” experts in attendance?
- Are peer review results reported to higher-level reviews?
- Are line organizations committed to providing the right people for sustained support of reviews?

Operations

- Has contingency planning been validated and tested?
- Are all teams trained to execute contingency plans?
- Have mission rules been formulated?
- Has the ops team executed mission rules in simulations?
- Are plans in place to ensure visibility and realtime telemetry during all critical mission phases?

Center Infrastructure

- Is a plan in place to ensure senior management oversight of the project?
- Is a plan in place to ensure line organization commitment and accountability?
- Is a plan in place to mentor new and/or inexperienced managers?

Documentation

- Have design decisions and limitations been documented and communicated?
- Is a process of continuous documentation in place to support unanticipated personnel changes?
- Is electronic/web-based documentation available?
- Are lessons-learned available and in use?

Continuity/Handovers

- Are handovers planned?
- Are special plans in place to ensure a smooth transition?
- Do core people transition? Who? How many?
- Is a development-to-operations transition planned?
- Does development-team knowledge exist on the operations team?
- Is a transition from the integration-and-test ground system to new-operations ground system planned? If so, is there a plan and schedule to revalidate databases and procedures?
- Have there been changes in management or other key technical positions? How was continuity ensured?
- Have processes changed? If so, has the associated risk been evaluated?

Mission Assurance

- Is staffing adequate?
- Are all phases of the mission staffed?
- Is mission assurance conducting high-level oversight to ensure that robust mission success processes are in place?

TECHNOLOGY

Technology Readiness

- Is any new technology needed that has not matured adequately?
- Has all appropriate new technology been considered?
- Has it been scheduled to mature before project baselining?
- Does it represent low deployment risk?
- Is there a plan in place to train operations personnel on new technology use and limitations?

7. Concluding Remarks

*Failure will never stand in the way of success
if you learn from it.*

— Hank Aaron

NASA's history is one of successfully carrying out some of the most challenging and complex engineering tasks ever faced by this nation. NASA's successes — from Mercury to Apollo to the Space Shuttle to Mars Pathfinder — have been based on its people, processes, execution and technology.

In recent years NASA has been asked to sustain this level of success while continually cutting costs, personnel and development time. It is the opinion of this Board that these demands have stressed the system to the limit. The set of recommendations described here is the first effort in a series of ongoing “continuous improvement” steps designed to refocus the Agency on the concept of **Mission Success First**, accompanied by adequate but not excessive resources.

We believe these steps will allow NASA to continue to lead and inspire the world with engineering triumphs and scientific wonders.

Appendix A

Letter Establishing the Mars Climate Orbiter Mishap Investigation Board

SD

TO: Distribution
FROM: S/Associate Administrator for Space Science
SUBJECT: Establishment of the Mars Climate Orbiter (MCO) Mission Failure Mishap Investigation Board

1. INTRODUCTION/BACKGROUND

The MCO spacecraft, designed to study the weather and climate of Mars, was launched by a Delta rocket on December 11, 1998, from Cape Canaveral Air Station, Florida. After cruise to Mars of approximately 9 1/2 months, the spacecraft fired its main engine to go into orbit around Mars at around 2 a.m. PDT on September 23, 1999.

Five minutes into the planned 16-minute burn, the spacecraft passed behind the planet as seen from Earth. Signal reacquisition, nominally expected at approximately 2:26 a.m. PDT when the spacecraft was to reemerge from behind Mars, did not occur. Fearing that a safehold condition may have been triggered on the spacecraft, flight controllers at NASA's Jet Propulsion Laboratory (JPL) in Pasadena, California, and at Lockheed Martin Astronautics (LMA) in Denver, Colorado, immediately initiated steps to locate and reestablish communication with MCO.

Efforts to find and communicate with MCO continued up until 3 p.m. PDT on September 24, 1999, when they were abandoned. A contingency was declared by MCO Program Executive, Mr. Steve Brody at 3 p.m. EDT on September 24, 1999.

2. PURPOSE

This establishes the NASA MCO Mission Failure Mishap Investigation Board and sets forth its terms of reference, responsibilities, and membership in accordance with NASA Policy Directive (NPD) 8621.1G.

3. ESTABLISHMENT

a. The MCO Mission Failure Mishap Investigation Board (hereinafter called the Board) is hereby established in the public's interest to gather information, analyze, and determine the facts, as well as the actual or probable cause(s) of the MCO Mission Failure Mishap in terms of (1) dominant root cause(s), (2) contributing cause(s), and (3) significant observations and to recommend preventive measures and other appropriate actions to preclude recurrence of a similar mishap.

b. The chairperson of the board will report to the NASA Office of Space Science (OSS) Associate Administrator (AA) who is the appointing official.

4. OBJECTIVES

- A. An immediate priority for NASA is the safe landing on December 3, 1999, of the Mars Polar Lander (MPL) spacecraft, currently en route to Mars. This investigation will be conducted recognizing the time-criticality of the MPL landing and the activities the MPL mission team must perform to successfully land the MPL spacecraft on Mars. Hence, the Board must focus first on any lessons learned of the MCO mission failure in order to help assure MPL's safe landing on Mars. The Board must deliver this report no later than November 5, 1999.
- i. The Board will recommend tests, analyses, and simulations capable of being conducted in the near term to prevent possible MPL failures and enable timely corrective actions.
 - ii. The Board will review the MPL contingency plans and recommend improvements where possible.
- B. The Board will review and evaluate all the processes used by the MCO mission, develop lessons learned, make recommendations for future missions, and deliver a final mishap investigation report no later than February 1, 2000. This report will cover the following topics and any other items the Board thinks relevant.
- i. Processes used to ensure mission safety and reliability with mission success as the primary objective. This will include those processes that do not just react to hard failures, but identify potential failures throughout the life of the mission for which corrective actions can be taken. It will also include asking if NASA has the correct philosophy for mission assurance in its space missions. That is:
 - a) "Why should it fly?" versus "why it should not fly?",
 - b) mission safety should not be compromised by cost and performance, and
 - c) definition of adequacy, robustness, and margins-of-safety as applied to clearly defined mission success criteria.
 - ii. Systems engineering issues, including, but not limited to:
 - a) Processes to identify primary mission success criteria as weighted against potential mission risks,
 - b) operational processes for data validation,
 - c) Management structure and processes to enable error-free communications and procedure documentation, and
 - d) processes to ensure that established procedures were followed.
 - iii. Testing, simulation and verification of missions operations:

- a) What is the appropriate philosophy for conducting end-to-end simulations prior to flight?
 - b) How much time and resources are appropriate for program planning?
 - c) What tools should be developed and used routinely?
 - d) How should operational and failure mode identification teams be formed and managed (teams that postulate failure modes and inspire in-depth review)?
 - e) What are the success criteria for the mission, and what is required for operational team readiness prior to the Flight Readiness Review (i.e., test system tolerance to human and machine failure)?, and
 - f) What is the recommended developmental process to ensure the operations team runs as many failure modes as possible prior to launch?
- iv. Personnel training provided to the MCO operations team, and assess its adequacy for conducting operations.
- v. Suggest specific recommendations to prevent basic types of human and machine error that may have led to the MCO failure.
- vi. Reexamine the current approach to planetary navigation. Specifically, are we asking for more accuracy and precision than we can deliver?
- vii. How in-flight accumulated knowledge was captured and utilized for future operational maneuvers.

5. AUTHORITIES AND RESPONSIBILITIES

- a. The Board will:
 - 1) Obtain and analyze whatever evidence, facts, and opinions it considers relevant. It will use reports of studies, findings, recommendations, and other actions by NASA officials and contractors. The Board may conduct inquiries, hearings, tests, and other actions it deems appropriate. It may take testimony and receive statements from witnesses.
 - 2) Determine the actual or probable cause(s) of the MCO mission failure, and document and prioritize their findings in terms of (a) the dominant root cause(s) of the mishap, (b) contributing cause(s), and (c) significant observation(s). Pertinent observations may also be made.
 - 3) Develop recommendations for preventive and other appropriate actions. A finding may warrant one or more recommendations, or it may stand-alone.
 - 4) Provide to the appointing authority, (a) periodic interim reports as requested by said authority, (b) a report by November 5, 1999, of those findings and recommendations and lessons learned necessary for consideration in preparation for the MPL landing, and (c) a final written report by

February 1, 2000. The requirements in the NPD 8621.1G and NASA Procedures and Guidelines (NPG) 8621.1 (draft) will be followed for procedures, format, and the approval process.

b. The Chairperson will:

- 1) Conduct Board activities in accordance with the provisions of NPD 8621.1G and NPG 8621.1 (draft) and any other instructions that the appointing authority may issue or invoke.
- 2) Establish and document rules and procedures for the organization and operation of the Board, including any subgroups, and for the format and content of oral and written reports to and by the Board.
- 3) Designate any representatives, consultants, experts, liaison officers, or other individuals who may be required to support the activities of the Board and define the duties and responsibilities of those persons.

6. MEMBERSHIP

The chairperson, other members of the Board, and supporting staff are designated in the Attachment.

7. MEETINGS

The chairperson will arrange for meetings and for such records or minutes of meetings as considered necessary.

8. ADMINISTRATIVE AND OTHER SUPPORT

- a. JPL will provide for office space and other facilities and services that may be requested by the chairperson or designee.
- b. All elements of NASA will cooperate fully with the Board and provide any records, data, and other administrative or technical support and services that may be requested.

9. DURATION

The NASA OSS AA, as the appointing official, will dismiss the Board when it has fulfilled its responsibilities.

10. CANCELLATION

This appointment letter is automatically cancelled 1 year from its date of issuance, unless otherwise specifically extended by the approving official.

Edward J. Weiler

Enclosure

Distribution:

S/Dr. E. Huckins
S/Dr. C. Pilcher
SD/Mr. K. Ledbetter
SD/Ms. L. LaPiana
SD/Mr. S. Brody
SR/Mr. J. Boyce
SPR/Mr. R. Maizel
SPR/Mr. J. Lee
Q/Mr. F. Gregory
QS/Mr. J. Lloyd
JPL/180-904/Dr. E. Stone
JPL/180-704/Dr. C. Elachi
JPL/180-703/Mr. T. Gavin
JPL/230-235/Mr. R. Cook
JPL/264-426/Mr. C. Jones
JPL/180-904/Mr. L. Dumas

MCO FIB Board Members, Advisors, Observers, and Consultants.

ATTACHMENT

Mars Climate Orbiter (MCO) Failure Investigation Board (FIB)

Members

MSFC/Mr. Arthur G. Stephenson	Chairperson Director, George C. Marshall Space Flight Center
HQ/Ms. Lia S. LaPiana	Executive Secretary SIRTF Program Executive Code SD
HQ/Dr. Daniel R. Mulville	Chief Engineer Code AE
HQ/Dr. Peter J. Rutledge (ex-officio)	Director, Enterprise Safety and Mission Assurance Division Code QE
GSFC/Mr. Frank H. Bauer	Chief Guidance, Navigation, and Control Center Code 570
GSFC/Mr. David Folta	System Engineer Guidance, Navigation, and Control Center Code 570
MSFC/Mr. Greg A. Dukeman	Guidance and Navigation Specialist Vehicle Flight Mechanics Group Code TD-54
MSFC/Mr. Robert Sackheim	Assistant Director for Space Propulsions Systems Code DA-01
ARC/Dr. Peter Norvig	Chief Computational Sciences Division

Advisors: (non-voting participants)

Legal Counsel:	Mr. Louis Durnya George C. Marshall Space Flight Center Code LS01
Office of Public Affairs:	Mr. Douglas Isbell NASA Headquarters Code P

Consultants:

Ms. Ann Merwarth	NASA/GSFC-retired Expert in ground operations and flight software development
Dr. Moshe F. Rubinstein	Prof. Emeritus, UCLA, Civil and Environmental Engineering
Mr. John Mari	Vice-President of Product Assurance Lockheed Martin Aeronautics
Mr. Peter Sharer	Senior Professional Staff Mission Concepts and Analysis Group The Johns Hopkins University Applied Physics Laboratory
Mr. Craig Staresinich	Program management and Operations Expert TRW
Dr. Michael G. Hauser	Deputy Director Space Telescope Science Institute
Mr. Tim Crumbley	Deputy Group Lead Flight Software Group Avionics Department George C. Marshall Space Flight Center
Mr. Don Pearson	Assistant for Advanced Mission Design Flight Design and Dynamics Division Mission Operations Directorate Johnson Space Center
<u>Observers:</u>	
JPL/Mr. John Casani (retired)	Chair of the JPL MCO special review board
JPL/Mr. Frank Jordan	Chair of the JPL MCO independent peer review team
JPL/Mr. John McNamee	Chair of Risk Assessment Review for MPL Project Manager for MCO and MPL (development through launch)
HQ/SD/Mr. Steven Brody (ex-officio)	MCO Program Executive NASA Headquarters

MSFC/DA01/Mr. Drew Smith

Special Assistant to Center
Director
George C. Marshall Space Flight
Center

HQ/SR/Dr. Charles Holmes

Program Executive for Science
Operations
NASA Headquarters

HQ/QE/Mr. Michael Card
(ex-officio)

Program Manager
NASA Headquarters

Appendix B

Mars Climate Orbiter Mishap Investigation Board Phase I Report

Nov. 10, 1999

Mars Climate Orbiter

Mishap Investigation Board

Phase I Report

November 10, 1999

Table of Contents

Mars Climate Orbiter Mishap Investigation Board Phase I Report

	Page
Signature Page (Board Members)	3
List of Consultants	4
Acknowledgements	5
Executive Summary	6
1. Mars Climate Orbiter (MCO) and Mars Polar Lander (MPL)	
Project Descriptions	9
2. MCO Mishap	13
3. Method of Investigation	15
4. MCO Root Causes and MPL Recommendations	16
5. MCO Contributing Causes and Observations and MPL Recommendations	17
6. MCO Observations and MPL Recommendations	25
7. MPL Observations and Recommendations	30
8. Phase II Plan	35
Appendix: Letter Establishing the MCO Mishap Investigation Board	37
Acronyms	45

Signature Page

/s/
Arthur G. Stephenson
Chairman
George C. Marshall Space Flight Center
Director

/s/
Lia S. LaPiana
Executive Secretary
Program Executive
Office of Space Science
NASA Headquarters

/s/
Dr. Daniel R. Mulville
Chief Engineer
NASA Headquarters

/s/
Dr. Peter J. Rutledge (ex-officio)
Director, Enterprise Safety and
Mission Assurance Division
NASA Headquarters

/s/
Frank H. Bauer
Chief, Guidance, Navigation and Control
Center
Goddard Space Flight Center

/s/
David Folta
System Engineer, Guidance,
Navigation and Control Center
Goddard Space Flight Center

/s/
Greg A. Dukeman
Guidance and Navigation Specialist
Vehicle Flight Mechanics Group
George C. Marshall Space Flight Center

/s/
Robert Sackheim
Assistant Director for Space
Propulsion Systems
George C. Marshall Space Flight Center

/s/
Dr. Peter Norvig
Chief, Computational Sciences Division
Ames Research Center

/s/
Approved
Dr. Edward J. Weiler
Associate Administrator
Office of Space Science

/s/
Approved
Frederick D. Gregory
Associate Administrator
Office of Safety and Mission Assurance

Advisors:

Office of Chief Counsel: MSFC/Louis Durnya
Office of Public Affairs: HQs/Douglas M. Isbell

Consultants

Ann Merwarth

NASA/GSFC-retired
Expert in ground operations & flight software development

Moshe F. Rubinstein

Prof. Emeritus,
University of California, Los Angeles
Civil and environmental engineering

John Mari

Vice-President of Product Assurance
Lockheed Martin Astronautics

Peter Sharer

Senior Professional Staff
Mission Concepts and Analysis Group
The Johns Hopkins University
Applied Physics Laboratory

Craig Staresinich

Chandra X-ray Observatory Program Manager
TRW

Dr. Michael G. Hauser

Deputy Director
Space Telescope Science Institute

Tim Crumbley

Deputy Group Lead
Flight Software Group
Avionics Department
George C. Marshall Space Flight Center

Don Pearson

Assistant for Advanced Mission Design
Flight Design and Dynamics Division
Mission Operations Directorate
Johnson Space Center

Acknowledgements

The Mars Climate Orbiter Mishap Investigation Board wishes to thank the technical teams from Jet Propulsion Laboratory (JPL) and Lockheed Martin Astronautics for their cooperation which was essential in our review of the Mars Climate Orbiter and Mars Polar Lander projects. Special thanks to Lia LaPiana and Frank Bauer for pulling this report together with the support of the entire Board and consultants.

Executive Summary

This Phase I report addresses paragraph 4.A. of the letter establishing the Mars Climate Orbiter (MCO) Mishap Investigation Board (MIB) (Appendix). Specifically, paragraph 4.A. of the letter requests that the MIB focus on any aspects of the MCO mishap which must be addressed in order to contribute to the Mars Polar Lander's safe landing on Mars. The Mars Polar Lander (MPL) entry-descent-landing sequence is scheduled for December 3, 1999.

This report provides a top-level description of the MCO and MPL projects (section 1), it defines the MCO mishap (section 2) and the method of investigation (section 3) and then provides the Board's determination of the MCO mishap root cause (section 4), the MCO contributing causes (section 5) and MCO observations (section 6). Based on the MCO root cause, contributing causes and observations, the Board has formulated a series of recommendations to improve the MPL operations. These are included in the respective sections. Also, as a result of the Board's review of the MPL, specific observations and associated recommendations pertaining to MPL are described in section 7. The plan for the Phase II report is described in section 8. The Phase II report will focus on the processes used by the MCO mission, develop lessons learned, and make recommendations for future missions.

The MCO Mission objective was to orbit Mars as the first interplanetary weather satellite and provide a communications relay for the MPL which is due to reach Mars in December 1999. The MCO was launched on December 11, 1998, and was lost sometime following the spacecraft's entry into Mars occultation during the Mars Orbit Insertion (MOI) maneuver. The spacecraft's carrier signal was last seen at approximately 09:04:52 UTC on Thursday, September 23, 1999.

The MCO MIB has determined that the root cause for the loss of the MCO spacecraft was the failure to use metric units in the coding of a ground software file, "Small Forces," used in trajectory models. Specifically, thruster performance data in English units instead of metric units was used in the software application code titled SM_FORCES (small forces). A file called Angular Momentum Desaturation (AMD) contained the output data from the SM_FORCES software. The data in the AMD file was required to be in metric units per existing software interface documentation, and the trajectory modelers assumed the data was provided in metric units per the requirements.

During the 9-month journey from Earth to Mars, propulsion maneuvers were periodically performed to remove angular momentum buildup in the on-board reaction wheels (flywheels). These Angular Momentum Desaturation (AMD) events occurred 10-14 times more often than was expected by the operations navigation team. This was because the MCO solar array was asymmetrical relative to the spacecraft body as compared to Mars Global Surveyor (MGS) which had symmetrical solar arrays. This asymmetric effect significantly increased the Sun-induced (solar pressure-induced) momentum buildup on the spacecraft. The increased AMD events coupled with the fact that the angular momentum (impulse) data was in English, rather than metric, units, resulted in

small errors being introduced in the trajectory estimate over the course of the 9-month journey. At the time of Mars insertion, the spacecraft trajectory was approximately 170 kilometers lower than planned. As a result, MCO either was destroyed in the atmosphere or re-entered heliocentric space after leaving Mars' atmosphere.

The Board recognizes that mistakes occur on spacecraft projects. However, sufficient processes are usually in place on projects to catch these mistakes before they become critical to mission success. Unfortunately for MCO, the root cause was not caught by the processes in-place in the MCO project.

A summary of the findings, contributing causes and MPL recommendations are listed below. These are described in more detail in the body of this report along with the MCO and MPL observations and recommendations.

Root Cause: Failure to use metric units in the coding of a ground software file, "Small Forces," used in trajectory models

Contributing Causes:

1. Undetected mismodeling of spacecraft velocity changes
2. Navigation Team unfamiliar with spacecraft
3. Trajectory correction maneuver number 5 not performed
4. System engineering process did not adequately address transition from development to operations
5. Inadequate communications between project elements
6. Inadequate operations Navigation Team staffing
7. Inadequate training
8. Verification and validation process did not adequately address ground software

MPL Recommendations:

- Verify the consistent use of units throughout the MPL spacecraft design and operations
- Conduct software audit for specification compliance on all data transferred between JPL and Lockheed Martin Astronautics
- Verify Small Forces models used for MPL
- Compare prime MPL navigation projections with projections by alternate navigation methods
- Train Navigation Team in spacecraft design and operations
- Prepare for possibility of executing trajectory correction maneuver number 5
- Establish MPL systems organization to concentrate on trajectory correction maneuver number 5 and entry, descent and landing operations
- Take steps to improve communications

MPL Recommendations (Continued):

- Augment Operations Team staff with experienced people to support entry, descent and landing
- Train entire MPL Team and encourage use of Incident, Surprise, Anomaly process
- Develop and execute systems verification matrix for all requirements
- Conduct independent reviews on all mission critical events
- Construct a fault tree analysis for remainder of MPL mission
- Assign overall Mission Manager
- Perform thermal analysis of thrusters feedline heaters and consider use of pre-conditioning pulses
- Reexamine propulsion subsystem operations during entry, descent, and landing

1. Mars Climate Orbiter (MCO) and Mars Polar Lander (MPL) Project Descriptions

In 1993, NASA started the Mars Surveyor program with the objective of conducting an on-going series of missions to explore Mars. The Jet Propulsion Laboratory (JPL) was identified as the lead center for this program. Mars Global Surveyor (MGS) was identified as the first flight mission, with a launch date in late 1996. In 1995, two additional missions were identified for launch in late 1998/early 1999. The missions were the Mars Climate Orbiter (MCO) and the Mars Polar Lander (MPL). JPL created the Mars Surveyor Project '98 (MSP '98) office with the responsibility to define the missions, develop both spacecraft and all payload elements, and integrate/test/launch both flight systems. In addition, the Program specified that the Mars Surveyor Operations Project (MSOP) would be responsible for conducting flight operations for both MCO and MPL as well as the MGS.

The MSP '98 Development Project used a prime contract vehicle to support project implementation. Lockheed Martin Astronautics (LMA) of Denver, Colorado was selected as the prime contractor. LMA's contracted development responsibilities were to design and develop both spacecraft, lead flight system integration and test, and support launch operations. JPL retained responsibilities for overall project management, spacecraft and instrument development management, project system engineering, mission design, navigation design, mission operation system development, ground data system development, and mission assurance. The MSP '98 project assigned the responsibility for mission operations systems/ground data systems (MOS/GDS) development to the MSOP, LMA provided support to MSOP for MOS/GDS development tasks related to spacecraft test and operations.

The MCO was launched December 11, 1998, and the MPL was launched January 3, 1999. Both were launched atop identical Delta II launch vehicles from Launch Complex 17 A and B at Cape Canaveral Air Station, Florida, carrying instruments to map the planet's surface, profile the structure of the atmosphere, detect surface ice reservoirs and dig for traces of water beneath Mars' rusty surface.

The lander also carries a pair of basketball-sized microprobes. These microprobes will be released as the lander approaches Mars and will dive toward the planet's surface, penetrating up to about 1 meter underground to test 10 new technologies, including a science instrument to search for traces of water ice. The microprobe project, called Deep Space 2, is part of NASA's New Millennium Program.

These missions were the second installment in NASA's long-term program of robotic exploration of Mars, which was initiated with the 1996 launches of the currently orbiting Mars Global Surveyor and the Mars Pathfinder lander and rover.

The MSOP assumed responsibility for both MCO and MPL at launch. MSOP is implemented in a partnering mode in which distinct operations functions are performed

by a geographically distributed set of partners. LMA performs all spacecraft operations functions including health and status monitoring and spacecraft sequence development. In addition, LMA performs real time command and monitoring operations from their facility in Denver, Colorado. JPL is responsible for overall project and mission management, system engineering, quality assurance, GDS maintenance, navigation, mission planning, and sequence integration. Each of the science teams is responsible for planning and sequencing their instrument observations, processing and archiving the resulting data, and performing off line data analysis. These operations are typically performed at the Principal Investigator's home institution. MSOP personnel are also currently supporting MGS operations.

Nine and a half months after launch, in September 1999, MCO was to fire its main engine to achieve an elliptical orbit around Mars. See figure 1. The spacecraft was to then skim through Mars' upper atmosphere for several weeks in a technique called aerobraking to reduce velocity and move into a circular orbit. Friction against the spacecraft's single, 5.5-meter solar array was to have slowed the spacecraft as it dipped into the atmosphere each orbit, reducing its orbit period from more than 14 hours to 2 hours. On September 23, 1999 the MCO mission was lost when it entered the Martian atmosphere on a lower than expected trajectory.

MPL is scheduled to land on Mars on December 3, 1999, 2 to 3 weeks after the orbiter was to have finished aerobraking. The lander is aimed toward a target sector within the edge of the layered terrain near Mars' south pole.

Like Mars Pathfinder, MPL will dive directly into the Martian atmosphere, using an aeroshell and parachute scaled down from Pathfinder's design to slow its initial descent. See figures 2 and 3. The smaller MPL will not use airbags, but instead will rely on onboard guidance, radar, and retro-rockets to land softly on the layered terrain near the south polar cap a few weeks after the seasonal carbon dioxide frosts have disappeared. After the heat shield is jettisoned, a camera will take a series of pictures of the landing site as the spacecraft descends.

As it approaches Mars, about 10 minutes before touchdown, the lander will release the two Deep Space 2 microprobes. Once released, the projectiles will collect atmospheric data before they crash at about 200 meters per second and bury themselves beneath the Martian surface. The microprobes will test the ability of very small spacecraft to deploy future instruments for soil sampling, meteorology and seismic monitoring. A key instrument will draw a tiny soil sample into a chamber, heat it and use a miniature laser to look for signs of vaporized water ice.

Also onboard the lander is a light detection and ranging (LIDAR) experiment provided by Russia's Space Research Institute. The instrument will detect and determine the altitude of atmospheric dust hazes and ice clouds above the lander. Inside the instrument is a small microphone, furnished by the Planetary Society, Pasadena, California, which will record the sounds of wind gusts, blowing dust and mechanical operations onboard the spacecraft itself.

The lander is expected to operate on the surface for 60 to 90 Martian days through the planet's southern summer (a Martian day is 24 hours, 37 minutes). MPL will use the MGS as a data relay to Earth in place of the MCO. The mission will continue until the spacecraft can no longer protect itself from the cold and dark of lengthening nights and the return of the Martian seasonal polar frosts.

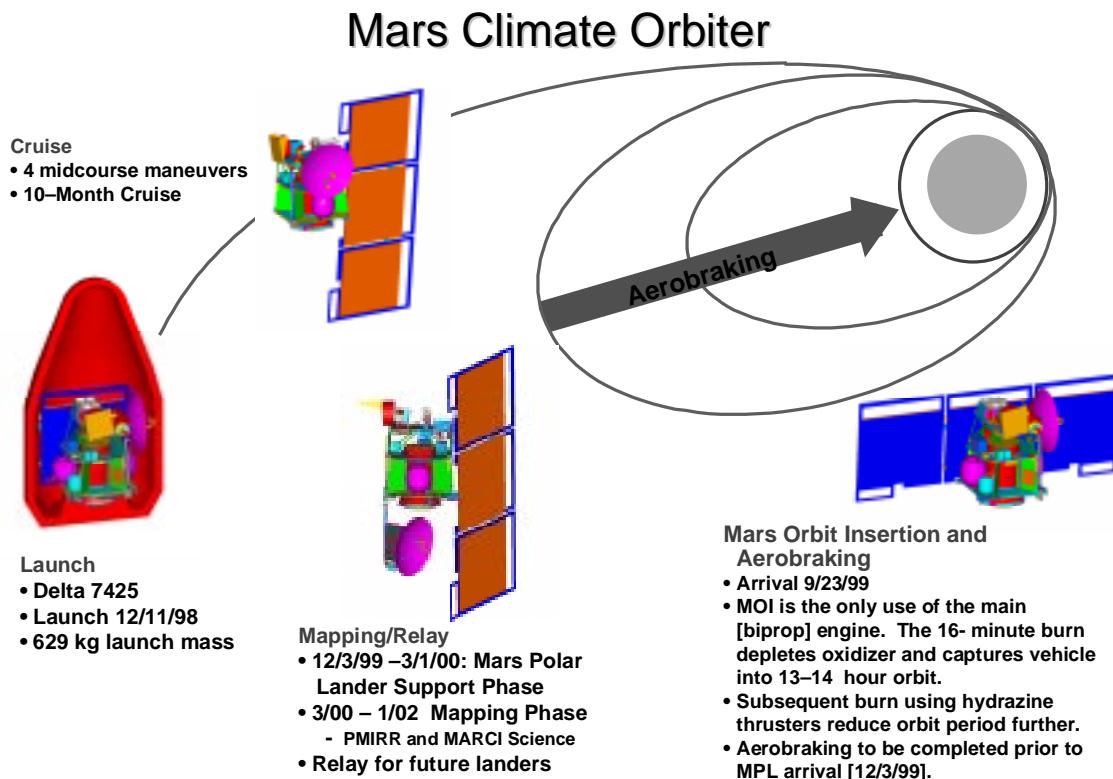


Figure 1

Mars Polar Lander

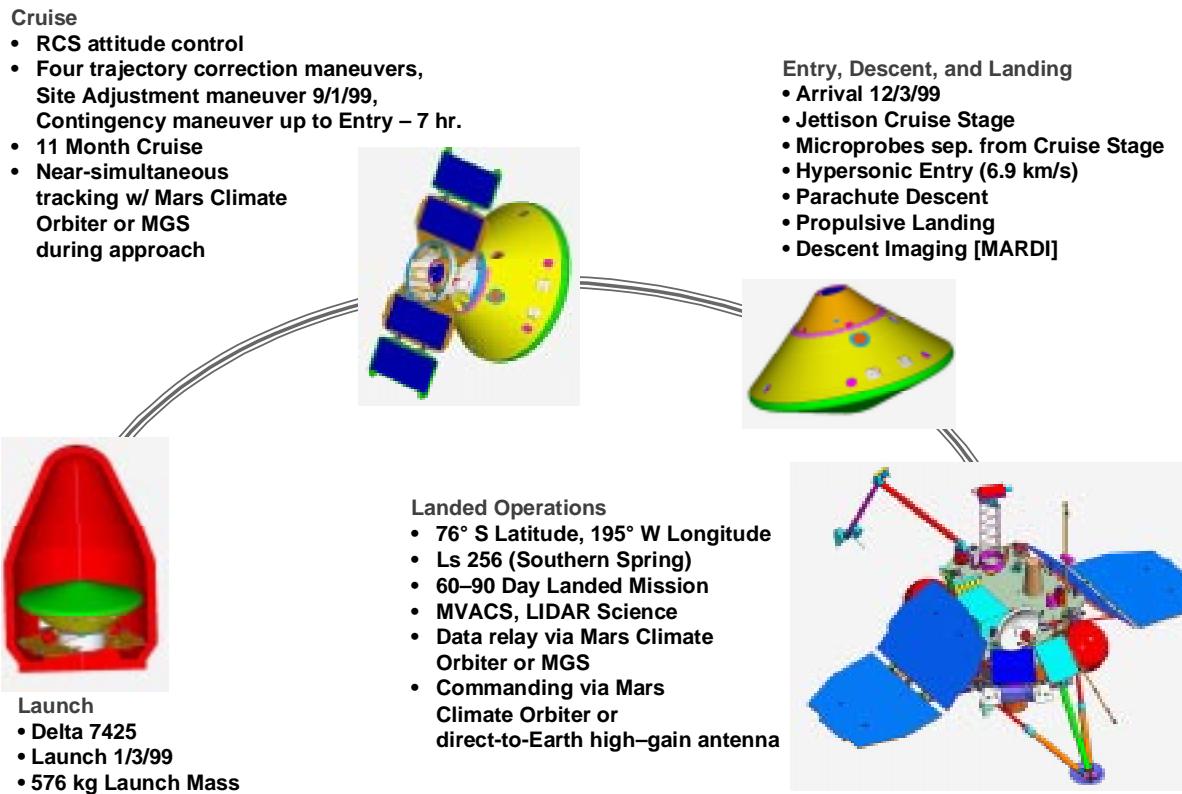


Figure 2

Entry/Descent/Landing Phase

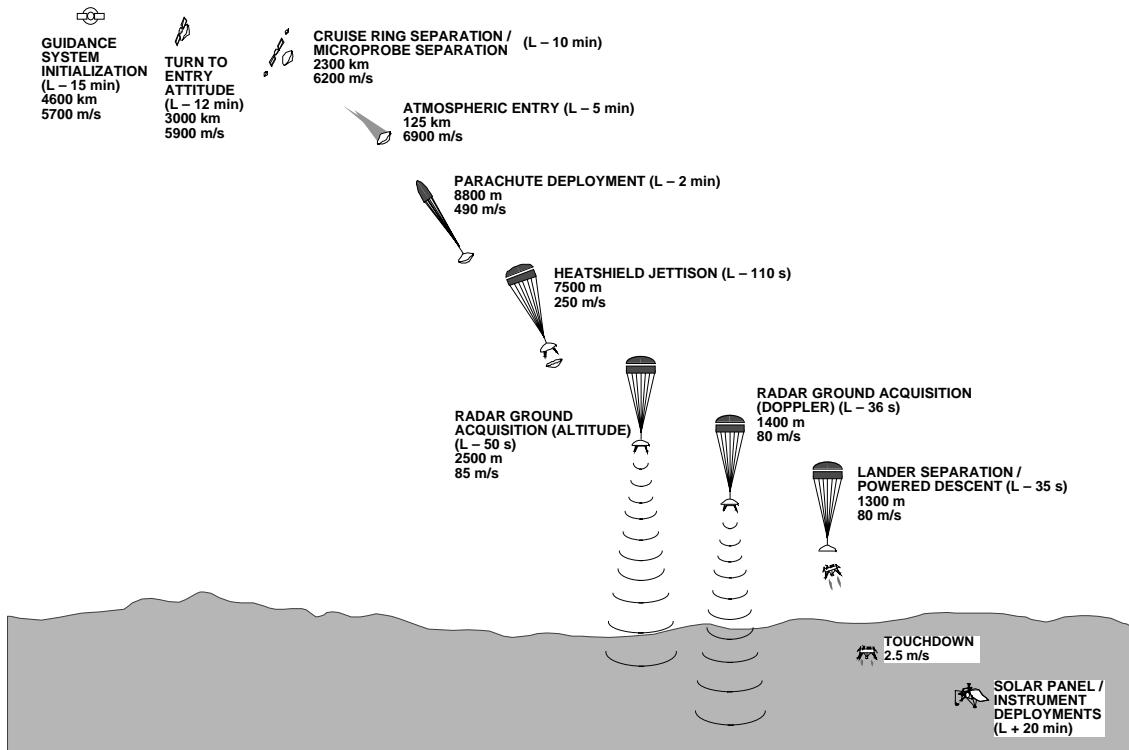


Figure 3

2. Mars Climate Orbiter (MCO) Mishap

The MCO had been on a trajectory toward Mars since its launch on December 11, 1998. All spacecraft systems had been performing nominally until an abrupt loss of mission shortly after the start of the Mars Orbit Insertion burn on September 23, 1999. Throughout spring and summer of 1999, concerns existed at the working level regarding discrepancies observed between navigation solutions. Residuals between the expected and observed Doppler signature of the more frequent AMD events was noted but only informally reported. As MCO approached Mars, three orbit determination schemes were employed. Doppler and range solutions were compared to those computed using only Doppler or range data. The Doppler-only solutions consistently indicated a flight path insertion closer to the planet. These discrepancies were not resolved.

On September 8, 1999, the final planned interplanetary Trajectory Correction Maneuver-4 (TCM-4) was computed. This maneuver was expected to adjust the trajectory such that soon after the Mars orbital insertion (MOI) burn, the first periapse altitude (point of closest approach to the planet) would be at a distance of 226km. See figure 4. This would have also resulted in the second periapse altitude becoming 210km, which was desired for the subsequent MCO aerobraking phase. TCM-4 was executed as planned on September 15, 1999.

Mars orbit insertion was planned on September 23, 1999. During the weeklong timeframe between TCM-4 and MOI, orbit determination processing by the operations navigation team indicated that the first periapse distance had decreased to the range of 150-170km

During the 24 hours preceding MOI, MCO began to feel the strong effects of Mars's gravitational field and tracking data was collected to measure this and incorporate it into the orbit determination process. Approximately one hour prior to MOI, processing of this more accurate tracking data was completed. Based on this data, the first periapse altitude was calculated to be as low as 110km. The minimum periapse altitude considered survivable by MCO is 80 km.

The MOI engine start occurred at 09:00:46 (UTC) on September 23, 1999. All systems performed nominally until Mars's occultation loss of signal at 09:04:52 (UTC), which occurred 49 seconds earlier than predicted. Signal was not reacquired following the 21 minute predicted occultation interval. Exhaustive attempts to reacquire signal continued through September 25, 1999, but were unsuccessful.

On September 27, 1999, the operations navigation team consulted with the spacecraft engineers to discuss navigation discrepancies regarding velocity change (ΔV) modeling issues. On September 29, 1999, it was discovered that the small forces ΔV 's reported by the spacecraft engineers for use in orbit determination solutions was low by a factor of 4.45 (1 pound force=4.45 Newtons) because the impulse bit data contained in the AMD file was delivered in lb-sec instead of the specified and expected units of Newton-sec.

Finally, after the fact navigation estimates, using all available data through loss of signal, with corrected values for the small forces ΔV 's, indicated an initial periapsis (lowest point of orbit) of 57 km which was judged too low for spacecraft survival.

Schematic MCO Encounter Diagram

Not to scale

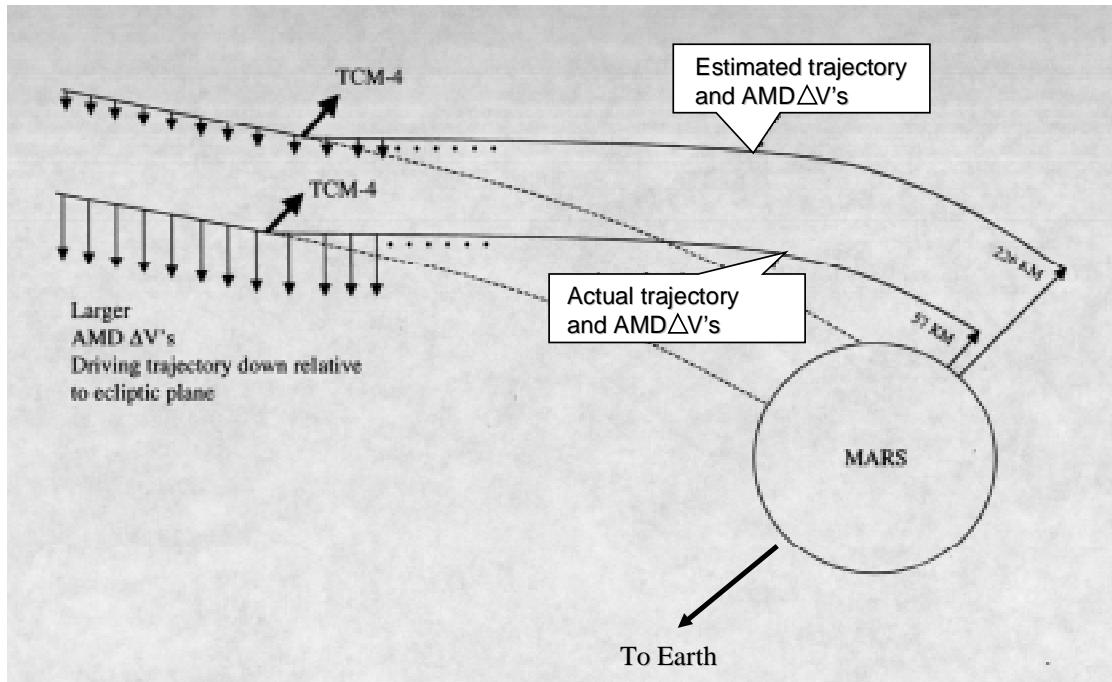


Figure 4

3. Method of Investigation

On October 15, 1999, the Associate Administrator for Space Science established the NASA MCO Mishap Investigation Board (MIB), with Art Stephenson, Director of Marshall Space Flight Center, Chairman. The Phase I MIB activity, reported herein, addresses paragraph 4.A, of the letter establishing the MCO MIB (Appendix). Specifically, paragraph 4.A. requests that the MIB focus on any aspects of the MCO mishap which must be addressed in order to contribute to the Mars Polar Lander's safe landing on Mars.

The Phase I Mishap Investigation Board meetings were conducted at the Jet Propulsion Lab (JPL) on October 18-22. Members of the JPL/Lockheed Martin Astronautics team provided an overview of the MCO spacecraft, operations, navigation plan, and the software validation process. The discussion was allowed to transition to any subject the Board deemed important, so that many issues were covered in great depth in these briefings.

Briefings were also held on the MPL systems, with emphasis on the interplanetary trajectory control and the Entry, Descent, and Landing aspects of the mission. The Board also sent a member to participate in MPL's critical event review for Entry, Descent, and Landing (EDL) held at LMA Denver on October 21. Several substantial findings were brought back from this review and incorporated into the Board's findings. A focused splinter meeting was held with the Board's navigation experts and the JPL navigation team on MCO and MPL questions and concerns. Splinter meetings were also held with the JPL and LMA propulsion teams and with the JPL MSP'98 project scientists.

Prior to the establishment of the MCO MIB, two investigative boards had been established by JPL. Both the Navigation Failure Assessment Team and the JPL Mishap Investigation Board presented their draft findings to the MCO Board.

The root cause, contributing causes and observations were determined by the Board through a process that alternated between individual brainstorming and group discussion. In addition, the Board developed MPL observations and recommendations not directly related to the MCO mishap.

A number of contributing causes were identified as well as number of observations. The focus of these contributing causes and observations were on those that could impact the MPL. Recommendations for the MPL were developed and are presented in this Phase I report. Recommendations regarding changing the NASA program processes to prevent a similar failure in the future are the subject of the Phase II portion of the Board's activity as described in Section 8 of this report.

The MPL observations contained in this report refer to conditions as of October 22, 1999, and do not reflect actions taken subsequent to that date.

4. Mars Climate Orbiter (MCO) Root Cause and Mars Polar Lander (MPL) Recommendations

During the mishap investigation process, specific policy is in-place to conduct the investigation and to provide key definitions to guide the investigation. NASA Procedures and Guidelines (NPG) 8621 Draft 1, "NASA Procedures and Guidelines for Mishap Reporting, Investigating, and Recordkeeping" provides these key definitions for NASA mishap investigations. NPG 8621 (Draft 1) defines a root cause as: "Along a chain of events leading to a mishap, the first causal action or failure to act that could have been controlled systematically either by policy/practice/procedure or individual adherence to policy/practice/procedure". Based on this definition, the Board determined that there was one root cause for the MCO mishap.

MCO Root Cause

The MCO MIB has determined that the root cause for the loss of the MCO spacecraft was the failure to use metric units in the coding of a ground software file, "Small Forces," used in trajectory models. Specifically, thruster performance data in English units instead of metric units was used in the software application code titled SM_FORCES (small forces). The output from the SM_FORCES application code as required by a MSOP Project Software Interface Specification (SIS) was to be in metric units of Newton-seconds (N-s). Instead, the data was reported in English units of pound-seconds (lbf-s). The Angular Momentum Desaturation (AMD) file contained the output data from the SM_FORCES software. The SIS, which was not followed, defines both the format and units of the AMD file generated by ground-based computers. Subsequent processing of the data from AMD file by the navigation software algorithm therefore, underestimated the effect on the spacecraft trajectory by a factor of 4.45, which is the required conversion factor from force in pounds to Newtons. An erroneous trajectory was computed using this incorrect data.

MPL Recommendations:

The Board recommends that the MPL project verify the consistent use of units throughout the MPL spacecraft design and operation. The Board recommends a software audit for SIS compliance on all data transferred between the JPL operations navigation team and the spacecraft operations team.

5. Mars Climate Orbiter (MCO) Contributing Causes and Mars Polar Lander (MPL) Recommendations

Section 6 of NPG 8621 (Draft 1) provides key definitions for NASA mishap investigations. NPG 8621 (Draft 1) defines a contributing cause as: “A factor, event or circumstance which led directly or indirectly to the dominant root cause, or which contributed to the severity of the mishap. Based on this definition, the Board determined that there were 8 contributing causes that relate to recommendations for the Mars Polar Lander.

MCO Contributing Cause No. 1: Modeling of Spacecraft Velocity Changes

Angular momentum management is required to keep the spacecraft’s reaction wheels (or flywheels) within their linear (unsaturated) range. This is accomplished through thruster firings using a procedure called Angular Momentum Desaturation (AMD). When an AMD event occurs, relevant spacecraft data is telemetered to the ground, processed by the SM_FORCES software, and placed into a file called the Angular Momentum Desaturation (AMD) file. The JPL operations navigation team used data derived from the Angular Momentum Desaturation (AMD) file to model the forces on the spacecraft resulting from these specific thruster firings. Modeling of these small forces is critical for accurately determining the spacecraft’s trajectory. Immediately after the thruster firing, the velocity change (ΔV) is computed using an impulse bit and thruster firing time for each of the thrusters. The impulse bit models the thruster performance provided by the thruster manufacturer. The calculation of the thruster performance is carried out both on-board the spacecraft and on ground support system computers. Mismodeling only occurred in the ground software.

The Software Interface Specification (SIS), used to define the format of the AMD file, specifies the units associated with the impulse bit to be Newton-seconds (N-s). Newton-seconds are the proper units for impulse (Force x Time) for metric units. The AMD software installed on the spacecraft used metric units for the computation and was correct. In the case of the ground software, the impulse bit reported to the AMD file was in English units of pounds (force)-seconds (lbf-s) rather than the metric units specified. Subsequent processing of the impulse bit values from the AMD file by the navigation software underestimated the effect of the thruster firings on the spacecraft trajectory by a factor of 4.45 (1 pound force=4.45 Newtons).

During the first four months of the MCO cruise flight, the ground software AMD files were not used in the orbit determination process because of multiple file format errors and incorrect quaternion (spacecraft attitude data) specifications. Instead, the operations navigation team used email from the contractor to notify them when an AMD desaturation event was occurring, and they attempted to model trajectory perturbations on

their own, based on this timing information. Four months were used to fix the file problems and it was not until April 1999 that the operations team could begin using the correctly formatted files. Almost immediately (within a week) it became apparent that the files contained anomalous data that was indicating underestimation of the trajectory perturbations due to desaturation events. These file format and content errors early in the cruise mission contributed to the operations navigation team not being able to quickly detect and investigate what would become the root cause.

In April 1999, it became apparent that there was some type of mismodeling of the AMD maneuvers. In attempting to resolve this anomaly, two factors influenced the investigation. First, there was limited observability of the total magnitude of the thrust because of the relative geometry of the thrusters used for AMD activities and the Earth-to-spacecraft line of sight. The navigation team can only directly observe the thrust effects along the line of sight using the measurements of the spacecraft's Doppler shift. In the case of Mars Climate Orbiter (MCO), the major component of thrust during an AMD event was perpendicular to the line-of-sight. The limited observability of the direct effect of the thruster activity meant a systematic error due to the incorrect modeling of the thruster effects was present but undetected in the trajectory estimation. Second, the primary component of the thrust was also perpendicular to the spacecraft's flight path. See figure 4. In the case of MCO, this perturbation to the trajectory resulted in the actual spacecraft trajectory at the closest approach to Mars being lower than what was estimated by the navigators.

MPL Recommendation:

The Board recommends that the small forces models used for MPL be validated to assure the proper treatment of the modeled forces, including thruster activity used for attitude control and solar radiation pressure. Additionally, several other navigation methods should be compared to the prime navigation method to help uncover any mismodeled small forces on MPL

Mars Climate Orbiter (MCO) Contributing Cause No. 2: Knowledge of Spacecraft Characteristics

The operations navigation team was not intimately familiar with the attitude operations of the spacecraft, especially with regard to the MCO attitude control system and related subsystem parameters. This unfamiliarity caused the operations navigation team to perform increased navigation analysis to quantify an orbit determination residual error. The error was masked by the lack of information regarding the actual velocity change (ΔV) imparted by the angular momentum desaturation (AMD) events. A line of sight error was detectable in the processing of the tracking measurement data, but its significance was not fully understood. Additionally, a separate navigation team was used for the MCO development and test phase. The operations navigation team came onboard shortly before launch and did not participate in any of the testing of the ground software. The operations navigation team also did not participate in the Preliminary Design review

nor in the critical design review process. Critical information on the control and desaturation of the MCO momentum was not passed on to the operations navigation team.

MPL Recommendation:

The Board recommends that the MPL operations navigation team be provided with additional training and specific information regarding the attitude subsystems and any other subsystem which may have an impact on the accuracy of navigation solutions. To facilitate this, a series face-to-face meetings should be conducted with the spacecraft development, and operations teams to disseminate updated information and to discuss anomalies from this point forward. Long-term onsite support of an LMA articulation and attitude control system (ACAS) person should be provided to the operations navigation team or a JPL resident ACAS expert should be brought on the team to help facilitate better communication.

MCO Contributing Cause No. 3: Trajectory Correction Maneuver (TCM-5)

During the MCO approach, a contingency maneuver plan was in place to execute an MCO Trajectory Correction Maneuver (TCM) -5 to raise the second periapsis passage of the MCO to a safe altitude. For a low initial periapsis, TCM-5 could also have been used shortly before the Mars Orbit Insertion (MOI) as an emergency maneuver to attain a safer altitude. A request to perform a TCM-5 was discussed verbally shortly before the MOI onboard procedure was initiated, but was never executed.

Several concerns prevented the operations team from implementing TCM-5. Analysis, tests, and procedures to commit to a TCM-5 in the event of a safety issue were not completed, nor attempted. Therefore, the operations team was not prepared for such a maneuver. Also, TCM-5 was not executed because the MOI maneuver timeline onboard the spacecraft took priority. This onboard procedure did not allow time for the upload, execution, and navigation verification of such a maneuver. Additionally, any change to the baselined orbit scenario could have exceeded the time for the MCO aerobraking phase when MCO was needed to support the communications of the MPL spacecraft. The criticality to perform TCM-5 was not fully understood by the spacecraft operations or operations navigation personnel.

The MPL mission sequence also contains a ‘contingency’ TCM-5 for a final correction of the incoming trajectory to meet the entry target conditions for the MPL Entry, Descent, and Landing (EDL) phase. The MPL TCM-5 is currently listed as a contingency maneuver. This TCM-5 also has not been explicitly determined as a required maneuver and there is still confusion over the necessity and the scheduling of it.

MPL Recommendation:

The board recommends that the operations team adequately prepare for the possibility of executing TCM-5. Maneuver planning and scheduling should be baselined as well as specific criteria for deciding whether or not the maneuver should be executed. The full operations team should be briefed on the TCM-5 maneuver execution scenario and should be fully trained and prepared for its execution. If possible, an integrated simulation of the maneuver computations, validation, and uplink should be performed to verify team readiness and sufficient time scheduling. Additionally, a TCM-5 lead should be appointed to develop the process for the execution and testing of the maneuver and to address the multiple decision process of performing TCM-5 with respect to the EDL.

MCO Contributing Cause No. 4: Systems Engineering Process

One of the problems observed by the Board on MCO was that the systems engineering process did not adequately transition from development to operations. There were a number of opportunities for the systems engineering organization to identify the units problem leading to mission loss of MCO.. The lack of an adequate systems engineering function contributed to the lack of understanding on the part of the navigation team of essential spacecraft design characteristics and the spacecraft team understanding of the navigation challenge. It also resulted in inadequate contingency preparation process to address unpredicted performance during operations, a lack of understanding of several critical operations tradeoffs, and it exacerbated the communications difficulties between the subsystem engineers (e.g navigation, AACs, propulsion).

For example, the Angular Momentum Desaturation (AMD) events on MCO occurred 10-14 times more often than was expected by the operations navigation team. This was because the MCO solar array was asymmetrical relative to the spacecraft body as compared to Mars Global Surveyor which had symmetrical solar arrays. This asymmetric effect significantly increased the Sun-induced (solar pressure-induced) momentum buildup on the spacecraft. To minimize this effect, a daily 180° flip was baselined to cancel the angular momentum build up. Systems engineering trade studies performed later determined that this so-called “barbecue” mode was not needed and it was deleted from the spacecraft operations plan. Unfortunately, these systems engineering decisions and their impact to the spacecraft and the spacecraft trajectory were not communicated to the operations navigation team. The increased AMD events resulting from this decision coupled with the fact that the angular momentum (impulse) data was in English, rather than metric, units contributed to the MCO mission failure.

MPL Recommendation:

The Board recommends that the MPL project establish and fully staff a systems engineering organization with roles and responsibilities defined. This team should concentrate on the TCM-5 and EDL activities. They should support updating MPL risk assessments for both EDL and Mars ground operations, and review the systems

engineering on the entire MPL mission to ensure that the MPL mission is ready for the EDL sequence.

MCO Contributing Cause No. 5: Communications Among Project Elements

In the MCO project, and again in the MPL project, there is evidence of inadequate communications between the project elements, including the development and operations teams, the operations navigation and operations teams, the project management and technical teams, and the project and technical line management.

It was clear that the operations navigation team did not communicate their trajectory concerns effectively to the spacecraft operations team or project management. In addition, the spacecraft operations team did not understand the concerns of the operations navigation team. The Board found the operations navigation team supporting MCO to be somewhat isolated from the MCO development and operations teams, as well as from its own line organization, by inadequate communication. One contributing factor to this lack of communication may have been the operations navigation team's assumption that MCO had Mars Global Surveyor (MGS) heritage and the resulting expectation that much of the MCO hardware and software was similar to that on MGS. This apparently caused the operations navigation team to acquire insufficient technical knowledge of the spacecraft, its operation, and its potential impact to navigation computations. For example, the operations navigation team did not know until long after launch that the spacecraft routinely calculated, and transmitted to Earth, velocity change data for the angular momentum desaturation events. An early comparison of these spacecraft-generated data with the tracking data might have uncovered the units problem that ultimately led to the loss of the spacecraft. When conflicts in the data were uncovered, the team relied on e-mail to solve problems, instead of formal problem resolution processes such as the Incident, Surprise, Anomaly (ISA) reporting procedure. Failing to adequately employ the problem tracking system contributed to this problem "slipping through the cracks."

A splinter meeting between some members of the Board and the operations navigation team illustrated the fact that there was inadequate communication between the operations navigation team and mission operations teams. While the Board was notified of potential changes in the MPL landing site, it was discovered that this knowledge was not fully conveyed to the entire MPL operations navigation team. Inadequate systems engineering support exacerbated the isolation of the navigation team. A robust system's engineering team could have helped improve communication between the operations navigation team and other, navigation critical subsystems (e.g. propulsion, AACCS). Systems engineering support would have enhanced the operations navigation team's abilities to reach critical decisions and would have provided oversight in navigation mission assurance.

The operations navigation team could have benefited from independent peer reviews to validate their navigation analysis technique and to provide independent oversight of the trajectory analyses.

Defensive mechanisms have also developed between the team members on MPL as a result of the MCO failure. This is causing inadequate communication across project elements and a failure to elevate concerns with full end-to-end problem ownership.

MPL Recommendations:

The board recommends that the MPL project should stress to the project staff that communication is critical and empower team members to forcefully elevate any issue, keeping the originator in the loop through formal closure. Project management should establish a policy and communicate it to all team members that they are empowered to forcefully and vigorously elevate concerns as high, either vertically or horizontally in the organization, as necessary to get attention. This policy should be constantly reinforced as a means for mission success.

The MPL project should increase the amount of formal and informal face-to-face communications with all team elements including science, navigation, propulsion, etc. and especially for those elements that have critical interfaces like navigation and spacecraft guidance and control. (e.g. co-location of a navigation team member with the spacecraft guidance and control group).

The project should establish a routine forum for informal communication between all team members at the same time so everyone can hear what is happening. (e.g. a 15 minute stand-up tag-up meeting every morning).

The project and JPL management should encourage the MPL team to be skeptics and raise all concerns. All members of the MPL team should take concerns personally and see that they receive closure no matter what it takes.

The operations navigation team should implement and conduct a series of independent peer reviews in sufficient time to support MPL mission critical navigation events.

The Board also recommends that the MPL project assign a mission systems engineer as soon as possible. This mission systems engineer would provide the systems engineering bridge between the spacecraft system, the instrument system and the ground/operations system to maximize the probability of mission success.

MCO Contributing Cause No. 6: Operations Navigation Team Staffing

The Board found that the staffing of the operations navigation team was less than adequate. During the time leading up to the loss of the MCO, the Mars Surveyor

Operations Project (MSOP) was running 3 missions simultaneously (MGS, MCO, MPL). This tended to dilute the focus on any one mission, such as MCO. During the time before Mars orbit insertion (MOI), MCO navigation was handled by the navigation team lead and the MCO navigator. Due to the loss of MCO, MPL is to have three navigators, but only two were on-board at the time of the Board's meetings during the week of Oct. 18-22, 1999. The Board was told that 24 hour/day navigation staffing is planned for a brief period before MPL entry, descent, and landing (EDL). Such coverage may be difficult even for a team of three navigators and certainly was not possible for the single navigator of MCO.

MPL Recommendation:

The Board recommends that the operations navigation staff be augmented with experienced people to support the MPL EDL sequence. The MPL project should assign and train a third navigator to the operations team to support the EDL activities as soon as possible. In addition, the operations navigation team should identify backup personnel that could be made available to serve in some of the critical roles in the event that one of the key navigators becomes ill prior to the EDL activity.

The Board also recommends that the MPL project prepare contingency plans for backing up key personnel for mission-critical functions in any area of the Project.

MCO Contributing Cause No. 7: Training of Personnel

The Board found several instances of inadequate training in the MCO project. The operations navigation team had not received adequate training on the MCO spacecraft design and its operations. Some members of the MCO team did not recognize the purpose and the use of the ISA. The small forces software development team needed additional training in the ground software development process and in the use and importance of following the Mission Operations Software Interface Specification (SIS). There was inadequate training of the MCO team on the importance of an acceptable approach to end to end testing of the small forces ground software. There was also inadequate training on the recognition and treatment of mission critical small forces ground software.

MPL Recommendation:

The Board recommends that the MPL operations navigation team receive proper training in the spacecraft design and operations. Identify the MPL mission critical ground software and ensure that all such ground software meets the MPL software development plans. Ensure that the entire MPL team is trained on the ISA Process and its purpose--emphasize a "Mission Safety First" attitude. Encourage any issue to be written up as an ISA. Review all current anomalies and generate appropriate ISAs.

MCO Contributing Cause No. 8: Verification and Validation Process

Several verification and validation process issues were uncovered during the Board's review of the MCO program that should be noted. The Software Interface Specification (SIS) was developed but not properly used in the small forces ground software development and testing. End-to-end testing to validate the small forces ground software performance and its applicability to the specification did not appear to be accomplished. It was not clear that the ground software independent verification and validation was accomplished for MCO. The interface control process and the verification of specific ground system interfaces was not completed or was completed with insufficient rigor.

MPL Recommendation:

The Board recommends that the MPL project develop a system verification matrix for all project requirements including all Interface Control Documents (ICDs). The MPL team should review the system verification matrix at all remaining major reviews. The MPL project should require end users at the technical level to sign off on the ground software applications and products and the MPL project should review all ground software applications, including all new and reused software packages for applicability and correct data transfer.

6. Mars Climate Orbiter (MCO) Observations and Recommendations

Section 6 of NPG 8621 (Draft 1) provides key definitions for NASA mishap investigations. NPG 8621 (Draft 1) defines a significant observation as: “A factor, event or circumstance identified during the investigation which was not contributing to the mishap, but if left uncorrected, has the potential to cause a mishap...or increase the severity should a mishap occur.” Based on this definition, the Board determined that there were 10 observations that relate to recommendations for the MLP.

MCO Observation No. 1: Trajectory Margin for Mars Orbit Insertion

As the MCO proceeded through cruise phase for the subsequent MOI and aerobraking phases, the margins needed to ensure a successful orbit capture eroded over time. During the cruise phase and immediately preceding MOI, inadequate statistical analyses were employed to fully understand the dispersions of the trajectory and how these would impact the final MOI sequence. This resulted in a misunderstanding of the actual vehicle trajectory. As described previously, the actual trajectory path resulted in a periapsis much lower than expected. In addition, TCM-5 contingency plans, in the event of an anomaly, were not adequately worked out ahead of time. The absence of planning, tests, and commitment criteria for the execution of TCM-5 may have played a significant role in the decision to not change the MCO trajectory using the TCM-5 maneuver. The failure to execute TCM-5 is discussed as a contributing cause of the mishap. Spacecraft propellant reserves and schedule margins during the aerobraking phases were not used to mitigate the risk of uncertainties in the closest approach distance at MOI.

MPL Recommendations:

The Board recommends that the MPL project improve the data analysis procedures for fitting trajectory data to models, that they implement an independent navigation peer panel and navigation advisory group as a means to further validate the models to the trajectory data, and that they engage the entire MPL team in TCM and Entry, Descent, and Landing (EDL) planning.

MCO Observation No. 2: Independent Reviews

The Board noted that a number of reviews took place without the proper representation of key personnel; operations navigation personnel did not attend the spacecraft Preliminary and Critical Design Reviews. Attendance of these individuals may have allowed the flow of pertinent and applicable spacecraft characteristics to the operations navigation team.

Knowledge of these characteristics by the operations navigation may have helped them resolve the problem.

Key modeling issues were missed in the interpretation of trajectory data by the operations navigation team. The absence of a rigorous, independent navigation peer review process contributed to these issues being missed.

MPL Recommendations:

Provide for operations navigation discipline presence at major reviews. Ensure subsystem specialists attend major reviews and participate in transfer of lessons learned to the operations navigation team and others. Implement a formal peer review process on all mission critical events, especially critical navigation events.

MCO Observation No. 3: Contingency Planning Process

Inadequate contingency planning for TCM-5 was observed to play a part in the MCO failure. The MCO operational contingency plans for TCM-5 were not well defined and or completely understood by all team members on the MCO operational team.

The MCO project did not have a defined set of Go–No Go criteria for using TCM-5. There was no process in place to review the evaluation and decision criteria by the project and subsystem engineers before commitment to TCM-5. Polling of the team by the MCO Flight Operations Manager should establish a clear commitment from each subsystem lead that he or she has reviewed the appropriate data and believes that the spacecraft is in the proper configuration for the event.

MPL Recommendations:

Contingency plans need to be defined, the products associated with the contingencies fully developed, the contingency products tested and the operational team trained on the use of the contingency plans and on the use of the products. Since all possible contingency plans cannot be developed, a systematic assessment of all potential failure modes must be done as a basis for the development of the project contingency plans. The MPL team should establish a firm set of “Go no-go” criteria for each contingency scenario and the individual members of the operations team and subsystem experts should be polled prior to committing to the event.

MCO Observation No. 4: Transition from Development to Operations

The Board found that the overall project plan did not provide for a careful handover from the development project to the very busy operations project. MCO was the first JPL

mission to transition a minimal number of the development team into a multi-mission operations team. Very few JPL personnel and no MCO navigation personnel, transitioned with the project. Furthermore, MCO was the first mission to be supported by the multi-mission MSOP team.

During the months leading up to MCO MOI, the MSOP team had some key personnel vacancies and a change in top management. The operations navigation personnel in MSOP were working MGS operations, which had experienced some in-flight anomalies. They were expecting MCO to closely resemble MGS. They had not been involved in the initial development of the navigation plan and did not show ownership of the plan, which had been handed off to them by the MCO development team. The MSOP had no systems engineering and no mission assurance personnel who might have acted as an additional set of eyes in the implementation of the process.

It should be noted that the MPL navigation development engineer did transition to operations.

MPL Recommendations:

Increase the MPL operations and operations navigation teams as appropriate. Augment the teams by recalling key members of the development team and specialists from the line organization. Consider more collocation of JPL/LMA personnel through EDL. Conduct a rigorous review of the handoff from the JPL operations navigation team to the LMA EDL team, particularly the ICD and all critical events.

MCO Observation No. 5: Matrix Management

The Board observed that line organizations, especially that of the operations navigation team, were not significantly engaged in project-related activity. In the case of navigation, the Board observed little evidence of contact between line supervision and navigators supporting the project.

MPL Recommendation:

Expeditiously involve line management in independently reviewing and following through the work remaining to achieve a successful MPL landing.

MCO Observation No. 6: Mission Assurance

The Board observed the absence of a mission assurance manager in MSOP. It was felt that such a presence earlier in the program might have helped to improve project communication, insure that project requirements were met. Items that the mission assurance manager could have addressed for MCO included ensuring that the AMD file met the requirements of the SIS and tracking ISA resolutions. The mission assurance

manager would promote the healthy questioning of “what could go wrong.” The Board explicitly heard an intention to fill the mission assurance position for MPL, but this had not happened as of October 22, 1999.

MPL Recommendation:

Assign a mission assurance manager in MSOP as soon as possible.

MCO Observation No. 7: Science Involvement

The paradigm for the Mars Surveyor program is a capabilities-driven mission in which all elements, including science, were traded to achieve project objectives within the overall constraints of cost and schedule. Success of such missions requires full involvement of the mission science personnel in the management process. In addition, science personnel with relevant expertise should be included in all decisions where expert knowledge of Mars is required. While this was generally the case for the Mars '98 program, such experts were not fully involved in the decisions not to perform TCM-5 prior to Mars orbit insertion.

MPL Recommendation:

Fully involve the Project Scientist in the management process for the remainder of the MPL mission, including decisions relating to Entry, Descent, and Landing.

MCO Observation No. 8: Navigation Capabilities

JPL's navigation of interplanetary spacecraft has worked well for 30 years. In the case of MCO there was a widespread perception that “Orbiting Mars is routine.” This perception resulted in inadequate attention to navigation risk mitigation.

MPL Recommendation:

MPL project personnel should question and challenge everything—even those things that have always worked. JPL top management should provide the necessary emphasis to bring about a cultural change.

MCO Observation No. 9: Management of Critical Flight Decisions

During its deliberations, the Board observed significant uncertainty and discussions about such things as the project's plan for trajectory correction maneuvers (TCMs) and the planned primary and alternate landing sites for MPL. Planning for TCM 5 on MCO was inadequate. TCM 5 for MPL was still being described as a contingency maneuver during

the Board's deliberations. The Board also notes evidence of delayed decisions at the October 21, 1999, MPL Critical Events Review for Entry, Descent, and Landing.

MPL Recommendation:

Require timely, disciplined decisions in planning and executing the remainder of the MPL mission.

MCO Observation No. 10: Analyzing What Could Go Wrong

The Board observed what appeared to be the lack of systematic analyses of "what could go wrong" with the Mars '98 projects. For example, the Board observed no fault tree or other *a priori* analyses of what could go wrong with MCO or MPL.

MPL Recommendation:

Conduct a fault tree analysis for the remainder of the MPL mission; follow-up on the results. Consider using an external facilitator; e.g., from nuclear industry or academia, if the necessary expertise in the *a priori* use of fault tree analysis does not exist at JPL.

7. Mars Polar Lander (MPL) Observations and Recommendations

As part of the MCO Phase I activity, the Board developed eight MPL observations and recommendations not directly related to the MCO mishap.

MPL Observation No. 1: Use of Supplemental Tracking Data Types

The use of supplemental tracking data types to enhance or increase the accuracy of the MPL navigation solutions was discussed. One data type listed in the MPL Mission Planning Databook as a requirement to meet the Entry Descent Landing (EDL) target condition to a performance of better than 95 percent is the Near Simultaneous Tracking (NST). Additional data types discussed were the use of a three-way measurement and a difference range process. These data types would be used independently to assess the two-way coherent measurement data types (range and Doppler) baselined by the prime operations navigation team. During the presentations to the MIB, it was stated that the MPL navigation team lead would be involved in the detailed analysis of the NST data. The application of a NST data type is relatively new to the MPL mission navigation procedure. These data types have not been previously used for MCO or MPL navigation. The results of the new data types in addition to range and Doppler only-solutions could potentially add to the uncertainty of the best estimate of the trajectory at the EDL conditions.

MPL Recommendation:

Identify the requirement for the use of the NST, 3-way, and difference range. Determine if the EDL target conditions can be met without them. An independent team should be responsible for the processing and assessment of these alternative tracking schemes. A process should be developed to utilize these data types as a crosscheck of the current 2-way coherent method. Ensure that the NST process is streamlined and well understood as it is incorporated into the nominal operations. If NST is necessary, focus work so as to not affect other routine navigation operations.

MPL Observation No. 2: Star Camera Attitude Maneuver (SCAM)

Prior to Entry, Descent and Landing (EDL), a multi-hour attitude calibration is planned on MPL. This so-called Star Camera Attitude Maneuver (SCAM) will reorient the spacecraft to provide optimal observation of stars in the star camera. The purpose of this maneuver is to calibrate the gyro drift bias and determine the vehicle attitude to a level of performance necessary to initiate the EDL maneuver sequence. The specific attitude required to successfully perform the SCAM results in a loss of spacecraft telemetry due

to the fact that the MPL antenna is pointed away from Earth. Currently, the exact timing of the planned SCAM activity has not been finalized.

MPL Recommendation:

The MPL flight operations team should establish definitive SCAM requirements, especially the attitude accuracy needed prior to EDL and the length of time that MPL is required in the SCAM attitude. Clear operations scenarios should be developed and specific contingency operations procedures should be developed.

MPL Observation No. 3: Verification and Validation (V&V) of Lander Entry State File

Although the board was informed that a plan existed, the final end-to-end verification and validation of the Entry-Descent-Landing operational procedures had not been completed when the Board reviewed the project. This cannot be completed until after the ground software has successfully completed acceptance testing. Moreover, the generation and subsequent use of the Lander Entry State File (LESF) has not been tested. The data in the LESF is used to update the onboard estimate of Mars-relative position and velocity just prior to entry interface. Apparently this is a relatively new procedure for JPL and thus should receive focused attention.

MPL Recommendation:

The Board recommends that the MPL team perform an end-to-end V&V test of EDL including use of the LESF. Coordinate transformations and related equations used in the generation of this file should be checked carefully. The end-to-end test should include simulated uplinks of the LESF to the spacecraft and propagation of the simulated state vector to landing in a 6 degree-of-freedom simulation like the Simulation Test Laboratory. It may be beneficial to test it more than once with perhaps different scenarios or uplinked state vectors. Related to this issue is the need to have a baselined spacecraft timeline especially when entry interface is approaching. Any spacecraft maneuvers, e.g., SCAM maneuvers, from shortly before uplink of the LESF until entry interface need to be well-planned ahead of time, i.e., modeled by the navigators, so that the onboard navigation state at entry interface will be as accurate as possible.

If possible, provide for the capability to use a preliminary navigation solution for EDL navigation initialization in case of a temporary uplink problem, i.e., uplink an LESF file before it is really needed so that if an anomaly occurs in that process, the onboard EDL navigation system will have something reasonable to work with, albeit perhaps not as accurate as desired.

MPL Observation No. 4: Roles and Responsibilities of Individuals

In the wake of the MCO loss and the subsequent augmentation of the MPL team, the Board observed that roles and responsibilities of some individuals in MSOP are unclear. A recurring theme in the Board's deliberations was one of "Who's in charge?" Another such recurring theme was one of "Who's the mission manager?" The Board perceived hesitancy and wavering on the part of people attempting to answer this question. One answer was that the Flight Operations Manager (FOM) was acting like a mission manager, but is not actually designated as such.

MPL Recommendation:

The Board recommends that the MPL project clarify roles and responsibilities for all individuals on the team. Assign a person the role of mission manager for MPL and ensure that the entire team understands the leadership role that this person is empowered to provide to the MPL team.

MPL Observation No. 5: Cold Firing of Thrusters

Hydrazine has physical properties that are very similar to water. Hydrazine is a monopropellant that will be used in thrusters to slow the MPL spacecraft from about 75-80 meters/second to its landing velocity around 2.5 meters/second. This is accomplished by simultaneously pulse mode firing twelve (12) parallel catalytic thrusters. The key concern is the freezing point of hydrazine. Hydrazine freezes around 1 to 2° C, depending on the exact environmental conditions and hydrazine's purity. Furthermore, the spontaneous catalyst (i.e., initiates hydrazine decomposition at "room temperature") used in all thrusters flying today, loses spontaneous reactivity as the catalyst bed temperature is lowered below 7°C. If the catalyst bed is very cold (i.e. well below 0° C), then there will be long ignition delays when the thrusters are commanded to fire. The results of these extremely cold and long ignition delay firings could produce high-pressure spikes and even possibly detonations. As a minimum, the cold catalyst bed induced ignition delays and the resulting irregular, pulses on startup, could seriously impact MPL dynamics and potentially the stability of the vehicle during the terminal descent operations, possibly leading to a non-upright touchdown.

Additional concern exists as to when the EDL operations team plans to turn on the heaters on the propellant lines feeding the hydrazine thrusters. The outer lines and the thrusters will have been cold "soaking" during the 11-month trip to Mars. If any of these lines are cold enough (well below 0°C), then the hydrazine might freeze when bled into the thruster valves. If this occurs, then there will be no impulse when the thrusters are commanded to fire.

It was stated by the project operations manager that all 12 thrusters (operating at 267 Newtons each) must all operate as commanded. Therefore, the above described thermal deficiencies should be a major concern for the MPL project team.

MPL Recommendations

The Board recommends that the MPL team examine the thermal analysis and determine when the heaters on the lines feeding the thrusters should be turned on to ensure adequate, stable liquid flow with sufficient positive margins. The Board also suggests that the MPL team should consider the use of very short catalyst bed thermal preconditioning pulses during lander propulsion system utilization (i.e., startup) to insure uniform pulse firing during terminal descent.

MPL Observation No. 6: MPL Terminal Descent Maneuver

The MPL terminal descent maneuver will use simultaneous soft pulse mode firings of 12 monopropellant hydrazine thrusters operating at 267 Newtons of thrust each. All these thrusters must operate in unison to ensure a stable descent. This type of powered descent maneuver has always been considered to be very difficult and stressing for a planetary exploration soft landing. Hence, in the last 35 years of planetary exploration, MPL is the first user of this soft pulsed thrust soft landing technique.

The concern has been that the feedline hydraulics and water hammer effects could be very complex and interactive. This issue could be further aggravated by fuel slosh, uneven feeding of propellant from the two tanks and possible center of gravity mismatch on the vehicle. Additional complications could result from non-uniform exhaust plume impingement on the lander legs sticking below the thruster nozzles due to any uneven pulse firings.

It should be recognized that under extreme worst case conditions for feedline interactions, it is possible that some thrusters could produce near zero thrust and some could produce nearly twice the expected thrust when commanded to operate.

MPL Recommendation:

It was stated many times by the MPL project team during the reviews with the Board, that a vast number of simulations, analyses and rigorous realistic tests were all carefully conducted during the development program to account for all these factors during the propulsive landing maneuver.

However, because of the extreme complexity of this landing maneuver, the EDL team should carefully re-verify that all the above described possible effects have been accounted for in the terminal maneuver strategies and control laws and the associated software for EDL operations.

MPL Observation No. 7: Decision Making Process

Discussions with MPL team members revealed uncertainty about mission-critical decisions that inhibited them from doing their job in a timely manner. The Board observed that there was discussion about the landing site for MPL at the time of our meetings at JPL. According to plan, there was consideration of moving to the backup site based on new information from MGS regarding landing site characteristics. Some elements of the Project team, e.g., some members of the operations navigation team, were not informed of this new information or the fact that the landing site was being reconsidered. There also was apparently uncertainty about the process for addressing this time-critical decision and about when it would be made.

MPL Recommendation:

Communicate widely the need for timely decisions that enable the various elements of the Project to perform their jobs. Establish a formal decision need-date tracking system that is communicated to the entire team. This system would identify the latest decision need date and the impact of not making the decision. All elements of the Project should provide input for establishing these dates and be informed of the decision schedules.

Assign an overall Mission Manager responsible for the success of the entire mission from spacecraft health to receipt of successful science data.

MPL Observation No. 8: Lander Science

The Board was informed that preparations for the Lander science program were in an incomplete state at the time of the Board's meeting due to the impacts resulting from the loss of the MCO. The redirection of resources due mainly to the loss of MCO caused the science team to become further behind in preparation for MPL science operations. Since the landed science program is limited to about three months by the short summer season near the Martian South Pole, maximum science return requires full readiness for science operations prior to EDL. Several additional managers were being assigned to address preparations for the science program.

MPL Recommendation:

Ensure that a detailed Lander science plan, tools, and necessary support are in place before the landing. The Project Scientist should be fully involved in the management of the science operations planning and implementation.

8. Phase II Plan

During the Phase II activity, the Board will review and evaluate the processes used by the MCO and MPL missions and other past mission successes and failures, develop lessons learned, make recommendations for future missions, and deliver a report no later than February 1, 2000. This report will cover the following topics and any other items the Board feels relevant as part of the investigation process.

1. Processes to detect, articulate, interpret and correct errors to ensure mission safety and reliability
2. Systems engineering issues, including, but not limited to:
 - Processes to identify primary mission success criteria as weighted against potential mission risks
 - Operational processes for data validation
 - Management structure and processes to enable error-free communications and procedure documentation
 - Processes to ensure that established procedures were followed
3. Testing, simulation and verification of missions operations
4. Work Force Development
5. Workforce culture: confidence or concern?
6. Independent assessments
7. Planetary Navigation Strategies: Ground and Autonomous
 - Accuracy & Precision that can be delivered
 - Current & future technologies to support Mars missions
 - Navigation requirements and pre-flight documentation

During the Phase II investigation process, the Board will obtain and analyze whatever evidence, facts, and opinions it considers relevant. It will use reports of studies, findings, recommendations, and other actions by NASA officials and contractors. The Board may conduct inquiries, hearings, tests, and other actions it deems appropriate. They will develop recommendations for preventive and other appropriate actions. Findings may warrant one or more recommendations, or they may stand-alone. The requirements in the NASA Policy Document (NPD) 8621.1G and NASA Procedures and Guidelines (NPG) 8621.1 (draft) will be followed for procedures, format, and the approval process.

Appendix

Letter Establishing the Mars Climate Orbiter Mishap Investigation Board

SD

TO: *Distribution*
FROM: *S/Associate Administrator for Space Science*
SUBJECT: *Establishment of the Mars Climate Orbiter (MCO) Mission Failure Mishap Investigation Board*

1. INTRODUCTION/BACKGROUND

The MCO spacecraft, designed to study the weather and climate of Mars, was launched by a Delta rocket on December 11, 1998, from Cape Canaveral Air Station, Florida. After cruise to Mars of approximately 9 1/2 months, the spacecraft fired its main engine to go into orbit around Mars at around 2 a.m. PDT on September 23, 1999.

Five minutes into the planned 16-minute burn, the spacecraft passed behind the planet as seen from Earth. Signal reacquisition, nominally expected at approximately 2:26 a.m. PDT when the spacecraft was to reemerge from behind Mars, did not occur.

Fearing that a safehold condition may have been triggered on the spacecraft, flight controllers at NASA's Jet Propulsion Laboratory (JPL) in Pasadena, California, and at Lockheed Martin Astronautics See figure 1. The spacecraft was to then skim through Mars' upper atmosphere for several weeks in a

Efforts to find and communicate with MCO continued up until 3 p.m. PDT on September 24, 1999, when they were abandoned. A contingency was declared by MCO Program Executive, Mr. Steve Brody at 3 p.m. EDT on September 24, 1999.

2. PURPOSE

This establishes the NASA MCO Mission Failure Mishap Investigation Board and sets forth its terms of reference, responsibilities, and membership in accordance with NASA Policy Directive (NPD) 8621.1G.

3. ESTABLISHMENT

a. *The MCO Mission Failure Mishap Investigation Board (hereinafter called the Board) is hereby established in the public's interest to gather information, analyze, and determine the facts, as well as the actual or probable cause(s) of the MCO Mission Failure Mishap in terms of (1) dominant root cause(s), (2) contributing cause(s), and (3) significant observations and to recommend preventive measures and other appropriate actions to preclude recurrence of a similar mishap.*

b. *The chairperson of the board will report to the NASA Office of Space Science (OSS) Associate Administrator (AA) who is the appointing official.*

4. OBJECTIVES

A. *An immediate priority for NASA is the safe landing on December 3, 1999, of the Mars Polar Lander (MPL) spacecraft, currently en route to Mars. This investigation will be conducted recognizing*

the time-criticality of the MPL landing and the activities the MPL mission team must perform to successfully land the MPL spacecraft on Mars. Hence, the Board must focus first on any lessons learned of the MCO mission failure in order to help assure MPL's safe landing on Mars. The Board must deliver this report no later than November 5, 1999.

i. The Board will recommend tests, analyses, and simulations capable of being conducted in the near term to prevent possible MPL failures and enable timely corrective actions.

ii. The Board will review the MPL contingency plans and recommend improvements where possible.

B. The Board will review and evaluate all the processes used by the MCO mission, develop lessons learned, make recommendations for future missions, and deliver a final mishap investigation report no later than February 1, 2000. This report will cover the following topics and any other items the Board thinks relevant.

i. Processes used to ensure mission safety and reliability with mission success as the primary objective. This will include those processes that do not just react to hard failures, but identify potential failures throughout the life of the mission for which corrective actions can be taken. It will also include asking if NASA has the correct philosophy for mission assurance in its space missions. That is:

- a) "Why should it fly?" versus "why it should not fly?",*
- b) mission safety should not be compromised by cost and performance, and*
- c) definition of adequacy, robustness, and margins-of-safety as applied to clearly defined mission success criteria.*

ii. Systems engineering issues, including, but not limited to:

- a) Processes to identify primary mission success criteria as weighted against potential mission risks,*
- b) operational processes for data validation,*
- c) Management structure and processes to enable error-free communications and procedure documentation, and*
- d) processes to ensure that established procedures were followed.*

iii. Testing, simulation and verification of missions operations:

- a) What is the appropriate philosophy for conducting end-to-end simulations prior to flight?*
- b) How much time and resources are appropriate for program planning?*
- c) What tools should be developed and used routinely?*
- d) How should operational and failure mode identification teams be formed and managed (teams that postulate failure modes and inspire in-depth review)?*
- e) What are the success criteria for the mission, and what is required for operational team readiness prior to the Flight Readiness Review (i.e., test system tolerance to human and machine failure)?, and*
- f) What is the recommended developmental process to ensure the operations team runs as many failure modes as possible prior to launch?*

iv. Personnel training provided to the MCO operations team, and assess its adequacy for conducting operations.

v. Suggest specific recommendations to prevent basic types of human and machine error that may have led to the MCO failure.

vi. Reexamine the current approach to planetary navigation. Specifically, are we asking for more accuracy and precision than we can deliver?

vii. How in-flight accumulated knowledge was captured and utilized for future operational maneuvers.

5. AUTHORITIES AND RESPONSIBILITIES

a. The Board will:

1) Obtain and analyze whatever evidence, facts, and opinions it considers relevant. It will use reports of studies, findings, recommendations, and other actions by NASA officials and contractors. The Board may conduct inquiries, hearings, tests, and other actions it deems appropriate. It may take testimony and receive statements from witnesses.

2) Determine the actual or probable cause(s) of the MCO mission failure, and document and prioritize their findings in terms of (a) the dominant root cause(s) of the mishap, (b) contributing cause(s), and (c) significant observation(s). Pertinent observations may also be made.

3) Develop recommendations for preventive and other appropriate actions. A finding may warrant one or more recommendations, or it may stand-alone.

4) Provide to the appointing authority, (a) periodic interim reports as requested by said authority, (b) a report by November 5, 1999, of those findings and recommendations and lessons learned necessary for consideration in preparation for the MPL landing, and (c) a final written report by February 1, 2000. The requirements in the NPD 8621.1G and NASA Procedures and Guidelines (NPG) 8621.1 (draft) will be followed for procedures, format, and the approval process.

b. The Chairperson will:

1) Conduct Board activities in accordance with the provisions of NPD 8621.1G and NPG 8621.1 (draft) and any other instructions that the appointing authority may issue or invoke.

2) Establish and document rules and procedures for the organization and operation of the Board, including any subgroups, and for the format and content of oral and written reports to and by the Board.

3) Designate any representatives, consultants, experts, liaison officers, or other individuals who may be required to support the activities of the Board and define the duties and responsibilities of those persons.

6. MEMBERSHIP

The chairperson, other members of the Board, and supporting staff are designated in the Attachment.

7. MEETINGS

The chairperson will arrange for meetings and for such records or minutes of meetings as considered necessary.

8. ADMINISTRATIVE AND OTHER SUPPORT

a. JPL will provide for office space and other facilities and services that may be requested by the chairperson or designee.

b. All elements of NASA will cooperate fully with the Board and provide any records, data, and other administrative or technical support and services that may be requested.

9. DURATION

The NASA OSS AA, as the appointing official, will dismiss the Board when it has fulfilled its responsibilities.

10. CANCELLATION

This appointment letter is automatically cancelled 1 year from its date of issuance, unless otherwise specifically extended by the approving official.

Edward J. Weiler

Enclosure

Distribution:

S/Dr. E. Huckins

S/Dr. C. Pilcher

SD/Mr. K. Ledbetter

SD/Ms. L. LaPiana

SD/Mr. S. Brody

SR/Mr. J. Boyce

SPR/Mr. R. Maizel

SPR/Mr. J. Lee

Q/Mr. F. Gregory

QS/Mr. J. Lloyd

JPL/180-904/Dr. E. Stone

JPL/180-704/Dr. C. Elachi

JPL/180-703/Mr. T. Gavin

JPL/230-235/Mr. R. Cook

JPL/264-426/Mr. C. Jones

JPL/180-904/Mr. L. Dumas

MCO FIB Board Members, Advisors, Observers, and Consultants.

ATTACHMENT

Mars Climate Orbiter (MCO) Failure Investigation Board (FIB)

Members

MSFC/Mr. Arthur G. Stephenson Chairperson

*Director,
George C. Marshall Space
Flight Center*

HQ/Ms. Lia S. LaPiana Executive Secretary

*SIRTF Program Executive
Code SD*

HQ/Dr. Daniel R. Mulville

*Chief Engineer
Code AE*

*HQ/Dr. Peter J. Rutledge
(ex-officio)*

*Director,
Enterprise Safety and Mission Assurance
Division
Code QE*

GSFC/Mr. Frank H. Bauer

*Chief
Guidance, Navigation, and Control Center
Code 570*

GSFC/Mr. David Folta

*System Engineer
Guidance, Navigation, and Control Center
Code 570*

MSFC/Mr. Greg A. Dukeman

*Guidance and Navigation Specialist
Vehicle Flight Mechanics Group
Code TD-54*

MSFC/Mr. Robert Sackheim

*Assistant Director for Space Propulsions
Systems
Code DA-01*

ARC/Dr. Peter Norvig

*Chief
Computational Sciences Division*

Advisors: (non-voting participants)

Legal Counsel:

*Mr. Louis Durnya
George C. Marshall Space Flight Center
Code LS01*

Office of Public Affairs:

*Mr. Douglas Isbell
NASA Headquarters
Code P*

Consultants:

Ms. Ann Merwarth NASA/GSFC-retired

*Expert in ground operations and flight
software development*

*Dr. Moshe F. Rubinstein, Prof. Emeritus,
UCLA, Civil and Environmental
Engineering*

Mr. John Mari *Vice-President of Product Assurance*
Lockheed Martin Aeronautics

Mr. Peter Sharer *Senior Professional Staff*
Mission Concepts and Analysis Group
The Johns Hopkins University
Applied Physics Laboratory

*Mr. Craig Staresinich Program management and Operations Expert
TRW*

Mr. Tim Crumbley *Deputy Group Lead*
Flight Software Group
Avionics Department
George C. Marshall Space Flight Center

Observers:

JPL/Mr. John Casani (retired) Chair of the JPL MCO special review board

JPL/Mr. Frank Jordan

Chair of the JPL MCO independent peer review team

JPL/Mr. John McNamee

*Chair of Risk Assessment Review for MPL
Project Manager for MCO and MPL
(development through launch)*

*HQ/SD/Mr. Steven Brody
(ex-officio)*

*MCO Program Executive
NASA Headquarters*

MSFC/DA01/Mr. Drew Smith

*Special Assistant to Center Director
George C. Marshall Space Flight
Center*

HQ/SR/Dr. Charles Holmes

*Program Executive for Science
Operations
NASA Headquarters*

*HQ/QE/Mr. Michael Card
(ex-officio)*

*Program Manager
NASA Headquarters*

Acronym list

AA = Associate Administrator
AACS = Articulation and Attitude Control System
AMD = Angular Momentum Desaturation
EDL = Entry, Descent, Landing
GDS = Ground Data System
ICD = Interface Control Document
ISA = Incident, Surprise, Anomaly
JPL = Jet Propulsion Laboratory
lbf-s = pounds (force)-second
LESF = Lander Entry State File
LIDAR = Light Detection and Ranging
LMA = Lockheed Martin Astronautics
MCO = Mars Climate Orbiter
MGS = Mars Global Surveyor
MIB = Mishap Investigation Board
MOI = Mars Orbital Insertion
MOS = Mission Operations System
MPL = Mars Polar Lander
MSOP = Mars Surveyor Operations Project
MSP = Mars Surveyor Program
MSP'98 = Mars Surveyor Project '98
NASA = National Aeronautics and Space Administration
NPD = NASA Policy Directive
NPG = NASA Procedures and Guidelines
N-s = Newton-seconds
NST = Near Simultaneous Tracking
OSS = Office of Space Science
PDT = Pacific Daylight Time
SCAM = Star Camera Attitude Maneuver
SIS = System Interface Specifications
TCM = Trajectory Correction Maneuver
UTC = Universal Time Coordinated
V&V = Verification and Validation
 ΔV = Velocity Change

Appendix C

Letter Providing Revised Charter for Mars Climate Orbiter Mishap Investigation Board

SD

TO: Distribution

FROM: S/Associate Administrator for Space Science

SUBJECT: Revised Charter of the Mars Climate Orbiter (MCO) Mission Mishap Investigation Board (MIB)

This is referenced to the establishment of the Mars Climate Orbiter (MCO) Mission Failure Mishap Investigation Board memorandum, dated October 15, 1999.

1. INTRODUCTION/BACKGROUND

The MCO MIB, hereafter called the Board, was established on October 15, 1999.

The Board completed its first report, which was accepted, approved and released by the Associate Administrator for Space Science and the Associate Administrator for Safety and Mission Assurance on November 10, 1999. The first report was focused on identifying the root cause and contributing factors of the MCO failure and observations related to the Mars Polar Lander (MPL).

The purpose of this letter is to amend the objectives of the final report, as listed in section of 4.B. of the above referenced memorandum, to be delivered by the Board by February 1, 2000.

The terms of reference and the Board's responsibilities and membership remain unchanged from the referenced memorandum.

2. REVISED OBJECTIVES FOR THE FINAL REPORT

The intent of the revised objectives of the final report is to amend section 4.B. of the referenced memorandum and broaden the area investigation beyond the MCO failure. The Board is to investigate a wide range of space science programs and to make recommendations regarding project management based upon reviewing lessons learned from this broader list of programs.

The Board will review and evaluate the processes and/or lessons learned from:

- the MCO mission,
- selected recent NASA space science missions which experienced failure,
- selected recent NASA space science missions which were successful,
- NASA missions using the "Faster, Better, Cheaper" philosophy, and
- any other selected space programs which have recently experienced failures, like expendable launch vehicles, which may have lessons learned applicable to future space science missions.

The Board will not conduct an investigation on the Mars Polar Lander beyond the one already covered in the first report released on November 10, 1999.

The selection of additional NASA missions and program elements is left to the discretion of the Board Chair in order to address the following topics in the final report:

i. Processes used to ensure mission safety and reliability with mission success as the primary objective. This will include those processes that do not just react to hard failures, but identify potential failures throughout the life of the mission for which corrective actions can be taken. It will also include asking if NASA has the correct philosophy for mission assurance in its space missions. That is:

- a) "Why should it fly?" versus "why it should not fly?"
- b) Mission safety should not be compromised by cost and performance.
- c) Definition of adequacy, robustness, and margins-of-safety as applied to clearly defined mission success criteria.

ii. Systems engineering issues including, but not limited to:

- a) Processes to identify primary mission success criteria as weighted against potential mission risks,
- b) Operational processes for data validation,
- c) Management structure and processes to enable error-free communications and procedure documentation, and
- d) Processes to ensure that established procedures were followed.

iii. Testing, simulation and verification of missions operations:

- a) What is the appropriate philosophy for conducting end-to-end simulations prior to flight?
- b) How much time and resources are appropriate for program planning?
- c) What tools should be developed and used routinely?
- d) How should operational and failure mode identification teams be formed and managed (teams that postulate failure modes and inspire in-depth review)?
- e) What are the success criteria for the mission, and what is required for operational team readiness prior to the Flight Readiness Review (i.e., test system tolerance to human and machine failure)?, and
- f) What is the recommended developmental process to ensure the operations team runs as many failure modes as possible prior to launch?

iv. Personnel training provided to the MCO operations team, and assess its adequacy for conducting operations.

v. Suggest specific recommendations to prevent basic types of human and machine error that may have led to failure.

vi. Reexamine the current approach to planetary navigation. Specifically, are we asking for more accuracy and precision than we can deliver?

vii. How in-flight accumulated knowledge is captured and utilized for future operational maneuvers.

While addressing the above topics, the final report should describe:

The additional MCO findings and recommendations not related to MPL (and thus not reported in the first report), the ideal project management process to achieve "Mission Safety First," the current project management process and where improvements are needed, recommendations for bridging the gap between the current and ideal projects, and metrics for measuring project performance regarding mission safety.

/signed 1/3/00/
Edward J. Weiler

Distribution:

S/Dr. E. Huckins
S/Dr. C. Pilcher
SD/Mr. K. Ledbetter
SD/Ms. L. LaPiana
SD/Mr. S. Brody
SR/Mr. J. Boyce
SPR/Mr. R. Maizel
SPR/Mr. J. Lee
Q/Mr. F. Gregory
QS/Mr. J. Lloyd
JPL/180-904/Dr. E. Stone
JPL/180-704/Dr. C. Elachi
JPL/180-703/Mr. T. Gavin
JPL/230-235/Mr. R. Cook
JPL/264-426/Mr. C. Jones
JPL/180-904/Mr. L. Dumas

MCO FIB Consultants
GSFC retired/Ms. A. Merwarth
GSFC retired/Dr. M. Hauser
JSC/DM42/Mr. D. Pearson
MSFC/ED-14/Mr. T. Crumbley
JHU/APL/Mr. P. Sharer
LMA/Mr. J. Mari
TRW/Mr. C. Staresinich
UCLA/Prof. M. Rubinstein

MCO FIB Observers
SD/Mr. S. Brody
SR/Dr. C. Holmes
QE/Mr. M. Card
JPL retired/Mr. J. Casani
JPL/264-426/Mr. F. Jordon
JPL/301-335/Mr. J. McNamee
MSFC/DA01/Mr. D. Smith

MCO FIB Board Members

AE/Dr. D. Mulville
QE/Dr. P. Rutledge
ARC/269-1/Dr. P. Norvig
GSFC/570/Mr. F. Bauer
GSFC/570/Mr. D. Folta
MSFC/DA-01/Mr. A. Stephenson
MSFC/TD-54/Mr. G. Dukeman
MSFC/DA-1/Mr. Robert Sackheim

MCO FIB Advisors

Code P/Mr. D. Isbell
MSFC/LS-01/Mr. L. Durnya

Appendix D

List of Existing Processes and Requirements Applicable to Programs/Projects

Partial List of Existing Processes Applicable to Programs/Projects

Management

- Program/project management (NPD 7120.4; NPG 7120.5A)
New process for managing NASA programs and projects, including GPMCs and emphasis on risk management
- Risk Management
NASA Continuous Risk Management Course, taught by the Software Assurance Technology Center, NASA Goddard Space Flight Center, NASA-GSFC-SATC-98-001.
(URL: <http://www.hq.nasa.gov/office/codeq/mtecpage/mtechniq.htm>)
- Lessons Learned
Lesson Learned Information System (LLIS) (URL: <http://llis.gsfc.nasa.gov/>) to document and apply the knowledge gained from past experience to current and future projects in order to avoid the repetition of past failures and mishaps.

Training

- Academy of Program and Project Leadership (APPL)
(URL: <http://www1.msfc.nasa.gov/TRAINING/APPL/HOME.html>) Training for project managers
- NASA Engineering Training (NET)
(URL: <http://se-sun2.larc.nasa.gov/stae/net/net.htm>) Training for project engineers
- Site for On-line Learning and Resources (SOLAR)
(<http://solar.msfc.nasa.gov:8018/solar/delivery/public/html/newindex.htm>) Web-based training site containing large quantity of safety and mission assurance training for NASA (SMA personnel and others)
- NASA Safety Training Center (JSC)
Classroom-based training in safety, including safety engineering; conducted on-site or via ViTS

Design Information

- NASA Preferred Reliability Practices for Design and Test (NASA TM 4322)
(URL: <http://www.hq.nasa.gov/office/codeq/overvu.htm>) to communicate within the aerospace community design practices that have contributed to NASA mission success
- NASA Recommended Techniques for Effective Maintainability (NASA TM 4628)
(URL: <http://www.hq.nasa.gov/office/codeq/mtecpage/mtechniq.htm>) 40 experience-based techniques for assuring effective maintainability in NASA systems and equipment. Techniques are provided in four areas: Program

Management; Analysis & Test; Design Factors & Engineering; and
Operations and Operational Design Considerations

- Technical standards database
(URL: <http://standards.nasa.gov/>) preferred technical standards that they have been used on NASA programs and are generally considered to represent best current practice in specific areas
- Electronic Parts Information System (EPIMS)
(URL: <http://epims.gsfc.nasa.gov/>) a NASA-wide electronic database that captures, maintains, and distributes information on EEE parts and spacecraft parts lists for all NASA projects
- NASA Parts Selection List (NPSL)
(URL: <http://misspiggy.gsfc.nasa.gov/npsl/>) a detailed listing of EEE part types recommended for NASA flight projects based on evaluations, risk assessments and quality levels
- Radiation Effects and Analysis
(URL: <http://flick.gsfc.nasa.gov/radhome.htm>) addresses the effects of radiation on electronics & photonics
- Radiation Effects Database
(URL: <http://radnet.jpl.nasa.gov/>) contains radiation effects test data for total ionizing dose (TID) and single event effects (SEE) as they affect electronics parts
- NASA Orbital Debris Assessment
(URL: <http://sn-callisto.jsc.nasa.gov/mitigate/das/das.html>) orbital debris assessment software to analyze the man-made debris hazard in Earth orbit

Safety Reporting and Alerts

- NASA Safety Reporting System (NSRS)
(URL: <http://www.hq.nasa.gov/office/codeq/nsrsindx.htm>) a confidential, voluntary, and responsive reporting channel for NASA employees and contractors. The NSRS provides timely notification to (NASA) safety officials concerning safety hazards affecting any NASA-related activity.
- Government-Industry Data Exchange Program (GIDEP)
(URL: <http://www.gidep.corona.navy.mil/>) engineering data, failure experience, metrology data, product information, R&M data, urgent data requests to improve the quality and reliability, while reducing costs in the development and manufacture of complex systems and equipment

Partial List of Existing Requirements Applicable to Programs/Projects

Program/project management requirements

- NASA NPD 7120.4A, “Program / Project Management”
- NPG 7120.5A, “NASA Program and Project Management Processes and Requirements,” 3/3/98

Software policy

- NASA NPD 2820.1, “NASA Software Policies,” 5/29/98

Safety and Mission Assurance requirements

(URL: <http://www.hq.nasa.gov/office/codeq/doctree/doctree.htm>)

- NASA NPD 8700.1, “NASA Policy for Safety and Mission Success,” 6/12/97
- NASA STD 8709.2, “NASA Safety and Mission Assurance Roles and Responsibilities for Expendable Launch Vehicle Services,” 8/21/98
- NASA NPD 8730.3, “NASA Quality Management System Policy (ISO 9000),” 6/8/98
- NASA NPD 8710.2B, “NASA Safety and Health Program Policy,” 6/10/97
- NASA NPD 8720.1, “NASA Reliability and Maintainability (R&M) Program Policy,” 10/15/97
- NASA STD 8729.1, “Planning, Developing and Managing an Effective Reliability and Maintainability (R&M) Program,” 12/98
- NASA STD 2201, “Software Assurance Standard,” 11/10/92
- NASA TM 4322A, “NASA Preferred Reliability Practices for Design and Test,” 2/99
- NASA TM 4628A, “Recommended Techniques for Effective Maintainability,” 3/99
- NASA NPD 8730.2, “NASA Parts Policy,” 6/8/98
- NASA NPG 8735.1, “Procedures For Exchanging Parts, Materials, and Safety Problem Data Utilizing the Government-Industry Data Exchange Program and NASA Advisories,” 11/5/98
- NASA NPD 8730.1, “Metrology and Calibration,” 5/22/98
- NASA NPG 5300.4(2B-3), “Management of Government Quality Assurance Functions for NASA Contracts,” 12/24/97
- NASA STD 2100-91, “Software Documentation Standard,” 7/29/91
- NASA STD 2202-93, “Software Formal Inspections Standards,” 4/93
- NASA NPD 8070.6A, “Technical Standards,” 10/10/97 (URL: <http://standards.nasa.gov/>)
- NASA STD 8739.3, “Soldered Electrical Connections,” 12/15/97
- NASA STD 8739.4, “Crimping, Interconnecting Cables, Harnesses, and Wiring,” 2/9/98
- NASA STD 8739.5, “Fiber Optic Terminations, Cable Assemblies, and Installation,” 2/9/98

- NAS 5300.4 (3J-1), “NASA Workmanship Standard for Staking and Conformal Coating of Printed Wiring Boards and Assemblies,” 5/96
- NAS 5300.4 (3M), “NASA Workmanship Standard for Surface Mount Technology,” 8/31/99
- NASA STD 8739.7, “Electrostatic Discharge Control (Excluding Electrically Initiated Explosive Devices),” 12/15/97
- IPC-D-6011 & 6012, “Quality/Performance Specification for Rigid Printed Boards (Includes GSFC Supplement S-312-P003 Process Specification for Rigid Printed Boards for Space Applications and other High Reliability Uses)”
- NASA NHB 1700.1 (V1-B), “NASA Safety Policy and Requirements Document,” 6/11/93
- NASA STD 8719.8, “Expendable Launch Vehicle Payload Safety Review Process Standard,” 6/23/98
- NASA STD 8719.13A, “Software Safety,” 9/15/97
- NSS 1740.15, “Safety Standard for Oxygen and Oxygen Systems,” 1/96
- NASA-STD-8719.16, “Safety Standard for Hydrogen and Hydrogen Systems,” 2/12/97
- NASA NPD 8621.1G, “NASA Mishap Reporting and Investigating Policy,” 12/10/97
- NASA NHB 1700.1 (V2), “NASA Procedures and Guidelines for Mishap Reporting, Investigating, and Recordkeeping,” 6/9/83
- NASA NPD 8710.5, “NASA Safety Policy for Pressure Vessels and Pressurized Systems,” 3/17/98
- NASA NPD 8710.3, “NASA Policy for Limiting Orbital Debris Generation,” 5/29/97
- NASA STD 8719.14, “Guidelines and Assessment Procedures for Limiting Orbital Debris,” 8/95

Appendix E

List of Additional Projects Reviewed by Mars Climate Orbiter Mishap Investigation Board

Additional Projects Reviewed by Mars Climate Orbiter Mishap Investigation Board

- **Mars Polar Lander**
Presentations by Jet Propulsion Laboratory and Lockheed Martin Astronautics
- **Wide-Field Infrared Explorer Mishap Investigation**
Presentation by Darrell R. Branscome
- **Boeing Mission Assurance Review on Boeing Expendable Launch Vehicle Programs**
Presentation by Dr. Sheila E. Widnall
- **Lewis Spacecraft Mission Failure Investigation Board**
Final report released Feb. 12, 1998
- **Overview of Lockheed Martin Astronautics' flight systems organization and management approach for NASA missions**
Presentations by Lockheed Martin Astronautics
- **Lockheed Martin Expendable Launch Vehicle Programs Review**
Presentation by Bill Ballhouse
- **Lunar Prospector Lessons Learned**
Viewgraph report prepared by Sylvia Cox
- **Review of NASA's "Faster, Better, Cheaper" Approach**
Presentation by Tony Spear
- **Mars Pathfinder Lesson Learned**
Presentation by Tony Spear
- **Solar Heliospheric Observatory Mission Interruption Joint NASA/European Space Agency Investigation Board**
Final report released Aug. 13, 1998
- **Space Shuttle Independent Assessment Review**
Presentation by Dr. Henry McDonald
- **Chandra X-Ray Observatory Lessons Learned**
Presentation by Craig Staresinich

Appendix F

Recurring Themes From Failure Investigations and Studies

Table 1. Recurring Themes from Failure Investigations and Studies

PROJECT THEME	Mars Climate Orbiter (MCO)	Widefield Infrared Explorer	Lewis	Boeing MAR	Faster, Better, Cheaper	Solar Helio-spheric Observatory	LMA IAT on Mission Success	Space Shuttle IA Team	Frequency
Reviews	MCO7	WIRE1	L7	BMAR 3	FBC4			SIAT5	6
Risk Management/Assessment	MCO8		L6	BMAR 7	FBC3	SOHO1		SIAT4	6
Testing, Simulation, Verification/Validation	MCO4	WIRE2		BMAR 4		SOHO3	LMA1	SIAT6	6
Communications	MCO3		L1			SOHO4	LMA5	SIAT2	5
Health Monitoring During Critical Ops	MCO13	WIRE3			FBC5				3
Safety/Quality Culture	MCO9			BMAR 6			LMA4		3
Staffing	MCO2					SHOH5		SIAT1	3
Continuity	MCO10				FBC8				2
Cost/Schedule			L8		FBC2				2
Engineering Discipline			L4	BMAR 2					2
Government/Contractor Roles & Responsibilities			L5					SIAT3	2
Human Error							LMA2	SIAT8	2
Leadership	MCO6				FBC1				2
Mission Assurance	MCO11				FBC9				2
Overconfidence	MCO15							SIAT10	2
Problem Reporting	MCO12							SIAT7	2
Subcontractor, Supplier Oversight				BMAR 5			LMA6		2
Systems Engineering	MCO5			BMAR 1					2
Training	MCO1						LMA3		2
Configuration Control						SOHO2			1
Documentation					FBC7				1
Line Organization Involvement	MCO16								1
Operations	MCO17								1
Procedures									1
Project Team					FBC6				1
Requirements			L3						1
Science Involvement	MCO14								1
Technology Readiness					FBC10				1
Workforce Stress								SIAAT9	1

Table Key

From the Mars Climate Orbiter Mishap Investigation Board Phase I Report:

- MCO1 — “Train Navigation Team in spacecraft design and operations.” Train entire team and encourage use of problem-reporting process.
- MCO2 — “Augment Operations Team staff with experienced people to support entry, descent and landing.”
- MCO3 — “...stress to the project staff that communication is critical and empower team members to forcefully elevate any issue, keeping the originator in the loop through formal closure.” “Communicate widely the need for timely decisions that enable the various elements of the Project to perform their jobs.”
- MCO4 — “Conduct software audit for specification compliance on all data transferred between [NASA] and [the contractor].” “Develop and execute systems verification matrix for all requirements.”
- MCO5 — “...establish and fully staff a systems engineering organization with roles and responsibilities defined.”
- MCO6 — “Assign an overall Mission Manager responsible for the success of the entire mission from spacecraft health to receipt of successful science data.”
- MCO7 — “Implement a formal peer review process on all mission critical events, especially navigation events.”
- MCO8 — “Construct a fault tree for [the] mission.” “Contingency plans need to be defined, the products associated with the contingencies fully developed, the contingency products tested and the operational team trained on the use of the contingency plans and on the use of the products.”
- MCO9 — “...emphasize a “Mission Safety First” attitude.”
- MCO10 — “...provide for a careful handover from the development project to the ... operations project.”
- MCO11 — Involve mission assurance personnel early in the project to promote the healthy questioning of “what could go wrong.”
- MCO12 — “Project management should establish a policy and communicate it to all team members that they are empowered to forcefully and vigorously elevate concerns as high, either vertically or horizontally in the organization, as necessary to get attention.”
- MCO13 — While not brought up in the referenced report, it was noted during this Board’s deliberations that systems health monitoring was not provided for during Mars orbit insertion of the Mars Climate Orbiter — nor during the Mars Polar Lander’s entry, descent and landing. Such measures would have been useful in determining the causes of the failures.
- MCO14 — “Success of [capabilities-driven missions, in which all elements, including science, are traded to achieve project objectives] requires full involvement of the mission science personnel in the management process. In addition, science personnel with relevant expertise should be included in all decisions where expert knowledge of [the target environment] is required.”

- MCO15 — “...project personnel should question and challenge everything — even those things that have always worked ... top management should provide the necessary emphasis to bring about a cultural change.”
- MCO16 — “...line organizations ... were not significantly engaged in project-related activity.”
- MCO17 — A number of the contributing causes detailed in the referenced report related to operations; e.g., “systems engineering process did not adequately address transition from development to operations” and “inadequate operations Navigation Team staffing.”

From the Wide-field Infrared Explorer Mishap Investigation Board Report (Briefing by Darrell Branscome, Board Chair):

- WIRE1 — “Detailed, independent technical peer reviews are essential. Furthermore, it is essential that peer reviews be done to assess the integrity of the system design, including an evaluation of system/mission consequences of the detailed design and implementation.”
- WIRE2 — “Perform electronics power turn-on characterization tests, particularly for applications involving irreversible events.”
- WIRE3 — “Test for correct functional behavior and test for anomalous behavior, especially during initial turn-on and power-on reset conditions.”

From Lewis Spacecraft Mission Failure Investigation Board Report:

- L1 — Especially in “Faster, Better, Cheaper” projects, communication of decisions to senior NASA and contractor management is essential to successful program implementation.
- L3 — “Requirements changes without adequate resource adjustments” indirectly contributed to the failure.
- L4 — “Inadequate engineering discipline” indirectly contributed to the failure.
- L5 — “The Government and the contractor must be clear on the mutual roles and responsibilities of all parties, including the level of reviews and what is required of each side and each participant in the Integrated Product Development Team.”
- L6 — “Faster, Better, Cheaper methods are inherently more risk prone and must have their risks actively managed.”
- L7 — “The Government has the responsibility to ensure that competent and independent reviews are performed by either the Government or the contractor or both.”
- L8 — “Cost and schedule pressure” indirectly contributed to the failure. “Price realism at the outset is essential and any mid-program change should be implemented with adequate adjustments in cost and schedule.”

From Boeing Mission Assurance Review, Final Briefing, Nov. 18, 1999:

- BMAR1 — “Strengthen Systems Engineering. ...Develop robust interface between systems engineering and development of hardware, software, and integrated testing.”

- BMAR2 — “Ensure engineering accountability from design through post-flight analysis. Design engineering presence, oversight, and approval of first-time issuances and subsequent changes... Assure adequate/formal communication exists between engineering and manufacturing...”
- BMAR3 — “Boeing should establish an internal Independent Mission Assurance Team; increase independent reviews at all levels throughout the life of the program...”
- BMAR4 — “Rethink opportunities for enhanced flight instrumentation. Review ... flight instrumentation to ensure adequate information to identify design unknowns and provide a quantitative basis for continuous improvement. Compare flight data to analytical predictions. Trend analysis for identification of ‘out of family’ performance...”
- BMAR5 — “Strengthen Boeing management of subcontractors and suppliers...”
- BMAR6 — “Configure ... strong reliability/quality culture which should result in lower costs, on-time delivery, and increased satisfaction for all customers... Simplify and supplement the design engineering and manufacturing processes into a zero-defects paradigm...”
- BMAR7 — “Invoke a more rigorous risk management process at all levels...”

From the “Faster, Better, Cheaper” Study (Briefing by Tony Spear):

- FBC1 — NASA must pick capable PMs. PMs should be “certified.”
- FBC2 — Scope of projects should match cost cap; PMs should “push back” when they don’t.
- FBC3 — Important to communicate project risks to project team, senior management, and to the public. PMs should project a “risk profile” or “risk signature” at start of project, monitor for changes over life of project and explain them.
- FBC4 — Peer reviews must include the “right” people.
- FBC5 — For a lander mission, it’s important to have telemetry on spacecraft descent.
- FBC6 — PMs must pick capable project teams. Certification of project team members should be considered.
- FBC7 — Important to have project “documentation set” for the benefit of future projects.
- FBC8 — Continuity from development team to testing team to operations team is beneficial.
- FBC9 — A higher level of mission assurance activity is important; e.g., “go/no-go” at project start, ensuring that good systems engineering is being done.
- FBC10 — There is a need for a technology development effort separate from, but feeding into projects.

**From the Solar Heliospheric Observatory (SOHO) Mission Interruption
Joint NASA/European Space Agency Investigation Board, Final Report,
Aug. 31, 1998:**

- SOHO1 — “Failure to perform risk analysis of a modified procedure set. ... Each change was considered separately, and there appears to have been little evaluation performed to determine whether any of the modifications had system reliability or contingency mode implications...”
- SOHO2 — “Failure to control change. ...The procedure modifications appear to have not been adequately controlled by the ATSC configuration control board, properly documented, nor reviewed and approved by ESA and/or NASA.”
- SOHO3 — “The verification process was accomplished using a NASA computer-based simulator. There was no code walk-through as well as no independent review either by ESA, MMS, or an entity directly involved in the change implementation. ... a recommended comprehensive review of the software and procedures had not been implemented due to higher priorities given to other tasks...”
- SOHO4 — “The functional content of an operational procedure...was modified without updating the procedure name and without communicating either to ESA or MMS the fact that there had been a functional change.”
- SOHO5 — “Failure to recognize risk caused by operations team overload.”

From Independent Assessment Team on Mission Success (Briefing by Roman Matherne):

- LMA1 — “Rigorously applying ‘Test Like You Fly.’ Identifying mission-critical events that cannot ‘Test Like You Fly.’”
- LMA2 — “Identifying single human failure events that could cause mission failure.”
- LMA3 — “Training programs emphasize: doing it right the first time; asking hard questions; eliminating uncertainty.”
- LMA4 — “Stopping processes is OK in the name of Mission Success.”
- LMA5 — “Communicating lessons learned. Communicating our mission success commitment to the workforce.”
- LMA6 — “Assess subcontractor capabilities and risk in meeting program requirements for mission success — flow down mission success requirements to subcontractors; motivate and incentivize subcontractors for mission success.”

From “Space Shuttle Independent Assessment Team, Report to Associate Administrator, Office of Space Flight,” October-December 1999 (Briefing by Dr. Henry McDonald):

- SIAT1 through SIAT10 — Details withheld until referenced report is released.