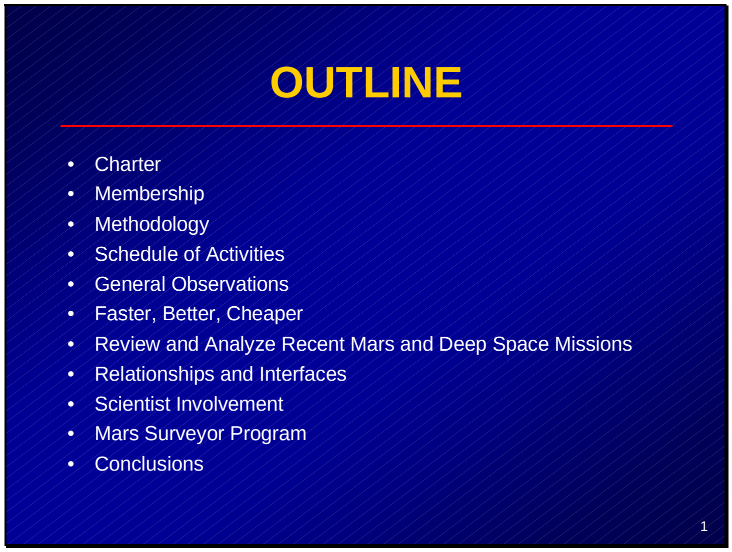


The Mars Program Independent Assessment Team (MPIAT) report follows this outline. There are three related reports produced under the direction of the MPIAT charter.

"Mars Program Independent Assessment Team Report" dated 3/14/00 (This Report)

"Mars Program Independent Assessment Team Summary Report" dated 3/14/00

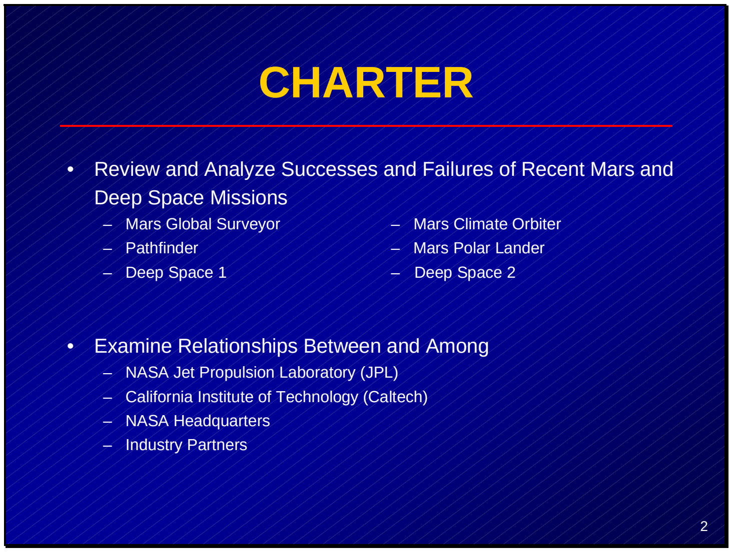
"Report on the Loss of the Mars Polar Lander and Deep Space 2 Missions" dated 3/22/00

Three additional relevant reports have been produced external to the MPIAT activities.

"Mars Climate Orbiter Mishap Investigation Board Phase I Report" dated 11/10/99

"Report on the Loss of the Mars Climate Orbiter Mission" dated 11/11/99

"Report on Project Management in NASA by the Mars Climate Orbiter Mishap Investigation Board" dated 3/13/00



The charter for the MPIAT was established by the NASA Administrator. This charter includes examination of the multiple facets of the Mars Program, with emphasis on the strengths and weaknesses in individual projects, the overall program, and relationships among participants. A critical aspect of the charter is to identify lessons learned for use by the future Mars Program.

CHARTER

- Assess Effectiveness of Involvement of Scientists
- Identify Lessons Learned From the Successes and Failures
- Review Revised Mars Surveyor Program to Assure Lessons Learned Are Utilized
- Oversee Mars Polar Lander and Deep Space 2 Failure Reviews
- Complete by March 15, 2000

Team membership is from a broad spectrum of organizations, including government, industry, and academia. Several engineering and science disciplines are represented as well as members with broad management experience in the aerospace community. Associations and biographies for the members appear at the end of this report.

Consultants were important contributors to the MPIAT activities. John Casani chaired the Mars Climate Orbiter, Mars Polar Lander, and Deep Space 2 failure reviews.

The team began work in early January 2000 with structured fact-finding reviews at the Jet Propulsion Laboratory (JPL) in Pasadena, California; Lockheed Martin Astronautics (LMA) in Denver, Colorado; and NASA Headquarters in Washington, D.C.

The structured sessions were followed by informal splinter sessions involving subsets of the team. These subsets met with representatives from a cross-section of managers and technical staff. The meetings focused on management and technical concerns raised in the structured reviews.

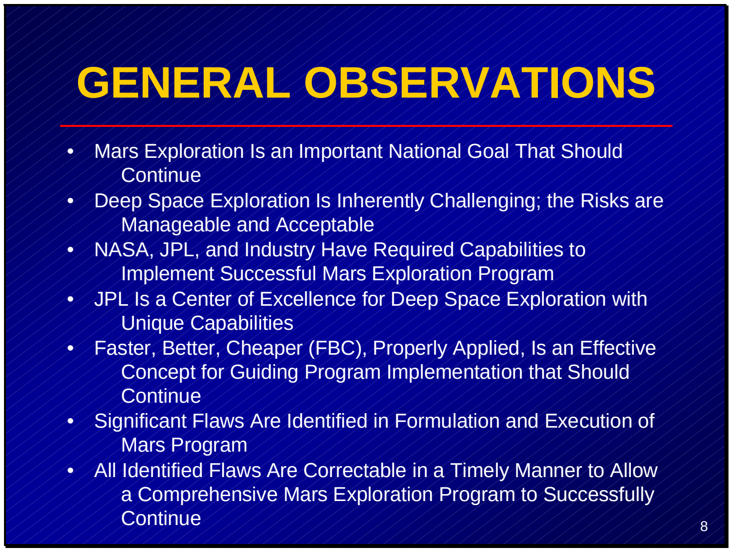
The informal sessions were complemented by executive sessions, involving the entire team with individual senior managers, technical personnel, and science leaders. Topics discussed included broad management and technical issues in the Mars Program.

The team met on a regular basis in discussions centering on its current understanding of the issues and identification of areas for further examination. Significant discussion and debate by the team resulted in this being an integrated report supported by all members.

SCHEDULE OF ACTIVITIES

DATE	LOCATION	ACTIVITY
Jan 7	NASA Headquarters	Kickoff Meeting
Jan 11, 12, 13	JPL	JPL Review
Jan 20, 21	LMA	Lockheed Martin Astronautics Review
Jan 25, 26	NASA Headquarters	NASA Headquarters Review
Feb 2, 3, 4	JPL	Follow-up JPL Review
Feb 8, 9	LMA	Follow-up Lockheed Martin Astronautics Review
Feb 16	NASA Headquarters	Process Status Report to NASA Administrator
Feb 22, 23, 24	NASA Headquarters	Report Preparation/Follow-up NASA Headquarters Review
Feb 29, March 1, 2, 3	NASA Headquarters	Report Preparation/Architecture Preview
March 13	NASA Headquarters	Report Review
March 14	NASA Headquarters	Final Report to NASA Administrator

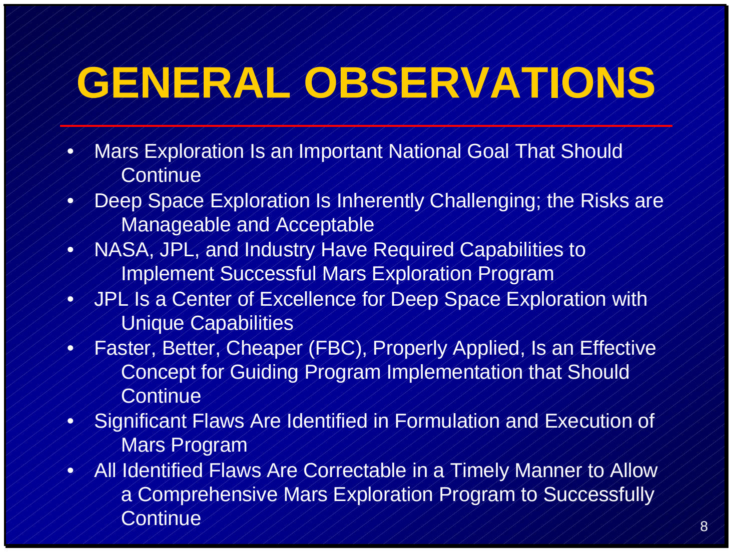
The team followed the schedule as outlined. Fact-finding trips were conducted between January 11, 2000, and February 9, 2000. The team spent the balance of the time on special topics and developing a common understanding of the issues and developing lessons learned.



Throughout history, people have pondered whether there is life beyond Earth. Now, the United States has the ability to pursue this question. Mars is the only planet feasible for human exploration in the near term. It is the only planet that appears viable to sustain a human presence. The Mars Pathfinder landing on July 4th, 1997, demonstrated extraordinary public interest in Mars, setting a record number of visits (over a half billion) to a Web site. The Mars Program Independent Assessment Team found no reason that the exploration of Mars should not continue.

The United States has enjoyed unprecedented and unmatched technological achievements in space over the last four decades. Nevertheless, pioneering exploration of the planets remains a challenging enterprise and is inherently risky. The distances are immense, the environment is hostile, the tolerance for error is small, the spacecraft resources are limited, and navigation of the heavens is demanding. While the challenges are high, the extraordinary deep space successes demonstrate that the risks are manageable and acceptable.

The significant successes of the deep space program illustrate that the United States has the required capabilities to implement a successful Mars Exploration Program. While the MPIAT found numerous instances in which this capability was not effectively applied, the team believes that observation to be correct.

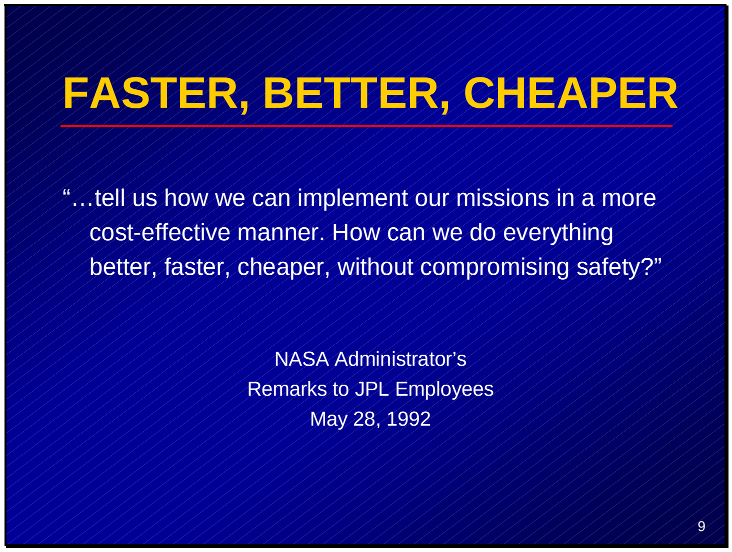


For more than four decades, the Nation has consistently invested in the NASA Jet Propulsion Laboratory. JPL is a vital national asset—a focal point for implementing deep space exploration with unique capabilities. The utilization of these capabilities has resulted in successful programs ranging from the Mariners to Galileo to Magellan to Pathfinder. The MPIAT found situations in which the JPL deep space expertise was not properly applied, resulting in significant problems, and areas in which it was effectively utilized thereby contributing significantly to mission success.

NASA has been applying a new way of doing business, Faster, Better, Cheaper (FBC), for much of the decade of the 1990s. FBC was reviewed extensively by the MPIAT and found to be an effective concept for guiding program implementation, if properly applied. The team believes that the FBC concept should continue to be the approach utilized in the future Mars Program.

Significant errors in the formulation and execution of the Mars Program were evident. This will be discussed in detail in this report, including the identification of appropriate lessons learned to be incorporated in the future program.

While the flaws are serious, the MPIAT believes they are correctable in a manner that will allow a comprehensive Mars Exploration Program to continue.



This quote was part of a speech given by Daniel S. Goldin to employees at JPL, approximately 2 months after he became NASA Administrator. In this speech, he challenged the employees of JPL to revolutionize future NASA space missions to provide the American people with a more cost-effective space science program. In this challenge, he also made it clear that this new, revolutionary program was not intended to compromise safety. In this context, safety relates to mission success.

Because the team could not find an established definition of FBC, the MPIAT developed the definition outlined on this and the following chart. The team used this definition in deriving findings and lessons learned.

The concept of smaller spacecraft and more frequent missions is intended to increase opportunities for scientist and public participation. It also distributes risk over a larger number of small missions as opposed to one large mission. The FBC strategy distributes the risk of achieving science objectives among more missions, minimizing the impact of a single mission failure. More frequent missions provide the opportunity to incorporate knowledge gathered (both science and engineering) into future missions in a more timely manner.

Faster does not mean arbitrarily reducing development and implementation time. It means reducing cycle time by eliminating inefficient or redundant processes. This must be done carefully to accomplish necessary tasks in the most efficient manner possible.

Utilization of new technology is integral to FBC success. FBC increases the ability to incorporate new technology into missions. New technology can be used to increase the scientific return of missions and/or reduce spacecraft size and overall mission cost. It is necessary that a new technology be adequately mature before it is incorporated in a flight program. Ideally, new technology (rover, virtual reality, etc.) can also serve to increase public interest in the program.

FBC implies taking prudent risks. Rather than using more limiting, flight-proven technologies, programs should incorporate new technologies that show promise of enabling new capabilities and increasing performance. With proper testing and validation, the benefits of technology infusion can be enormous. Likewise, the value of obtaining certain science data may justify additional risk for the mission. In all cases, risks should be evaluated and weighed against the expected return and acknowledged at all levels.

Over the decades, the space program has developed proven engineering and management practices, many of which are shown on the chart above and are applicable to FBC missions. This is not an exhaustive list but rather important examples. Clear lines of responsibility and authority should be established at the initiation of each project. Competent and efficient reviews of projects by experts from outside the projects and outside the implementing institutions should provide overall assessment of the projects and a thorough evaluation of risks. Membership on review panels should remain constant throughout the development and implementation of each project.

FBC is the right path for NASA's present and future. FBC has produced highly successful missions, such as Mars Pathfinder. More importantly, no other implementation philosophy can affordably accomplish NASA's ambitious future goals within a feasible budget and schedule.

However, NASA, JPL, and LMA have not completely made the transition to FBC. They have not documented the policies and procedures that make up their FBC approach; therefore, the process is not repeatable. Rather, project managers have their own and sometimes different interpretations. This can result in missing important steps and keeping lessons learned from others who could benefit from them.

The failure to effectively implement FBC has contributed to an unacceptably high failure rate in recent Mars missions. The team believes, that while 100 percent mission success is not a realistic target, with the right policies and procedures in place, and with a commitment to follow them, the vast majority of future FBC missions will be successful.

New technology is an essential part of FBC. The most positive example is Pathfinder. Of the missions studied, none of the failures was the result of new technology. Despite these findings, technology insertion has been too limited to date.

Like all major changes, converting to FBC is a serious leadership and management challenge. First, each participating institution must demonstrate leadership commitment to FBC through the Center Director or CEO and from a respected champion for FBC at the institution. Second, each institution must have a careful, disciplined plan for implementing the FBC approach across the institution and on each project.

The increased mission risk on FBC missions resulting from the use of new technology, innovation, or through the pursuit of important science objectives is acceptable when justified by the return. Increased risk is not acceptable when it is caused by inadequate design and review, incomplete testing, or mission goals that are unachievable within the allowed budget and schedule. Management must conscientiously and accurately assess, report, and manage risk throughout the course of a project.

Without new technology, the FBC approach can produce only incremental improvements. New technology, such as improved scientific instruments, solar-electric propulsion, autonomous navigation and fault diagnosis, automatic software synthesis and verification, aeroassist, and hazard avoidance during landing, can enable a new class of missions. New technology insertion should be encouraged on all FBC missions, and should be drawn from the best national sources.

REVIEW AND ANALYZE RECENT MARS AND DEEP SPACE MISSIONS

Mission	Successes	Failures
Mars Global Surveyor	x	
Pathfinder	x	
Deep Space 1	x	
Mars Climate Orbiter		x
Mars Polar Lander		x
Deep Space 2		x

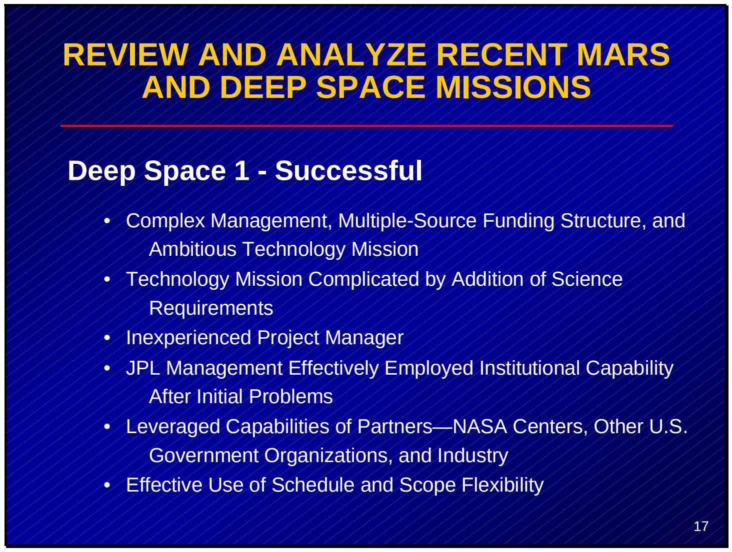
The team evaluated the six Mars and deep space projects listed on this chart. They represent JPL’s deep space FBC missions to date. The track record reflects several significant successes but also an unacceptably high failure rate.

Mars Global Surveyor represents a transition between a traditional project approach and FBC. The mission of MGS was to globally survey Mars and later to function as a communications satellite to relay information from other Mars spacecraft back to Earth. Despite a problem with the solar array damper arm that delayed the aerobraking phase of the mission, MGS is an enormously successful project with a high science return that has significantly changed the global understanding of Mars.

The mission was led by an experienced project manager. The project was undertaken with margins commensurate with the risk, and a stable requirements baseline was maintained. Other contributions to success included appropriate application of institutional expertise, a thorough test program, and continuity from the development to operations phases.

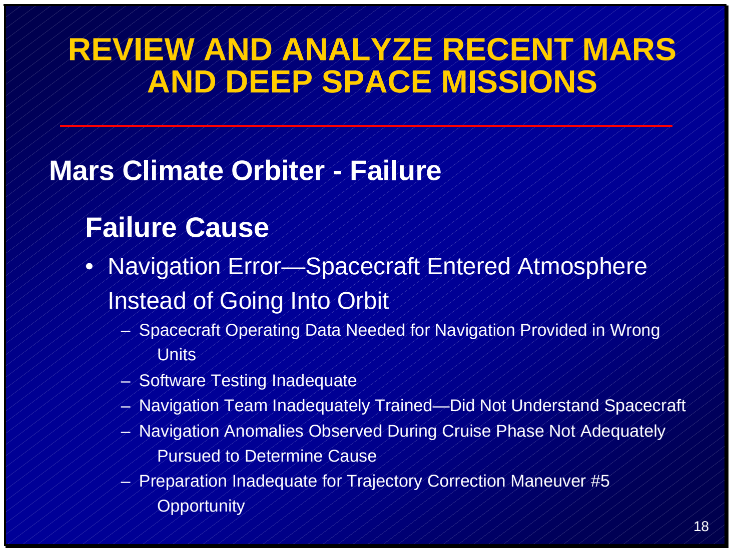
Pathfinder was the first truly representative implementation of FBC in the conduct of a Mars mission. It represents the most significant success to date in implementing the FBC concept for Mars missions and has set the standard for future FBC deep space missions. The mission was primarily driven by technology objectives while accomplishing limited but exciting Mars science results.

Attributes of Pathfinder success include adequate margins, an experienced project manager coupled with a capable but inexperienced staff, sensible application of innovative technology and processes, and the judicious use of institutional expertise at JPL, NASA Langley, NASA Ames, Sandia, and LMA. Pathfinder was also an unprecedented public relations success because of the real-time release of surface images, the public's fascination with the Sojourner rover on the Martian surface, and the public's feeling of participation while watching the exciting and dynamic personalities involved in the challenging exploration of Mars.



Deep Space 1 pushed the envelope as it successfully demonstrated 12 new technologies. Among these are ion propulsion, autonomous operations, and onboard optical navigation.

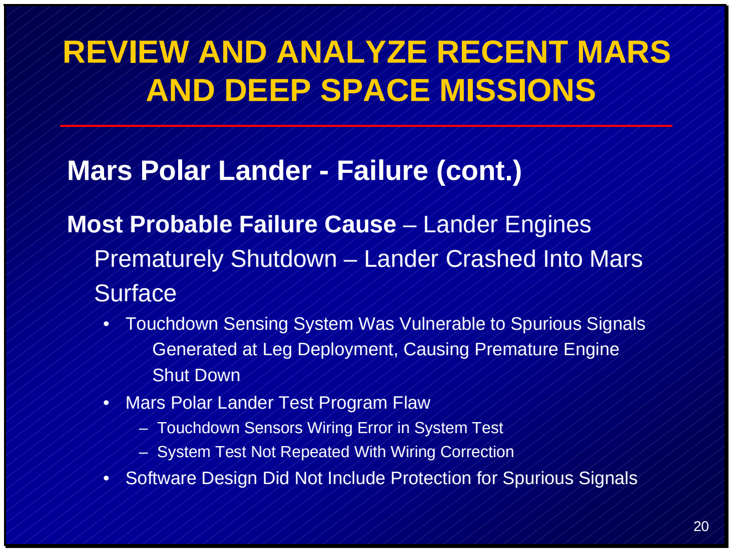
After an initially difficult development with many problems, effective application of institutional capability created a highly successful mission. Issues arising from competent but inexperienced project management and too much emphasis on science goals were mitigated by the effective involvement of technology partners and institutional expertise. Perhaps even more importantly, the mission could and did maximize the use of schedule and scope flexibility. The schedule was delayed several months, and the requirements were appropriately descoped. As will be discussed subsequently, a planetary mission typically does not have this flexibility, making adequate margins so critically important.



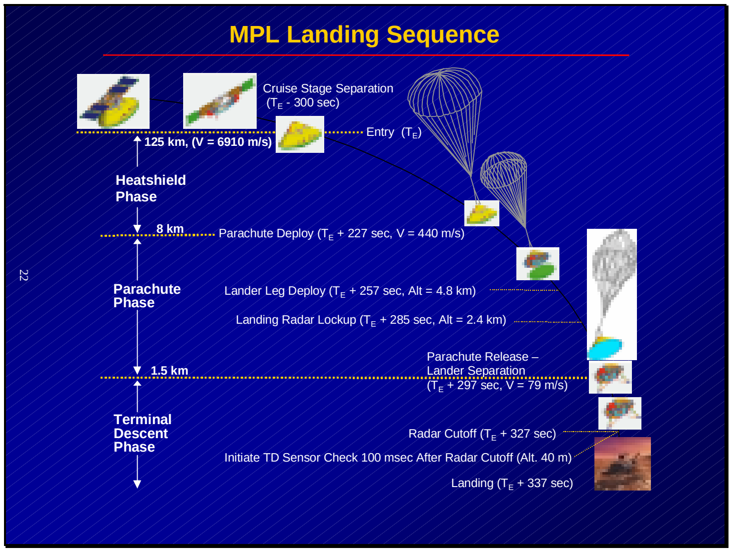
MCO was lost as a result of a navigation error that went unresolved. It caused the spacecraft to enter the atmosphere of Mars, rather than achieve orbit. Spacecraft operating data needed for navigation were provided to the navigation team by prime contractor Lockheed Martin in English units rather than the specified metric units.

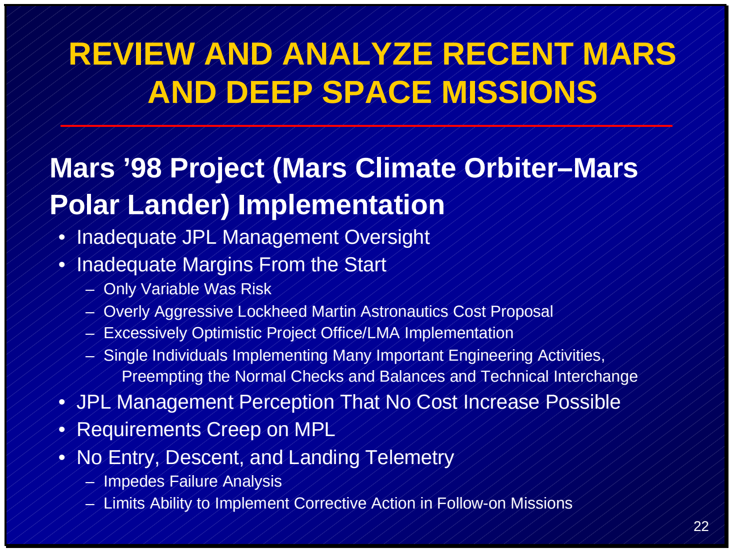
In developing complex space systems, errors are inevitable. Consequently, it is essential that development and operational processes be resilient enough to detect and correct errors when they occur. This is accomplished by a system of checks and balances built into the processes and by a discipline that follows established engineering practices. In the Mars Climate Orbiter mission, the system of checks and balances failed, allowing a single error to result in a mission failure. Multiple failures in system checks and balances included lack of training, software testing, communication, and adherence to anomaly reporting procedures, as well as inadequate preparation for contingencies. All of these contributed to the failure.

MPL was the companion mission developed concurrently with the Mars Climate Orbiter as the Mars ’98 project. The design of MPL did not include telemetry to provide entry, descent, and landing data. This was a major mistake that prevented an analysis of MPL performance and eliminated the ability to reflect knowledge gained from MPL in future missions. Given the absence of flight data, MPL failure analysis focused on reviews, analyses, and tests. The result was the identification of numerous possible failure modes. Several of the likely candidates are given in this chart, with the most probable scenario on the next page.

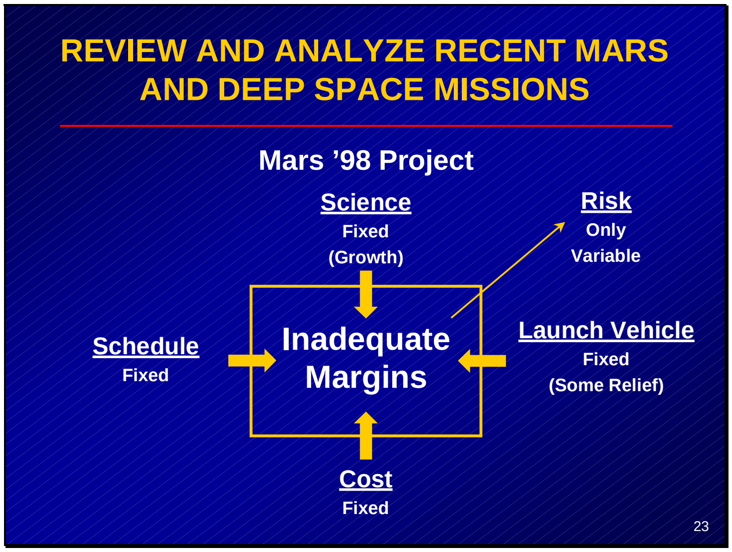


The most probable cause of the MPL failure is premature shutdown of the lander engines due to spurious signals generated at lander leg deployment during descent. The spurious signals would be a false indication that the lander had landed, resulting in premature shutdown of the lander engines. This would result in the lander being destroyed when it crashed into the Mars surface. In the absence of flight data, there is no way to know whether the lander successfully reached the terminal descent propulsion phase of the mission. If it did, extensive tests have shown that it would almost certainly have been lost due to premature engine shutdown. The following chart provides a pictorial of the MPL entry and landing sequence. Lander leg deployment is at Entry +257 seconds. Initial sensor interrogation is at an altitude of 40 meters. It is at this point that the spurious signals would have prematurely shut down the lander engines. As with MCO, the most probable failure of the Mars Polar Lander resulted from inadequate checks and balances that permitted an incomplete systems test and allowed a significant software design flaw to go undetected.

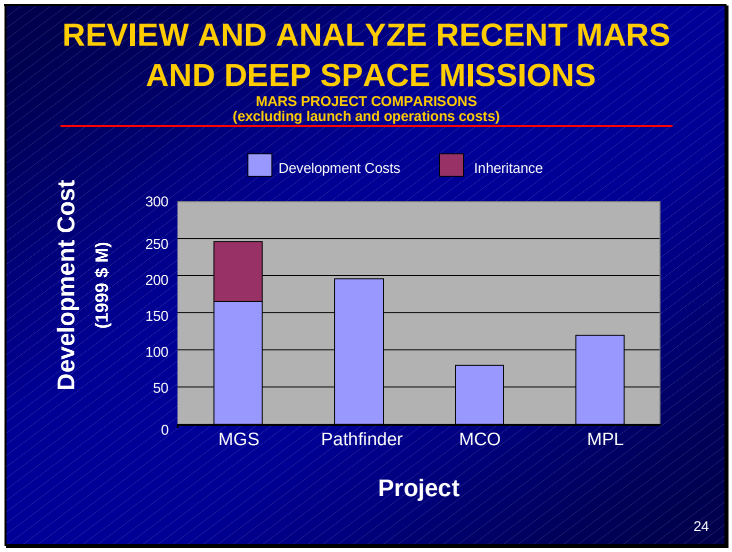

MPL Landing Sequence
Cruise Stage Separation
(T_E - 300 sec)
Entry (T_E)
125 km, (V = 6910 m/s)
Heatshield Phase
8 km
Parachute Deploy (T_E + 227 sec, V = 440 m/s)
Parachute Phase
Lander Leg Deploy (T_E + 257 sec, Alt = 4.8 km)
Landing Radar Lockup (T_E + 285 sec, Alt = 2.4 km)
Parachute Release –
Lander Separation
(T_E + 297 sec, V = 79 m/s)
1.5 km
Terminal Descent Phase
Radar Cutoff (T_E + 327 sec)
Initiate TD Sensor Check 100 msec After Radar Cutoff (Alt. 40 m)
Landing (T_E + 337 sec)



Mars ’98 had inadequate resources to accomplish the requirements. Through a combination of perceived NASA Headquarters mandates and concern for loss of business, JPL and LMA committed to overly challenging programmatic goals. The JPL management perception was that no cost increase was permissible and the aggressive pricing strategy adopted by LMA exacerbated the problem. The pressure of meeting the cost and schedule goals resulted in an environment of increasing risk in which too many corners were cut in applying proven engineering practices and the checks and balances required for mission success. Examples include incomplete systems testing, lack of critical event telemetry, and requirements creep. JPL and LMA also failed to ensure adequate independent reviews and adherence to established policies and practices.



This diagram illustrates the overly constrained situation that characterized the Mars ’98 project. Schedule, cost, science requirements, and launch vehicle were established constraints and margins were inadequate. The only remaining variable was risk. Accordingly, project management was faced with managing excessive risk. Lack of adequate risk identification, communication, management, and mitigation compromised mission success.



This diagram illustrates the striking contrast in cost between successful and unsuccessful FBC Mars projects. Mars Global Surveyor benefited from significant hardware spares and software inheritance from Mars Observer. Pathfinder was successful in part because of adequate margins. Pathfinder sets the standard for an FBC mission. In effect, the Mars ’98 project attempted to deliver two spacecraft for the price of a Pathfinder. If efficiencies from shared development and operations are factored in, it appears that the Mars ’98 project was underfunded by at least 30 percent.

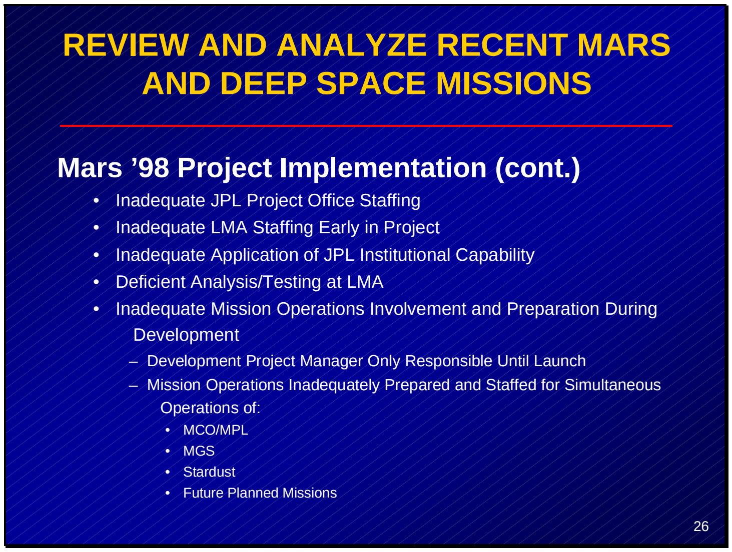
REVIEW AND ANALYZE RECENT MARS AND DEEP SPACE MISSIONS

Pathfinder–Mars ’98 Development Cost Comparison

(1999 $ M)

Element	**Pathfinder**	**Mars ’98 (MCO & MPL)**
Project Management	11	5
Mission Engineering and Operations Development	10	6
Flight System	134	133
Science and Instrument Development	14	37
Rover	25	
Other	2	7
Total	196	188

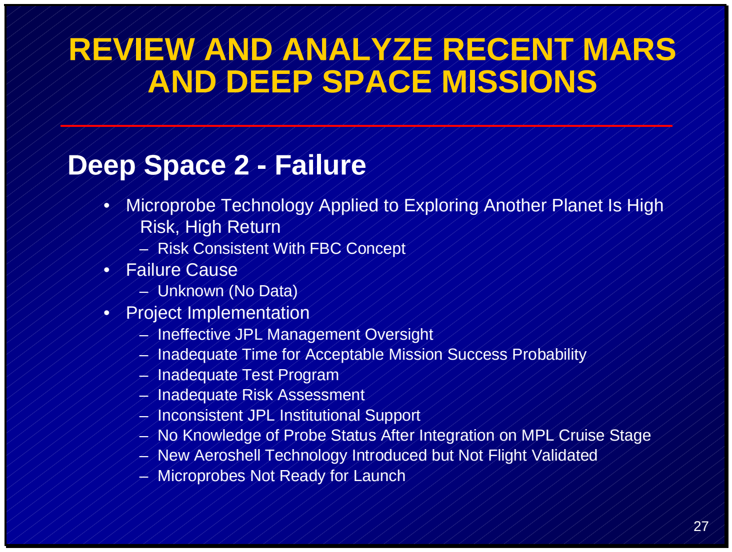
This comparison breaks down the aggressive cost goal for the Mars ’98 project. Project management and mission engineering and operations costs on Mars ’98 were approximately half of that for Pathfinder. In addition, flight system costs were equivalent in the two programs. This is striking, given the fact that the Mars ’98 project was delivering both an orbiter and a lander as well as three times the amount of science.



Inadequate project staffing and application of institutional capability by JPL contributed to reduced mission assurance. Pressure from an already aggressive schedule was increased by LMA not meeting staffing objectives early in the project. This schedule pressure led to inadequate analysis and testing.

The desire to reduce cost led to the decision by JPL to create a multimission operations project separate from the flight project. The result was to bypass the traditional cradle-to-grave responsibility of the project manager in most projects. This led to a discontinuity of expertise in the development and operations handover, characterized by a lack of understanding of navigation and operations issues by the development team and a lack of understanding of the spacecraft by the operations team.

Another important factor was that the operations team was managing four spacecraft (MGS, MCO, MPL, and Stardust) simultaneously with limited resources. Additionally, unplanned effort was required to respond to aerobraking delays due to the damaged solar panel on MGS.



Deep Space 2 was designed as a high-risk project to demonstrate a new capability for landing on Mars and other solid bodies of the solar system. This capability could ultimately result in high scientific return when used in future applications. The new technology could deliver a network of small payloads to the surface of Mars. Although the failure mechanism is unknown because there was no post-launch telemetry, the mission likely failed as a result of deviation from fundamental management and engineering principles. The inadequacies listed above indicate that the microprobes were not ready for launch.

The dominant Mars '98 problem was inadequate funding to accomplish the established requirements. The Mars '98 project was in the FBC category, and the project management team was given insufficient guidance as to proper implementation of FBC. It is important in such a situation that institutional management closely monitors project implementation.

The challenges associated with deep space exploration drive the need for innovation and critical evaluation of conventional approaches to project implementation. At the same time, certain fundamental engineering and management principles must be maintained: involvement of experienced project management, adequate margins, stable requirements, and adherence to sound engineering principles. This combination of inadequate management oversight and violations of fundamental engineering and management principles became the underlying contributor to mission failure.

Commitment, while important, must not overshadow an objective assessment and reporting of risk. This requires responsible intervention by senior management.

An additional important role for senior management, whether at NASA, JPL, or LMA, is to ensure the establishment of, and compliance with, policies that will assure mission success. For example, these policies should address design (at the component, system, and mission life cycle level), test and verification, operations, risk management, and independent reviews.

The technical expertise required for deep space exploration is a national resource. Successful missions must draw upon the top talent for the task regardless of organizational boundaries. Equally important to mission success is a thorough test and verification program.

Each involved organization should establish a policy requiring telemetry coverage of mission-critical events.

Development and operations are tightly coupled in complex projects. It is critical that engineering expertise be included in operations and operational insight in design. This is best achieved by assigning the project manager cradle-to-grave responsibilities.

New technology can represent significant risk in science-driven missions. Separate technology demonstration missions can play a significant role in validating new enabling technologies. If technology is the primary objective of a specific mission, science objectives should not conflict with or compromise the achievement of technology objectives.

While risk is a fact of life in deep space missions, it is important to clearly understand what risks are appropriate and what risks are reckless. Accepting higher risks to achieve high return is appropriate. Accepting risk that deviates from sound engineering and management principles is never prudent.

In the final analysis, mission readiness must take priority over launch window.