# ASSESSING NASA STRATEGIC PROJECT LEADERSHIP IN AN ERA OF "BETTER, FASTER, CHEAPER"

by

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# ABSTRACT

Assessing NASA Strategic Project Leadership in an Era of “Better, Faster, Cheaper”

The purpose of this study was to develop a better understanding of the management of strategic system projects (and programs) at NASA and, in particular, what makes such projects successful or not in an era of “better, faster, cheaper” (BFC). Such projects are typically characterized by advanced technology, new types of missions, complex integration of hardware and software systems, and inflexible time frames that are often dictated by “launch windows.” To analyze strategic projects, this investigation used the framework of *Strategic Project Leadership®* (SPL)[1] correlated to the success of a systems development project through case study research. Four NASA projects were investigated that were managed as BFC projects. Two of them were successes (Mars Pathfinder and Lunar Prospector), and two failures (CONTOUR and Mars Climate Orbiter). The objectives were to (1) develop a better conceptual understanding of strategic system innovation through the study of BFC projects, (2) understand how SPL can describe BFC projects, and (3) provide feedback, recommendations, and lessons learned to NASA and the aerospace industry on potential success criteria for BFC projects. Of particular interest in this study was the analysis of fit between project type and the appropriate project management style. This research found that there was a good fit between project type and project management style in the two successful projects while in the unsuccessful projects this fit was apparently missing. It seems there is a need to develop a specific NASA framework to assess a project’s risk and its appropriate project management style.

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## DEDICATION

To my father, for 35 years of dedication and commitment to the United States space program, and believing I would one day get my Ph.D., even when I did not.

To my mother, for always being proud of me, only as a mother can.

To my beautiful wife Meg, she never lost faith in my commitment, never questioned my purpose, and always gave me the love and support that only comes from unconditional love.

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I would also like to acknowledge my graduate committee. Each brought a unique and exemplary perspective to project management and the study of complex systems. Without their guidance this would never have been possible.

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## 1. INTRODUCTION

Both “project” and “project management” can be defined in very basic terms (Meredith and Mantel, 1995; PMI, 2004). What are traditionally not well defined are the complex activity of a project and how this activity is managed. Although there are texts and guidebooks written on project management that give standard definitions, theories, processes, and strategies to apply to projects in general, some have theorized that projects carry a complexity all their own and that no single management style can fit all projects (Amara, 1990; Shenhar, 1998b; Shenhar, 2001a). The complexity of a project alone alters the management style and strategy of a project. Therefore, it should become clear that no one approach can solve the problems of project management, and thus no one strategy is best for any one project (Drejer, 1996). Various strategies for project management are prevalent throughout the literature (O’Brien and Smith, 1997; Husain and Sushil, 1997). Though the project management strategies for building the Space Shuttle or designing a calculator can be effective and efficient, both are very different.

Theories and processes for managing projects with a more effective and efficient approach are not new to project management (e.g. *Management by Objectives* [Druker, 1998], *Total Quality Management* [Berk and Berk, 1993], *Theory of Constraint* [Goldratt, 1997], *The Fifth Discipline* [Senge, et al., 1994]). Likewise, management strategies for a better, faster, cheaper or leaner project are not new to the field of project management. This type of management has been characterized by many other management classifications: Skunk Works (Johnson, 1990; Peters, 1983; Boomer, et al., 2000), Innovation Management, High-Velocity Leadership (Muirhead and Simon, 1999), Lean Thinking (Womak and Jones, 1996), or Blitz Projects (Shenhar, 1998a) to name a few. Common to each of these management strategies are characteristics such as empowerment, sense of mission, communication, customer involvement, breaking the rules, encouraging innovation, autonomy, and management involvement. But, as previously mentioned, not all projects are the same, so how can projects be characterized, classified, and distinguished and how should their management adapt to their specific attributes? This work is devoted to these questions.

## 2. BACKGROUND

Historically in the aerospace industry, projects have been difficult, large ventures that inevitably carried high costs. What resulted were expensive products, long development processes, complex management, the need for larger rockets, cost overruns that lengthened missions, and some troublesome failures (Kerr, 1994). Therefore, there have been concerted efforts within industry and government to try and understand the development of these large systems projects.

In 1991, Robert Bless stated in his article "Space Science: What's Wrong at NASA" that the three areas that left NASA's scientific programs less effective and more costly were an over reliance on the Space Shuttle, a propensity for big projects, and poor management. The increasing trend of launch delays and spacecraft redesigns that sprouted from the Space Shuttle Challenger accident resulted in larger and less frequent missions. What resulted was what Greg Davidson (1993) described in his article "Our National Space Science Program: Strategies to Maximize Science Return" as big versus small missions, multiple simple spacecraft versus servicing, a culture of risk avoidance, unrealistic budget planning, institutional and political forces, and linkage to the manned space program.

In 1992 a new initiative to address some of these issues was established at Massachusetts Institute of Technology (MIT) called the Lean Aerospace Initiative (LAI). LAI originated from developments by the Japanese automotive industry and the International Motor Vehicle Program's (IMVP) effort to minimize waste and be responsive to change while focusing on value and flexibility (Murman, et al., 2000). LAI was started through a consortium of leaders in the U.S. Air Force, MIT, labor unions, and defense businesses as a way of "significantly reducing the cost and cycle time for military aerospace products throughout the entire value chain while continuing to improve product performance" (Nightingale, 1998). LAI's mission is "to enable fundamental change within industry and government operations that supports the continuing transformation of the US aerospace enterprise towards providing aerospace systems offering best life-cycle value" (Lean Aerospace Initiative, 1999). The LAI effort of MIT has not been limited to the United States. LAI has cooperative agreements with the LAI of the UK and the Lean Aircraft Research Programme at the University of Linköping in Sweden.

Prior to the efforts of LAI, NASA was struggling with its own issues on how to manage its high-tech programs and projects as a result of the tragic loss of the Space Shuttle Challenger January 28, 1986. In compliance with Executive Order 12546 of February 3, 1986, NASA issued the *Report of the Presidential Commission on the Space Shuttle Challenger Accident* (Rogers, 1986). In this report, the Rogers Commission identified managerial deficiencies at NASA in management structure, key personnel in management, safety, critical reviews, and communication. This report exposed many managerial issues within NASA and prompted change throughout the agency. Some research suggests that the events leading up to the accident could have been the result of incorrect project management style (Shenhar, 1992).

The concerns of program and project management within NASA were not first realized with the Space Shuttle Program. In the late 1980's the government also began to identify some of these issues. The philosophy of "better, faster, cheaper" (BFC) was being fostered by the Reagan-Bush Administration under the nourishment and cultivation of the National Space Council (which no longer exists) as a way of reinventing the government and NASA. In March 1992, when Daniel S. Goldin became the NASA administrator, NASA pushed, with the support of the Clinton Administration, for the adoption of "better, faster, cheaper" as the motto for a new and improved NASA. On April 3, 1998, NASA issued a NASA Procedures and Guidelines document, *Program and Project Management Processes and Requirements* (NPG 7120.5A), that described and defined NASA program/project management. Although NPG 7120.5A defined NASA program/project management procedures and guidelines, it left a very open interpretation of exactly how NASA BFC management practices should be performed. In November 1996, a special study group from the NASA Advanced Project Management training program (NASA APM-23) attempted to provide guidance to BFC projects within the framework of NPG 7120.5A (NASA APM-23, 1996). What resulted was a report entitled *Fast Track Study*. This study brought changes to the development of NPG 7120.5A and how NPG 7120.5A applied to large projects with long life cycles.

In March 2000, NASA again attempted to define BFC when it formed the NASA Integrated Action Team (NIAT) to assess and develop recommendations for NASA programs and projects, as a result of the *Mars Climate Orbiter Mishap Investigation* (Stephenson, 2000), *Mars Program Independent Assessment* (Young, 2000), *NASA Faster, Better, Cheaper Task* (Spear, 2000), and *Shuttle Independent Assessment* (McDonald, 2000). This resulted in NIAT's report, *Enhancing Mission Success – Framework for the Future* (Griner and Keegan, 2000). As a result of the NIAT's recommendations, NASA revised NPG 7120.5A to produce NPD 7120.5B.

More recently, the tragic loss of the Space Shuttle Columbia has forced NASA to take an even deeper look at how programs and projects are managed. In August 2003, one of the most extensive and comprehensive investigative reports ever preformed by NASA was released: the *Columbia Accident Investigation Board Report, Volume 1* (CAIB Report). The CAIB Report detailed many of the organizational problems that existed not only within the Space Shuttle Program but within NASA, and chronicled some of these problems back to the Challenger accident. The CAIB Report cited organizational issues associated with communication, culture, reliance on past success, redundancy, training, lesson learned, structure, decision making, internal and independent reviews, and safety. NASA again is responding to this investigation with a planned release of revision C of NPD 7120.5.

These philosophies of managing high-tech projects have resulted in significant successes and costly failures. Although, companies are still demanding fast-paced, high-quality, low-cost products, and "doing more with less, faster" has become an engrained philosophy (Boomer, et.al., 2000). The challenge is how a project can achieve innovation when developing systems under these kinds of constraints. In a time of faster product development in less time, little has been learned or documented on how these concepts can apply to the development of innovative systems. In Leonard David's article (1995) "Better, faster, cheaper: Sloganeering or good engineering?," he states that, "In the 1990's faster, better, cheaper has become almost a mantra among top NASA, industry, and Pentagon officials, as well as project managers, space engineers, and university scientists." His article asks what is "better, faster, cheaper" engineering and the philosophy that surrounds it; can projects be managed faster, better, and cheaper; and what kind of strategic project leadership is needed to support such a philosophy? Despite the efforts of LAI, BFC, and the Space Shuttle accident responses, Murman, et al. (2000) state that it is still relatively early in the lean era and there are still many methods and tools to develop for improving the design, engineering, and manufacturing phases of aerospace products. With the challenges of innovating in the face of "better, faster, cheaper," the Space Shuttle accidents, and "lean aerospace," project management still has much to learn to effectively manage these types of projects.

## 3. RESEARCH OBJECTIVES

Classical distinctions in innovation state that there are three fundamental innovations: incremental, radical, and systems. Of these, incremental innovation has been studied the most, while systems innovation has been defined, but hardly studied. Systems innovation is a change in technology with a specific process that is generational, unpredictable, and variable in space and time, and a product that is a complex collection of interactive elements, subsystems, and systems that function together to achieve a common purpose. The purpose of this study was to develop a better understanding of the management of strategic system projects (and programs) at NASA, and in particular, what makes such projects successful or not in an era of "better, faster, cheaper." This investigation looked at how the theories of Strategic Project Leadership (SPL) could define the factors of success or failure of a systems innovation project (Shenhar, 2000). To accomplish this, case study research evaluated the theories of SPL and how they applied to BFC projects, a type of systems innovation. The objectives were to (1) develop a better conceptual understanding of strategic system innovation through the study of BFC projects, (2) understand how SPL can describe BFC projects, and (3) provide feedback, recommendations and lessons learned to NASA and the aerospace industry on potential success criteria for BFC projects.

## 4. THEORETICAL BACKGROUND

### 4.1 Systems Theory

At some level, all projects can be described as a system by the interconnection of their components (budgets, schedules, teams, managers, customers, etc.), but how these components come together and work as a system while achieving innovation is not always understood. First, we need to establish a basic understanding of what a system is, the primary unit of analysis of this investigation, to even begin to understand systems and how they are managed. A system is two or more subordinate entities that interact in some fashion to accomplish a process that transforms a set of predetermined inputs into a set of desired outputs, in time achieving a predetermined goal (Leach, 2000; Grandy, 2000). By this very definition, one can understand through deductive reasoning that the optimum for any one component of a system is not the optimum for the system.

Because this investigation examined systems projects and how they are managed, it was fundamental to use General Systems Theory (GST) as the foundation for the theoretical development; therefore, a fundamental understanding of GST is imperative to set the groundwork for the theoretical development. GST was proposed by Ludwig *von* Bertalanffy in the 1940s and published in his book *General Systems Theory* in 1968. GST is the transdisciplinary study of the abstract organization of phenomena, independent of their substance, type, or spatial or temporal scale of existence, while in a continual attempt to develop integrated phenomena of study in any of a number of different disciplines (Ruben and Kim, 1975). GST is based on eight fundamental concepts that underlie all systems and provide a basis for unification: (1) system-environment boundary, (2) input, (3) output, (4) process, (5) state, (6) hierarchy, (7) goal-directedness, and (8) information (von Bertalanffy, 1968).

These eight fundamental concepts are linked by four basic assumptions:

1. The sum is greater than the parts and there are consequences for not understanding the dynamics of each part.
2. There is multilateral causality among subsystems, systems, and the environments they function in.
3. One set of initial conditions can give rise to different final states.
4. There is concern with the flow of information between subsystems (components) (Ruben and Kim, 1975).

Ashby's development of GST states that a system has a self-organizing process where the organization of a system spontaneously increases with a decrease in statistical entropy and an increase in redundancy, information, and constraints (Ashby, 1956). Later in 1956, in *Introduction to Cybernetics*, Ashby explained that most systems are in a state of disequilibria and, as the systems progress, they make selections that will bring them closer to equilibrium. This is what some have called "organized complexity." GST asserts that a system begins in a condition of uncertainty and complexity and moves to a more certain state over time as conditions progress. The evolution of GST from von Bertalanffy in the 1940s has seen the fundamental concepts of GST applied to many areas and brought about new disciplines and phenomena: systems engineering, systems design, systems analysis, systems approach, cybernetics, and systems science to name a few (Brill, 1998). Because the theory of systems is still evolving, there is still not widespread use of GST within industry (Shell, 2001). Even though GST has evolved from the 1940s and has developed more rapidly in the last 10 years, it is not truly defined in project management of systems projects. The most complex projects that have been or will be developed are of systems to solve complex engineering problems. More recently Shenhar (2001a) defined systems based on a hierarchy of system scope: assemble, system, or array. System scope is defined by the way a project is organized, its scope, and the interconnection between project elements. This investigation used Shenhar's hierarchy to define systems development.

### 4.2 Systems Engineering

The attempt to understand the lifecycle of modern systems has been through the engineering of systems or systems engineering. Systems engineering (SE) is "the management technology that controls a total lifecycle process, which involves and which results in the definition, development, and deployment of a system that is of high quality, trustworthy, and cost effective in meeting user needs" (Sage, 1995; Sage and Rouse, 1999a). SE provides a process by which the organization, application, and delivery of systems can be managed, also called systems engineering management (Shenhar, 1999a). A key success driver in SE is the process by which the integration of people, processes, problem-solving mechanisms, and information come together, commonly called concurrent engineering (Kusiak and Larson, 1999). SE was first termed in the 1940s by Bell Laboratories and has been defined and documented ever since by various institutions in a multitude of documents. In 1962 Arthur Hall theorized three fundamental elements of SE: (1) SE is multifaceted; (2) SE has three distinct divisions: (a) the physical or technical, (b) the business or economic, and (c) the social; and (3) SE considers the needs of its customers and determines how the needs can best be met in light of all knowledge, both old and new (Hall, 1962). Historically, principles of SE have largely been utilized and developed in the government with projects such as manned space flight, nuclear-powered submarines, communications satellites, launch vehicles, aircraft, and deep-space probes. It is projects such as these in the aerospace/defense industry that carry characteristics like high complexity of the system with high technological risk, extreme design constraints, desire for complete answers, and auditability (Parth, 1998). Even within SE there are different types of projects that can be characterized by various management styles and practices. One of these characterizations is Large Systems Projects (LSP).

### 4.3 Large Systems Projects

LSPs carry a high level of complexity, uncertainty, and reliance on an understanding of the fundamental concepts of systems and can begin to define BFC projects. LSPs consist of customized, interconnected subsystems, carry high cost, are designed for one customer, are produced in low volume, require broad and deep knowledge and skills, engage multiple collaborators, involve the customer and suppliers throughout the life cycle, and have strong political considerations (Floricel and Miller, 2001; Miller and Lessard, 2000). LSPs tend to have life cycles that stay in the fluid phase of product innovation (Davies and Brady, 1998). Examples of LSPs are the Space Shuttle, the B-2 “Stealth” Bomber, the NY/NJ Mass Transit System, and the Hubble Space Telescope.

To understand LSPs we can distinguish them by some of the following characteristics (Hobday, et al., 2000; Miller and Lessard, 2000; Nightingale, 1998; Shenhar, 1998b):

- Consist of customized, interconnected elements with subsystems that are complex and customized and that carry high costs.
- Develop financial difficulties.
- Exhibit emergent properties during production.
- Allow for a high degree of direct-user involvement.
- Experience frequent requirement changes during the life cycle.
- Involve a prime contractor, systems integrators, technical personnel, and administrative staff.

- Products are never mass produced.
- Carry high levels of uncertainty.
- Can extend over decades.
- Lead to innovation long after the delivery of the product.
- Require a wide range of activities and functions to address an operational need.
- Require implementation of training, test equipment, maintenance equipment, logistic support, spares parts, and great deal of documentation.
- Tend to be regulated and bureaucratic with strong political considerations.
- Develop environmental concerns.

The literature has identified numerous difficulties associated with the development of LSPs (Sage and Rouse, 1999c; Hansen and Rush, 1998):

- Difficult to identify and capture user requirements.
- Expensive.
- Capabilities are often less then promised and expected.
- Deliveries are often late.
- Cost overruns often occur.
- Documentation is inappropriate and inadequate.
- Maintenance is complex and error prone.
- Unanticipated risks and hazards.
- May be no provision for risk management.
- Suffer in terms of reliability, maintainability, and availability.
- Often do not perform according to specifications.
- Difficult to identify suitable performance metrics that enable determination of system cost and effectiveness.
- Poor communication among program management, designers, and customers or program sponsors.
- Specifications do not always capture user needs and requirements.

- Technical uncertainty and difficulties.
- Dependence upon suppliers and difficulties with procurement systems.

The knowledge base of LSPs is limited in the area of systems innovation and only recently has this area been largely recognized and investigated. There is limited theory on how LSPs develop and are managed. This has become even more important as there has been increasing attention on LSPs in the economic activities of firms, industries, and nations (Hansen and Rush, 1998). Innovation in LSPs differs notably from smaller, mass-produced projects and thus requires different management techniques (Hobday, 1998). "Many of the current problems in the delivery of acceptable (or even usable) large, complex, systems solutions result from a failure to apply a rigorous systems-science approach" (Shell, 2001). Hobday, Rush, and Tidd (2000) state conventional innovation wisdom is derived from research on high volume consumer products; new evidence, models, and concepts are needed to properly understand the innovation process in complex products and systems. Even in 1987, Morris and Hough stated that "the application of conventional systems development for ordinary projects have been found to be inappropriate for complex projects." There is still much advancement that must occur before we have an adequate understanding of systems innovation (Amara, 1990).

### 4.4 Contingency Theory – Different Project Characteristics

Contingency theory states that an organization's effectiveness is dependant upon its ability to adjust or adapt to environmental uncertainty (external conditions). As uncertainty in environmental conditions increases, the need for integration or congruency among variables increases. As environmental uncertainties increase, a project must begin to function more as a system (Darzin and van de Ven, 1985; Souder, et al. 1998).

Shenhar (2001a) theorizes that projects carry a level of uncertainty which increases with a level of technological uncertainty, or as this investigation is proposing, moving toward a higher degree of systems innovation. Fundamental to this investigation is that BFC projects carry a greater level of uncertainty than most projects. In organizations, events, situations, or technology can be described with a level of certainty or uncertainty. Certainty can be planned for (routine), structurally managed (bureaucracy), and predicted. Uncertainty means that people have to adjust and be flexible to unpredictable occurrences. Uncertainty is more common than certainty, and it is nonlinear (Eisenhardt and Brown, 1998). The field of project management has only recently recognized that managing uncertainty is critical to project success. Even the Project Management Body Of Knowledge (PMBOK) did not recognize risk management until 1986. Others, like Laufer (1998), have described projects by managing the uncertainty. Senge's *Fifth Discipline*, states that "to change the behavior of a system, you must identify and change the limiting factor"—the uncertainty (Senge, 1994). The failure of all project systems can be linked to a failure to manage uncertainty (Leach, 2000).

Pender (2001) states that traditional project management is based on probability theory, which assumes there is knowledge of probable future states, rationality, frictionless transactions, random events, repeatability, comparability, and goal optimization. Accepting uncertainty as part of a project is to accept a nontraditional paradigm that is more representative of reality or the natural state of things. Discrete random events can be predicted and planned (e.g. the flip of a coin), while human actions tend not to be random. Uncertainty is risk with variability in future events, and risk is the ability to predict the future based on incomplete information with a level of chance (Knight, 1921). Therefore, the fundamental difference in risk and uncertainty is knowledge of the past and an ability to define the future. This investigation will distinguish between risk and uncertainty where risk is defined as factors that can be described by statistical terms and uncertainty as factors where potential outcomes and casual forces are not fully understood (Miller and Lessard, 2001).

Milliken (1987) theorized that there are three kinds of uncertainty: environmental state uncertainty, organizational effect uncertainty, and decision response uncertainty. These theories indicate that uncertainty would exist within and among systems. It is also clear that different types of uncertainty exist in all phases and areas of a project (Miller and Shamsie, 1999; Song and Montoya-Weiss, 2001). Within the literature, numerous, more specific types of uncertainty are cited: technological uncertainty, customer uncertainty, competitor uncertainty, and market uncertainty to name a few. Song and Montoya-Weiss (2001) suggest that uncertainty should be studied in relation to specific components in order to properly attribute its effects. Eisenhardt and Tabrizi (1995) stated that product development is a very uncertain path as well, with unpredictable shifts in events and technologies. Systems are inherently risky and carry a great level of uncertainty. What is true about today's systems is there is increasing uncertainty and thus they are prone to sudden unexpected changes. The process of systems innovation moves from an initial, ill-defined conception of a problem, through a series of subproblems, to a finished technology (Nightingale, 1998). In organizational behavior, this could be referred to as "storming and norming" (Greensberg and Baron, 1997). Laufer (1997) refers to this as diverging/converging. Some have even tried to explain uncertainty through chaos theory. Glass' chaos theory (1996) explains that most organizations believe there is a state of equilibrium that management tries to balance around. Fundamental to Glass' theories and chaos theory is that the environment is not inherently stable and there is a fine balance that produces order from disorder. This becomes a balance on the edge of chaos while letting a certain level of disorder bring order and direction. Brown and Eisenhardt (1998) refer to chaos theory in management as *structured chaos* (figuring out what to structure and not to structure, both on an organizational level and a managerial level).

Shenhar has worked toward the development of a theory to address the strategic, operational, and human issues of systems innovation and add strategic direction to a project. He theorizes that not all projects are the same and thus they should not be managed the same (Shenhar, 2001a). He has proposed a typology based on an elemental foundation in contingency theory for managing different types of projects (e.g. systems projects), called Strategic Project Leadership (SPL).

**4.5 Strategic Project Leadership**

SPL is an integrated, formal, strategically focused approach to project management to address the human issues of systems innovation. Its has a foundation built upon the research of the National Science Foundation Grant, *Strategic Project Management: Making Projects Our Next Competitive Weapon* (Shenhar, Merino, and Reilly, March 1998), and it theorizes a framework for project managers for the planning and execution phases of a project (Shenhar, 2000). Fundamental to SPL is that "one size does not fit all projects." SPL focuses on the effectiveness and efficiency of a project while maintaining a perspective on strategy, operation, and the human factor. While traditional project management stresses getting the job done on time and within budget, SPL focuses on the product, scope, and strategy to strategically position a project to be successful. This is accomplished by stressing the human side of project leadership. SPL is based on seven principles that are designed to help organizations implement a strategic approach (Shenhar, 2004):

**1. Leadership**: Project managers must become leaders and be held responsible for business results. They have to be accountable for the project's direction and plan, for the vision and execution, and for doing the right things right.

**2. Strategic Project Portfolio Management**: Projects should be grouped based on their strategic impact and form a policy for project selection. Portfolio management identifies two dimensions to determine the strategic impact of projects:

a. *Strategic Goal Dimension*, which includes:

(1) Operational Projects: Projects that deal with existing business, improvements in products, and line extensions.

(2) Strategic Projects: Projects that deal with new business made to create or sustain strategic position.

b. *Customer Dimension*, which involves:

(1) External Customer: For external customers—contracted or noncontracted.

(2) Internal Customers: Within the organization, doing work for other departments or units.

**3. Project Strategy**: Projects have to define the competitive advantage of the product and articulate a detailed project strategy to win in the market place. While project plans include decisions about activities, resources, timelines, and deliverables, strategy is what should drive the plan. Shenhar specifies that Project Strategy involves six elements:

a. *Objectives*: Defines the market, the customers, the need, the business opportunity, and how the opportunities will be addressed.

b. *Product Definition*: What is the product and what will it do?

c. *Competitive Advantage*: Why will the customer want this product?

d. *Business Perspective*: The business plans and expected results on several success dimensions (Shenhar, et al., 2002).

e. *Project Definition*: The scope, project type, project manager, team, and time and budget projections.

f. *Strategic Focus*: The policy, the behavior, and the desired processes, which when followed, will create the best competitive advantage.

**4. Project Spirit**: Project managers must articulate an inspiring project vision and develop an appropriate project spirit, which will support the strategy and create energy, excitement, and commitment. Spirit is further defined by:

a. *Product Vision*: Describes the feelings that will be present when a project is completed and its future impact and value.
b. *Project Individual Culture*: A unique culture is created and it is nurtured by a set of values that are demonstrated and practiced by the project manager.

**5. Adaptation**: Assessing the environment and the task, a project is classified on four dimensions and the right project management style to fit to the project type. Shenhar states that projects carry contingencies based on the four dimensions of novelty, complexity, technology, and pace (Shenhar, 1998b; Shenhar and Dvir, 2004), the NCTP Model:

a. *Novelty:* Defined by the products uniqueness to the market and existing technology, and impact on the project definition and market-related activities. To categorize product novelty, Shenhar uses Wheelwright and Clark's (1992) definition of new product development: derivative, platform, and breakthrough.
b. *Complexity*: Defined by the way a project is organized, its scope, and the interconnections among project elements. As the complexity of a project increases thus does the project size, extent and detail of planning, coordination, documentation, and bureaucracy. Shenhar classifies project complexity or scope as assembly, system, and array.
c. *Technology*: Defined as the uncertainty centered on a technology's development, maturity, and knowledge. As technical uncertainty increases, so do requirements for technical and professional skills, development efforts and time to completion, communication, and the impact and significance of project results. Shenhar classifies projects on technical uncertainty as low-tech, medium-tech, high-tech, and super-high-tech. As both technological uncertainty and system complexity

increase, so do the employment of systems engineering techniques, problems of systems integration, and the employment of configuration management and risk management techniques (Shenhar, 2001b).

d. *Pace*: Defined by the urgency and criticality of time goals for a project. Time constraints on a project can dictate varying project structures and management attention. Shenhar classifies a projects pace as regular, fast/competitive, or blitz/critical.

Once a project is classified based on these four dimensions, it defines certain characteristics of that project that make it unique in how it is managed. Figure 1 shows that connecting the NCTP classification with a straight line to form a diamond, gives a representation of the level of risk associated with a project. The greater the area of the diamond, the greater the degree of risk. While there is not a linear relationship between the area of the diamond for correct and incorrect project risk, it can represent a difference in the degree of risk.

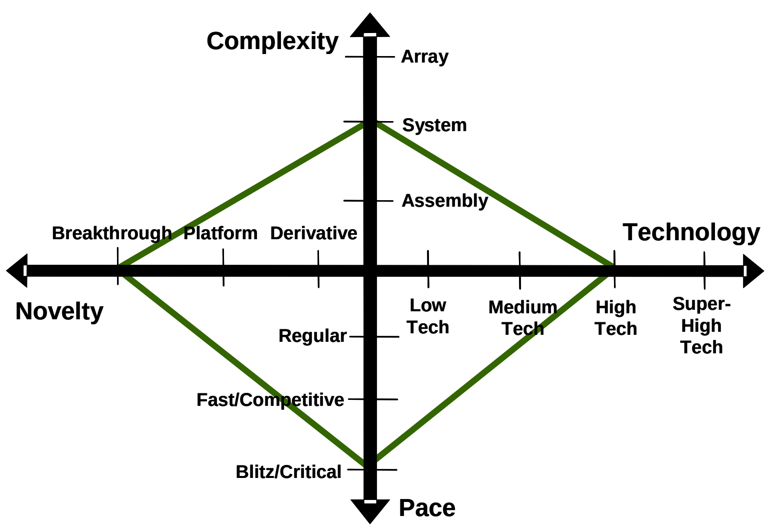


**Figure 1: NCTP Model**

**6. Integration**: A project must create an integrated hierarchical plan. Shenhar states that this plan should be built on five hierarchical elements that he calls the SPL Style: strategy, spirit, organization, processes, and tools.

a. *Strategy*: The project perspective, direction, and guidelines on what to do and how to do it, to achieve the highest competitive advantage and the best project results.

b. *Spirit*: Defining and nurturing the vision that energizes and brings out the best in people. How the team is empowered to make decisions and implement them. What style management uses, and who is defined or viewed as the leadership of the organization.

c. *Organization*: How the people within the project are structured, report, collaborate, deal with difficulties, receive advice and reviews, and are trained. Who is defined as top-level management, how they are involved, how they assembled the team, how much authority they have over the project, and how they assign work.

d. *Processes*: A project's phases and review processes, communication, project monitoring, planning, and control.

e. *Tools*: Serve to help plan, execute, and control the project. What form, means, and frequency of communication are used?

**7. Learning**: A project should create a project learning organization. Every monitoring and controlling activity should include lessons learned that are summarized in a lessons learned event and report.

Shenhar theorized that most projects are operationally managed instead of strategically managed. A strategically managed project as apposed to an operationally managed project has the flexibility to adjust to various project characteristics (e.g. size, scope, uncertainty), thus allowing for the “one size does not fit all projects” theory. O’Connor (1998) adds to Shenhar’s philosophy that academics “have not focused attention on the possibility that what may be sound management practice for the development of incremental improvements may well be detrimental to the development of discontinuous, breakthrough innovation.”

### 4.6 Summary

Figure 2 represents the evolutionary theoretical foundation that BFC projects will be defined upon. GST proposes a way to see the world and how systems progress and interact. The evolution of GST has lead to the typology of many different classifications of systems. With significant influence from systems engineering and innovation theory, one of the classifications that has evolved is Systems Innovation. Using Shenhar’s SPL, this investigation develops integrated, formal, strategically focused approaches to be used by NASA project management while stressing the human side of project management for systems innovation.

There are also theoretical conjectures that link the proposed theories with the characteristics of systems innovation projects:

- They are dynamic and change is normal.
- They are influenced by external events that are dynamic and unpredictable.
- They have multiple stakeholders.
- No two systems or projects are the same.
- Knowledge of the past and future is limited and thus decisions are reliant on self-reflection (heuristics) and comparison.

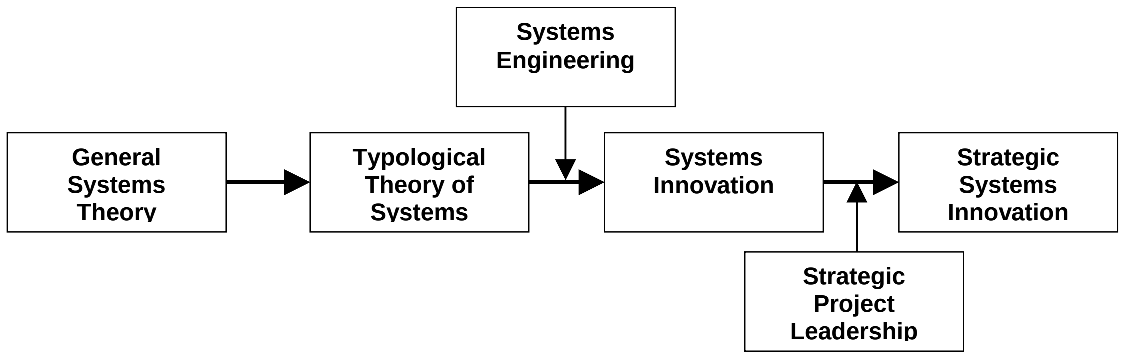


**Figure 2: Theoretical Foundation of Research Approach**

# 5. RESEARCH PLAN

## 5.1 Objectives

1. Develop a better conceptual understanding of system innovation through the study of BFC projects.
2. Understand how SPL can be applied to BFC projects.
3. Provide feedback, recommendations, and lessons learned to NASA and the aerospace industry on potential success criteria for BFC projects.

## 5.2 Research Design

For this investigation, a case study analysis was used, guided by theoretical proposition. After the completion of each case study, a within-case analysis was performed to gain familiarity with the data and evaluate the theories. The study of the next case was started before the previous ended; therefore, an overlap of the data collection and analysis strengthened the analysis and helped reveal any adjustments that needed to be made to the data collection methods. Once the case studies were developed for all of the projects, a cross-project analysis was preformed to determine patterns and anomalies. Once this was performed, the analysis was completed when only small marginal improvements could be made to the theoretical validation.

### *5.2.1 Research Question*

How and why can system innovation projects in the aerospace industry achieve successful results under demands of leaner, better, faster, and cheaper products?

### *5.2.2 Hypotheses*

1. NASA projects require a unique model or framework for project management.
2. SPL provides a fundamental framework for analyzing, planning, and managing NASA projects.

### *5.2.3 Threats to Validity*

Yin (1994) identifies three factors that are often overlooked when performing case study research: (1) bias, (2) little basis for scientific generalization, and (3) result in massive, unreadable documents. Each of these factors can be eliminated with awareness of the fundamental threats to validity. These threats will be addressed with the following precautions:

1. *Construct Validity*: (1) multiple sources of evidence, (2) establishing a chain of evidence, and (3) periodic review of research strategy, concepts, and analysis of data by colleagues.
2. *Internal Validity*: For the purposes of this study, internal validity was viewed with respect to inferences that could be made within the study. To overcome this, all evidence was viewed with respect to whether the inference was correct and the possibility of other explanations.
3. *External Validity*: Multiple-case studies were performed. Four projects were selected that represent two successes and two failures in BFC projects. With the knowledge that they apply to a specified sample, and cannot be generalized to a population, the goals of expanding theory and formulating truth were kept in perspective.
4. *Reliability*: A study protocol was established for future replication and to reduce any bias in the collection of data. In addition, a case study database was developed that would allow for the formatting of data archiving.

## 5.3 Methodology

This research evaluated theories around the how and why of BFC projects that were trying to achieve systems innovation in a time of leaner, faster, better, and cheaper. A case study research methodology was chosen because it allowed for the characterization of real-life events, such as organizational and managerial processes, and there was no requirement for control over behavioral events, thus allowing for the capture of holistic and significant experiences (Eisenhardt, 1989; Gillham, 2000; Yin, 1998). Eisenhardt (1989) states in “Building Theory from

Case Study Research" that case studies can provide description, test theory, or generate theory. She describes a fundamental difference in case study research as compared to experimental research is in the selection of the sample population. Cases are chosen for theoretical reasons, not statistical reasons. One of the reasons for this, and why case study research was chosen for this investigation, was to extend emerging theory, in this case SPL. Case study research provides a conduit to go from theory to data and back to theory. To describe the cases and provide a protocol for data collection Shenhar's (1999b) "Real Life Project Analysis – Guidelines," Shenhar and Dvir's (2004) "How Projects Differ and What to Do About It?," and Shenhar (2004) "Strategic Project Leadership: Toward A Strategic Approach to Project Management" were used. Four cases that represented two failures and two successes in BFC projects were chosen.

The mode of analysis for this project was a modified Multi-Attribute Utility Theory (MAUT) for case study research (Scholz and Tietje, 2002). MAUT was used to attain a systematic measure of the attractiveness of each outcome of a set of attributes (e.g. SPL). This method works best when evaluating alternatives to determine which performs best. MAUT allows comparison among what people do, what people intend to do, and what they should do. For this research, MAUT was used to evaluate SPL and describe the processes and structure of SPL and how it applied to BFC projects.

The analysis followed the following steps:

**1. Analysis of the decision situation**: This involves the definition of the cases to be evaluated, the framework in which the cases were described, and the possible alternatives and their consequences. The cases were defined as projects that represented a maturation of BFC with the following attributes:

a. Tasked to be completed under a BFC management style.

b. LSPs.

c. Government or industry aerospace development project.

d. Prime contractor is based in the United States.

e. Projects were completed in the last 12 years.

f. Project life cycle made it through launch.

The framework for collection and formulation of the data was with Shenhar's "Real Life Project Analysis – Guidelines," and the possible alternatives and the consequences were defined by Shenhar and Dvir's (2004) "How Projects Differ and What to Do About It?" and Shenhar's (2004) "Strategic Project Leadership: Toward A Strategic Approach to Project Management."

**2. Inquiry of existing evaluation structures**: This defines the techniques for data collection. Data collection was performed using the following sources of evidence:

a. *Interviews*: Project team members were approached through e-mail or telephone via personal contact or through a colleague. Each potential interviewee was provided with a one-page letter of introduction that included a statement of the dissertation project, purpose/rational, and people conducting and sponsoring the study, and background on SPL. Interviews were conducted in a semistructured, open-ended conversational format to allow interviewees to speak freely and openly about their experiences. Interviews ranged from 30 minutes to 2 hours based on the interviewee's availability and depth of information. A single interview session was performed with each subject, with follow-up interviews on an as-needed basis. Each interview included identification of the interviewers and the interviewee, including a list of the interviewee's position, role in the project, when he/she was involved, length of the interview, and information on how he/she could be contacted for more questions (address, phone, and e-mail). At least five key personnel related to each project were interviewed. These people represented program management, project management, administration, team member, and customer. Each interview was recorded on audiotape and transcribed.

b. *Documentation (related to the project, but not a product of the parent organization)*: Formal studies, evaluations, journal articles, survey data, mass media, and physical artifacts (samples of work done).

c. *Archival and Historical Information (directly related to a product of the project or parent organization)*: Letters, memoranda, policy statements, regulations, proposals, guidelines, procedures, summary reports, organizational records, and personal records.

d. *Participant Observation*: NASA gave permission for participation in its Academy of Program and Project Leadership training programs. This included project management training classes.

**3. The alternatives-versus-attributes matrix**: Attributes are defined as preference-related dimensions of a system, or variables. Attributes characterize and describe a project, with each attribute having a set of alternatives. Alternatives define and describe the attractiveness of the attributes for a case. Once a case study was completed, an alternatives-versus-attributes matrix was used to evaluate the project. For this research, the alternatives and attributes were defined by Shenhar and Dvir's (2004) "How Projects Differ and What to Do About It?" and Shenhar (2004) "Strategic Project Leadership: Toward A Strategic Approach to Project Management." For example, an attribute in SPL would be Technology and the alternatives would be Low-Tech, Medium-Tech, High-Tech, and Super High-Tech.

**4. Utility functions**: Utility functions serve as a measure of the attractiveness of an alternative with respect to its attributes; are a measure that makes attributes comparable; and reflect the values or intentions of an individual, group, or organization. For this research, the utility functions were defined by Shenhar and Dvir's (2004) "How Projects Differ and What to Do About It?," Shenhar (2004)'s "Strategic Project Leadership: Toward A Strategic Approach to

Project Management," and the case studies as defined by Shenhar's "Real Life Project Analysis – Guidelines."

**5. Evaluation and discussion**: Once all the cases were analyzed, a final iteration was performed to develop and refine a final theoretical statement about the findings. This was defined as the evaluation and discussion. Evaluation and discussion describes the results of the evaluation of each case, provides a cross-case analysis, and offers recommendations for the management of BFC projects.

**Table 1: Methods Table**

| Step | Task | Tool |
|---|---|---|
| (1) Analysis of the Decision Situation | Definition of the case | Large Systems Projects (BFC) |
| | Framework of the case | "Real Life Project Analysis – Guidelines" (Shenhar, 1999b) |
| | Alternatives and consequences | "How Projects Differ and What to Do About It" (Shenhar and Dvir, 2004)<br>Strategic Project Leadership (Shenhar, 2004) |
| (2) Inquiry of Existing Evaluation Structure | Data collection | Interviews<br>Documentation<br>Archival and Historical Information<br>Participant Observation |
| (3) Alternatives-versus-Attributes Matrix | Alternative | "How Projects Differ and What to Do About It" (Shenhar and Dvir, 2004)<br>Strategic Project Leadership (Shenhar, 2004) |
| | Attributes | "How Projects Differ and What to Do About It" (Shenhar and Dvir, 2004)<br>Strategic Project Leadership (Shenhar, 2004) |
| (4) Utility Functions | Functions | "How Projects Differ and What to Do About It" (Shenhar and Dvir, 2004)<br>Strategic Project Leadership (Shenhar, 2004) |
| | Utility | "How Projects Differ and What to Do About It" (Shenhar and Dvir, 2004)<br>Strategic Project Leadership (Shenhar, 2004) |
| (5) Evaluation and Discussion | Cross case analysis | |

*Individual Case Study Reports*

Individual case study reports will follow a theory-building structure using the following outline:

1. *Source Material*: Type and source of information obtained for case study.
2. *Executive Summary*: Background – why did they do it? Objective – what did they want to achieve? Product Definition – what was the product of this project and what did it do? Project Definition – what was the scope of work; how long did it take and how much did it cost? History and Events – how did it go? Success/Failure – what were some of the factors to its success or failure?

3. *Background*: This will give the background, history, and unfolding events of the project leading up to its start. Why was it done, what was the motivation, how was it initiated, and who came up with the idea? What happened before the project was initiated, how did the idea evolve, who pushed it, and how did it turn into a formal project, how long did it take?
4. *Mission Description*: Detailing the unfolding events of the project and who was involved. Detailed description of the project's unfolding history, process, and timeline; description of main events, milestones, decisions, difficulties, and crises, and the way they were handled.
5. *Technology Description*: A detail description of the technology, product, and engineering/scientific objectives.
6. *Strategic Project Leadership*: A description of the project and how it was defined by SPL.
7. *Adapting Project Management to Project Type*: Analysis of how the project fit the NCTP Model.
8. *Success Factors*: What was unique about this project and what was done successfully?
9. *Recommendations*: As an investigator, what would be recommended for improving the project? A critical evaluation of the project as compared to SPL.

*Cross-Case Study Analysis*

A final report will perform a cross-case analysis using a theory-building, comparative structure according to the following outline:

1. *Comparative Project Description (Major Findings)*: The projects will be described in how they compared each other.

2. *Comparative Theory Analysis (Conclusions)*: A critical evaluation of the cross-case analysis as compared to SPL. This section will represent the culmination of the theoretical evaluation.
3. *Recommendations*: A final statement will be made about the cases, lessons learned, and future direction based on the theoretical analysis.

# 6. CROSS-CASE ANALYSIS

This study investigated four NASA BFC projects that represented a maturation of BFC and its success and failure (two successes: Mars Pathfinder and Lunar Prospector; two failures: CONTOUR and Mars Climate Orbiter). Therefore, BFC is defined in the context of the physical constraints of deep-space missions and all results are described based on the cases investigated. The following is a cross-case analysis of the four projects investigated as defined by the five elements of planning with Strategic Project Leadership (SPL) and the seven principles of SPL: (1) Leadership; (2) Strategic Project Portfolio Management; (3) Project Strategy; (4) Project Spirit; (5) Adaptation; (6) Integration; and (7) Learning. The analysis will focus on the elements and principles of SPL that could explain and interpret the case investigations for verifying the hypotheses. Where the cross-case analysis could not provide significant explanation to formulate conclusive results to verify or falsify the hypotheses, the SPL variables are not discussed.

## 6.1 Case Summaries

### *6.1.1 Mars Pathfinder*

In 1993, Congress approved a plan proposed by NASA's Space Science Enterprise for better, faster, cheaper planetary missions called the Discovery Program. To show Congress that it could be done, NASA selected two charter missions: one at the Jet Propulsion Laboratory (JPL) and one at the Johns Hopkins University Applied Physics Laboratory (APL). Mars Pathfinder was chosen at JPL as a scientific mission set out to broaden the understanding of Mars and show that BFC could be done successfully.

As a product, Mars Pathfinder was a single vehicle (lander), with microrover and several instruments designed to demonstrate a low-cost system for cruise, entry, descent, and landing on Mars. Additional objectives included the deployment and operation of various scientific instruments: stereoscopic imager with filters on a pop-up mast, alpha proton x-ray spectrometer (APXS), and atmospheric structure instrument/meteorology package.

As a project, Mars Pathfinder, at the time one of the most complex planetary exploration projects in space science history, was to design, test, and develop a lander and rover to launch and safely land on the surface of Mars. With 3 years for development and a total cost no greater than $280 million (including the launch vehicle and mission operations), Mars Pathfinder was to demonstrate a simple, low-cost system, at a fixed price for placing a science payload on the surface of Mars at 1/15 the cost of Viking (Viking cost $2.8 billion in 1997 dollars). Mars Pathfinder was a breakthrough product that introduced to the world a new way of landing on Mars, and what was more significant, a robotic rover to traverse the planet. As a system of a complex collection of interactive elements and subsystems, it functioned as one unit to meet its operational needs. While most of the technology to accomplish this was commercial off-the-shelf, a significant portion of the technology was new to planetary exploration and made it a high-tech project. As with most deep space projects, schedule, cost, and technology have limited margins, making Mars Pathfinder a blitz-critical project.

On July 4, 1997, Americans watched the first pictures come back from Mars, marking one of NASA's most celebrated, historic, and accomplished days. A whole new generation was being introduced to the Red Planet through television and the Internet, as Mars Pathfinder shattered records for web site hits, peaking at 1 million in a day. From its start, Mars Pathfinder had project constraints that were unmatched by another NASA project and science objectives that would return an unparalleled amount of data to the largest science community associated with a NASA mission. For all of Mars Pathfinder's interest and success, it was not the landing on Mars that marked its success (Viking I and II accomplished this in 1976 and 1978 respectively)—it was the means by which it was accomplished that made it unique, innovative, and electrifying.

To be successful, the Mars Pathfinder team had to do business differently from traditional and standard operating procedures. They worked to develop a unique culture centered on leaner staff, reduced overhead, empowered team members, a willingness to do things in new ways, and a management team that believed in a team of capable, self-directed members. To build this cultural rules were lifted and authoritative structures were minimized. The team was hand-picked, with many being experts in their fields, but most of all, these people had to be generalist and multidisciplined. These people were picked from a skill set of different ages and experiences, but all brought with them a level of energy and creativity to carry the project from beginning to end. The leadership was committed to the project goals of launching a spacecraft that was better, faster and cheaper and all actions were in line with these goals. This meant having a clear vision and making sure that that vision was part of every action. Mars Pathfinder was successful at being completed on time, on budget, and met first line project objectives, and management valued the people that they empowered every day. A more detailed description and analysis of Mars Pathfinder based on SPL can be found in Appendix A.

### *6.1.2 Lunar Prospector*

Lunar Prospector was the first competitively selected mission in the NASA Discovery Program, developed to produce frequent, low-cost missions to explore the solar system. Lunar Prospector was a spin-stabilized spacecraft designed to map the surface composition and magnetic field of the Moon and begin investigating some of the 80 percent of the Moon’s surface features, structure, and composition not investigated during Apollo.

As a product, Lunar Prospector was a single vehicle (orbiter) and several instruments designed to demonstrate a low cost system for orbiting the Moon and expanding our scientific knowledge of it. Additional objectives included the deployment and operation of various scientific instruments: neutron spectrometer, gamma ray spectrometer, magnetometer/electron reflectometer, doppler gravity experiment, and alpha particle spectrometer. While much of the technology was known, its application and what Lunar Prospector was planned to accomplish made it different than anything that had been done before.

As a project, Lunar Prospector was to design, test, and develop an orbiter that would obtain scientific data and demonstrate, as the first competitively selected Discovery Program mission, the philosophy of "better, faster, cheaper." Lunar Prospector had a development time of almost 3 years and a project cost that included development ($34 million), launch vehicle ($25 million), and operations ($4 million), for a total of $63 million. Lunar Prospector involved 75 to 100 people from Ames Research Center, Goddard Space Flight Center, Jet Propulsion Laboratory, University of California – Berkley, University of Arizona, Lockheed-Martin, Lunar Research Institute (Alan Binder, principal investigator, left Lockheed Martin to establish the Lunar Research Institute), and Los Alamos National Laboratory. Lunar Prospector was a high-tech project. Much of the technology was proven from previous spacecraft but had not been incorporated in this configuration. Lunar Prospector was a complex collection of interactive elements and subsystems developed to perform a wide range of functions under extreme conditions. The pace development was a blitz-critical. While many of the characteristics of such deep-space-mission projects point to a fast pass, it is the inflexible launch date that moves deep space missions like Lunar Prospector into a blitz-critical mode. In addition, termination of the project was directly related to any significant deviation in schedule and budget margins

Lunar Prospector ended on July 31, 1999, when the spacecraft was jettisoned into a crater near the south pole of the Moon as part of an experiment to confirm the existence of water ice. The mission ran for 19 months and successfully completed all of its objectives. The data collected has allowed for the construction of a detailed map of the surface composition of the Moon, and the information gathered was far more comprehensive than any data ever collected.

Lunar Prospector was successful because the management team understood well before the project started that simplicity would be the key to project success. Lunar Prospector was well defined with a clear understanding of the scope, technical uncertainty, and pace. This guided management toward design constraints that kept Lunar Prospector on budget and on schedule. Lunar Prospector management determined their strategy early with customer-defined objectives that were simple, attainable, and valuable. A focused, unspoken, and common commitment from a collocated team laid a foundation for limited top-management involvement and a dedication of staff from project start to finish. The Lunar Prospector team understood the value of informal and formal reviews, how they related to when to freeze designs, and how they impacted requirements. They also believed that only a good test program could reduce uncertainty. A more detailed description and analysis of Lunar Prospector based on SPL can be found in Appendix B.

#### *6.1.3 CONTOUR*

As the sixth mission in NASA's successful Discovery Program, the Comet Nucleus Tour (CONTOUR) was a joint project between Cornell University and Johns Hopkins University Applied Physics Laboratory (APL), along with 14 other university, government, and industry co-investigators to study three major near-Earth comets. With a budget of $159 million and a development time of almost 3 years, it was scheduled to fly within 60 miles of each of three comets. From 2003 to 2008, CONTOUR would take images, make spectral maps, and analyze dust flowing from the comets to substantially improve the knowledge base and expand the understanding of comets.

As a breakthrough product, CONTOUR was a single spacecraft and six scientific instruments designed to provide a detailed look at comets and answer questions about how comets act and evolve. While much of the technology was known, its application and what CONTOUR was planned to accomplish made it different from anything that had been done before. No one in the history of space exploration had brought a spacecraft as close to a comet as CONTOUR would. While using predominantly existing, off-the-shelf technology and technology from previous missions, CONTOUR was flying for the first time a non-coherent DOPPLER navigation system and a Solid Rocket Motor (SRM) that had not been thoroughly tested with the spacecraft.

As a project, CONTOUR was to design, test, and develop an orbiter that would obtain scientific data on comets and reaffirm the success of "better, faster, cheaper." CONTOUR could be described as a high-tech project. While much of the technology was proven from the Stardust and Near Earth Asteroid Rendezvous (NEAR) spacecrafts, its application and its unprecedented scientific objectives made it different than anything that had been done before. The complexity of the project could be described as a system with a collection of interactive elements and subsystems that had to perform a wide range of functions under extreme requirements. The pace of the project was a blitz-critical project. While many of the characteristics point to a fast-competitive project, it is the inflexible launch date of CONTOUR and most Discovery Program missions that moved it into a blitz-critical mode. Any error in time or budget meant cancellation for the project.

CONTOUR was on track to be a storied success for both Cornell and APL, but the loss of communications on August 15, 2002 could not have been expected. On that day, CONTOUR was scheduled to accelerate the spacecraft and place it on a trajectory toward its first comet. While operations continued based on the assumption that the firing took place on schedule, no signal was received from the spacecraft. From August 16 through August 21, three objects were identified near the expected position of CONTOUR. Communications attempts continued with the spacecraft once a week through December 2002, and the mission was declared officially lost after the December communication attempts failed.

Widespread faults were hard to find in CONTOUR, and it embodied many of the characteristics of successful Discovery Program missions. Management brought to the project years of success and a firm belief that they knew what it would take to make CONTOUR successful. However, with overconfidence from past success, and the lack of a good framework for determining the technological complexity, CONTOUR was challenged with not having a clear understanding of the technological uncertainty. The challenges and pressures of BFC resulted in a need for clearer lines of leadership, collocating key subsystems, having team members 100 percent on the project (cradle to grave), and independent in-depth, active technical reviews with outside experts. A more detailed description and analysis of CONTOUR based on SPL can be found in Appendix C.

#### *6.1.4 Mars Climate Orbiter*

In 1993, NASA started the Mars Surveyor Program to develop a series of missions to study Mars. A Mars Program Office was established and given the responsibility of defining the objectives of these Mars exploration missions. Chartered under this office would be two missions with biennial launching opportunities (Mars Climate Orbiter and Mars Polar Lander). The Jet Propulsion Laboratory (JPL) created the Mars Surveyor Project ’98 (Mars ‘98), which would be responsible for these missions. One of these missions, the Mars Climate Orbiter (MCO), was a strategic project that would help build a sustained position in space exploration with recent successes in Mars exploration (Mars Pathfinder and Mars Global Surveyor). MCO would build upon those successes and lay the groundwork for several planned Mars exploration missions over the next 15 years. MCO was a tangible product of a spacecraft, orbiter, and scientific instruments, which required a significant level of insight and creativity both technically and managerially, built around a core of talented, experienced people to produce a valued product.

As a project, MCO was to design, test, develop, launch, and operate an orbiter that would collect weather data from Mars and act as a relay station for 5 years, assisting in data transmission to and from the Mars Polar Lander (MPL). Jointly developed with the MPL and 300 people from JPL and Lockheed-Martin, the project had a 37-month development schedule, with spacecraft launch masses of a medium-light class launch vehicle and a financial cap of about $184 million (covering development of the spacecraft, scientific payloads, and the ground operations system). MCO was a high-tech project with development of one-of-a-kind, single-flight systems. While some of the technology was new, much of it existed at the time the project was initiated. What was unique was how the technology was brought together in a single spacecraft. As a complex collection of assemblies that were to perform multiple functions under the guidance of a main contractor with tight and formal controls, MCO could be described as a system. The pace of the project was a blitz-critical project. Time was critical for project success and marginal fluctuations in time and budgets meant project failure.

On September 23, 1999, MCO began its orbiter insertion maneuver, but shortly after beginning, the signal was lost from MCO, and on September 24, search for the orbiter was abandoned. On September 30, a JPL peer review committee reported that small forces of velocity changes reported by the spacecraft engineers used in orbit insertion were low and the likely causes of the MCO loss. On October 6, a MCO Mission Failure Investigation Board was appointed by NASA to independently investigate all aspects of the failure of the mission. On November 10, the Board released its report that idenified the root cause for the loss of the MCO spacecraft as the failure to use metric units in the coding of a ground software file.

While the root technical cause was a software coding failure, the overarching cause of the MCO loss was a stategy designed to address cost goals more than capability objectives. This can be attribued to the pressures and challenges of BFC, which resulted in cuts in areas that later proved to be key in contributing to MCO’s failure. Because of cost constrains, peer reviews were de-emphasized, there was not an active involvement from experts, dual development was used on subsystems for multiple missions, the number of people on the project was kept below minimum, expertise for key subsystems was unavailable to the project, testing was streamlined in key areas, and key policy was reduced.  Designing to capabilities might have revealed that this project could not have been completed under the specified budget.  With all of its constraints, the MCO team maintained a high spirit with an unmatched drive to be successful.  Unfortunately, not managing the spirit resulted in team members overworking themselves and not having enough time to stop and think about their actions.  A more detailed description and analysis of MCO based on SPL can be found in Appendix D.

## 6.2 Analysis

### *6.2.1 Leadership*

In SPL, leaders create vision and meaning, and develop fresh approaches to long-standing problems. SPL states that projects are where ideas are transferred into tangible results through a vision. Project managers must be effective leaders, efficient managers, and technically competent. They must take responsibility for the vision, its execution, and the ultimate business results.

**Project managers must be effective leaders, an efficient managers, and technically competent:** For the projects investigated, project managers were experienced both as project managers and as engineers or scientists. In all four projects, the project managers had previous experience in managing multiple deep space projects and brought to the projects at least 15 years of experience as engineers. Most of the project managers and/or principal investigators were far enough along in their careers at the time of the project that many retired shortly after the projects were completed. Therefore, the failures or successes in the projects cannot be directly correlated to the talent but may more be reflect the leadership style.

In Mars Pathfinder and Lunar Prospector, project managers were quick to explain that they were willing to “pick up a wrench” to help ensure a project stayed on schedule. Brian Muirhead, Mars Pathfinder Lander manager, stated “…a manager must confidently reach into a project to move it forward.” Alan Binder, Lunar Prospector principal investigator, and Matt Dougherty, Lunar Prospector project manager, understood the systems they were developing very well and believed in working side by side with engineers to meet a project’s milestones. For CONTOUR and MCO, the project management took a more hands-off approach. They believed in letting the engineers and scientist concentrate on the tasks at hand so they did not have to worry about management issues. Mary Chiu, CONTOUR project manager, believed that managers should work for an informed, nonintrusive style. CONTOUR management believed that engineers should be allowed to perform their jobs without the restriction of managerial interference and believed the efforts of project management should be focused on maintaining the project strategy, structure, and lines of communication. MCO management also believed in empowering their engineers to be engineers and concentrating their own efforts on managing the cost, schedule, and budget.

**Project managers take responsibility for the vision, its execution, and the ultimate business results:** For Mars Pathfinder and Lunar Prospector, the lines of leadership were clearly defined. Team members explained that they knew exactly who they were accountable to and what they were accountable for. Managers instilled a clear vision of success in each of the team members. Donna Shirley, Rover project manager, stated that the leadership had a clear vision and backed up their words with actions. For Lunar Prospector, leadership followed a more dictatorial style. Alan Binder brought his belief in the vision for project success and stated “you get nowhere by doing things by committee.” He and Matt Dougherty took complete control of Lunar Prospector and quickly removed anyone from the project who could not work in that environment. With this control, Binder and Dougherty believed that a person must be able to “take blame when something goes wrong.” In CONTOUR and MCO, lines of leadership were unclear and some described confusion about who was in charge or who to go to in certain situations. The CONTOUR Mishap Investigation Board Report sited communication problems between major subsystems during the spacecraft development. In addition, some managers commented that conflicting directions came from top management, and it was “unclear who within top management was in charge.” The MCO Mishap Investigation Board Report sited that there was “little evidence of contact” between line supervisors and system engineers on some systems. Many team members did not identify project managers as team leaders, and one manager identified the leadership style as “autocratic with tendencies to breed conflict.” Table 2 summarizes the leadership successes or faults in the four projects studied.

## Table 2: Cross-Case Analysis: Leadership

| Mission | Leadership Style | Interview | Archival/Documentation |
|---|---|---|---|
| **Mars Pathfinder** | Empowered the people; brought a willingness to do things differently; made the people, not the policy, responsible for project success. | "The most successful leaders have learned to channel their own emotional energy, focusing it to energize their people." | Leaders have to reassure their people that they share the same goals for the final products.<br>— *High Velocity Leadership: The Mars Pathfinder Approach*<br><br>Once they've gone beyond your ability to understand them, then you have to make a choice as a manager. You can limit them and the project by your intelligence, or you can trust them and use your management skills to keep them focused on the goal.<br>— *Managing Martians* |
| **Lunar Prospector** | Hands-on (pick-up a wrench), included people in the decision-making process, spent time on the front end, and then let the project go. | "I was not the manager who sat in my big soft chair somewhere and just wrote memos. I was down there."<br><br>"It was very much by delegation and holding people accountable to high level requirements rather than detailed specifications." | The first things the project manager did was sit the engineers down and explain the philosophy, history, and what Lunar Prospector was trying to accomplish.<br>— project presentation and plan |
| **CONTOUR** | Limited oversight and guidance from leadership. | "We basically tried to reach a balance between enough structure to do things well, also enough flexibility to allow individuals the opportunity to do the things they needed to do." | Significant reliance on subcontractors without adequate oversight, insight, and review.<br>— Mishap Investigation Board Report |
| **MCO** | There were limited accountability and authority, unclear lines of leadership, inexperience in some areas of management, and a lack of trust from all the team. | "The openness to the navigation process while empowering junior engineers with limited depth was too much for those engineers to handle."<br><br>Team member stated at times they were not sure who was in charge or who was the mission manager. | Project managers were competent, but inexperienced. Inexperience was identified by the MIB as one of the root causes for MCO's failure.<br>— Mishap Investigation Board Report<br><br>The inadequacies in experience on MCO and the MIB Report resulted in the establishment of a new position at JPL to specifically monitor projects. |

#### *6.2.2 Strategy*

SPL states that project strategy feeds the project plan. While plans detail the events, resources, schedule, requirements, and deliverables, strategy is the action and philosophy that makes the plan work. In SPL, project strategy begins by defining the product and its expected competitive advantage through six elements: objectives, product definition, competitive advantage, business perspective, project definition, and strategic focus. The four projects investigated were products defined as single spacecraft, with four or more scientific instruments, developed on a low-cost budget, and designed to encounter a celestial body (Mars Pathfinder and MCO – Mars; Lunar Prospector – the Moon; and CONTOUR – multiple comets). These products were then defined by projects that were competitively selected to design, test, develop, launch and operate the spacecraft with minimal government funding.

**While plans detail the events, resources, schedule, requirements, and deliverables, strategy is the action and philosophy that makes the plan work:** For the four projects, the strategies were set early, articulated often, and focused on project success. Mars Pathfinder and Lunar Prospector believed that the philosophy of a strategic approach supported by a commitment to the vision was one of the keys to success. Wayne Lee stated that for Mars Pathfinder to be successful the nonstrategic focus that had been present in many past space exploration projects had to change. For Brian Muirhead, this meant having clear linkages among the strategy, vision and objectives. Mars Pathfinder took what Donna Shirley called, “modest, simple objectives,” added to it what Brian Muirhead called a philosophy of “take risk, don’t fail,” and created a project strategy that was “committed to success.” Management then believed that this strategy and the philosophy that it was built on should be reevaluated and articulated often throughout the project. For Lunar Prospector, the strategy focused on what Scott Hubbard, Lunar Prospector program manager, called “value-added requirements.” When Alan Binder was asked what the strategy for Lunar Prospector was, he answered simply, “You are responsible, you’re responsible to me, no passing the buck, keep it simple, and do it on time. If there is a problem, we sit down together and fix it right then and there. That was the whole strategy."

For CONTOUR and MCO, the strategy was focused on operational success and not strategic success. CONTOUR believed in setting the strategy early, articulating it to the team, and then considering it a "done deal." Mary Chiu stated that her responsibility as project manager was to keep the team focused on the strategy by reiterating it several times throughout the project. But for CONTOUR, as the plan changed, the strategy never wavered. For MCO, technical motivations were strong, but the drive to develop MCO at a bare minimum cost was what fostered the strategy. JPL made several cost-driven strategic decisions that ultimately became key for MCO. One of those decisions was to use much of the science from the failed Mars Observer. The second was to award a contract for spacecraft development that would result in an opportunity for up to eight almost identical spacecraft. Noel Hinners, Lockheed-Martin program manager, said, "Your competitive environment tends to push you to bidding lower cost to try and squeeze all of the cost out the first time. To try to win." This approach fostered an operational approach to MCO and was later described by Peter Rutledge, investigative lead from the Office of Safety and Mission Assurance, as not what was done to guarantee success but what was not done.

**SPL states that project strategy begins by defining the product and its expected competitive advantage through the six elements:** Usually, NASA projects are supported by a congressional or administrative push. In some cases, they are developed from a scientific community pull. In either case, there is usually minimal traditional business competition. For each of the projects, one of the hardest questions to answer was "What was your competitive advantage?" The most common answer was "We were a government project, so we do not have competition." While this may have been the belief of many of the interviewees, it was not the case for all of the projects. Mars Pathfinder was hand-picked by NASA to be the "hallmark" mission for BFC, but fought hard to differentiate itself from a mission at Ames Research Center that was also in consideration. Lunar Prospector was the first competitively selected Discovery Program mission using a peer review process. CONTOUR was also competitively selected through the Discovery Program, and APL's proposal was rejected the first time they applied. While MCO was defined by NASA, the spacecraft development was awarded to Lockheed-Martin through an intensely competitive selection. Though each of the projects brought a competitive advantage that the interviewees could not clearly define, they were able to define the value. Because these were scientific projects with scientific objectives, they defined their value as delivering "category one" science to the scientific community, and success was defined as meeting their scientific objectives. For Mars Pathfinder and Lunar Prospector, they maintained a focus on the value of scientific return without being distracted by traditional project constraints of cost, schedule, and performance. For CONTOUR and MCO, cost pressures overshadowed performance goals and resulted in project failure. For CONTOUR, this became evident when, after the Phase A/B evaluation, the project was threatened with cancellation because of high cost estimations. For MCO, the extreme pressure to perform two missions (MCO and MPL) on the same budget as Mars Pathfinder resulted in a design to cost and not requirements. Table 3 summarizes the strategy successes or faults in the four projects studied.

**Table 3: Cross-Case Analysis: Strategy**

| Mission | Strategy Style | | | | Interview | Archival Documentation |
|---|---|---|---|---|---|---|
| | **Business Perspective** | **Strategic Focus** | **Competitive Advantage** | **Value** | | |
| **Mars Pathfinder** | "Develop a plan, then improvise;" success based on customer perception. | The vision was part of the process. | Past success; skill; political positioning. | Matched the objectives (low cost, short development, scientific return). | "You sort of do it because you have to, but you sort of build a gut feeling of how its really going."<br><br>"Modesty and simplicity were really the strategies for Mars Pathfinder." | Develop a plan, then improvise.<br>— *High Velocity Leadership: The Mars Pathfinder Approach* |
| **Lunar Prospector** | Stay within budget and on schedule, and meet project objectives. | No passing the buck; keep it simple and do it on time | Competitively selected; simple spacecraft for low cost. | Low cost, short development, scientific return. | "It is a matter of saying this is what we are going to do and we don't change anything we build."<br><br>"We went in there with a very realistic definition of what we could do and it turned out that our optimistic assessments were correct. | What was unique about Lunar Prospector was that the mission that was defined in 1988 was the mission that flew in 1998. |
| **CONTOUR** | Strict to NASA procedures (7120.5B); built on science requirements. | Set the strategy early, articulate it to the team, and then consider it done. | Past success; competitively selected; category "one" science; unique mission for low cost. | Scientific return, low cost. | "There is first all the planning, then what actually happened."<br><br>"The overall value is that you are doing the mission you sold." | Success was to be judged on what was specified in the project plan.<br>— project plan |
| **MCO** | Extreme pressure to be successful based on staying within budget and schedule. | Cost-driven and not requirement-driven. | Past success; experience and cost. | Duplicate science lost on Mars Observer; first of successive missions to Mars. | "What they did to guarantee success. I would address that question from a different view… What did they do to try and guarantee that it did not fail."<br><br>"There is no way, no way, that mission could have been done for anywhere near what people were talking about." | We pushed the boundaries like never before… And had not yet reached what we thought was the limit.<br>— Speech by NASA Administrator |

### *6.2.3 Spirit*

In SPL, the leaders are responsible for creating a spirit that effectively articulates an inspiring vision that mobilizes people's motivation. SPL defines spirit by the product vision and individual project culture.

**The leaders are responsible for creating a spirit that effectively articulates an inspiring vision that mobilizes people's motivation:** For the projects investigated, the vision grew from a fundamental challenge of developing a complex product on an extremely reduced budget and schedule. For these projects, the vision was focused on doing what others could not, and finding new ways of accomplishing what many defined as impossible. Alan Binder stated, "You've got to change the culture, you can't do things this way if you're going to keep the old culture." In each of the projects, the interviewees described the spirit that rose from the project vision as unlike any other project they had worked on. For the four projects, management found themselves in the position of not having to create spirit, but managing it. In Mars Pathfinder and Lunar Prospector management kept a tight eye on the spirit to make sure that team members did not overwork themselves because of their self-motivation and when needed, effectively reached into the project to pull them along. Wayne Lee stated that Mars Pathfinder "found ways to take things out of the rigor of the everyday process of NASA's very straight-laced organization and put some humanity and some fun into the process." Alan Binder, when asked about Lunar Prospector's spirit, said, "Without that we would have never had achieved anything." In each of the four projects, team members felt a personal ownership in the project's success or failure. Mary Chiu described this ownership of CONTOUR as a sense of "family."

Unfortunately, this strong cohesive spirit became a mixed blessing when it was unmanaged and resulted in some failures. For CONTOUR, management held the spirit back or did not effectively pull it along at the right time, and for MCO it did not effectively limit the spirit. After the Phase A/B Study on CONTOUR, management was hit with the reality of enormous cost constraints, and the prospect of significant cost overruns. Budgetary issues in any NASA project can quickly lead to project termination, so the CONTOUR team was under great pressure to reduce costs. This was a time when CONTOUR's spirit was at its lowest and a time when management needed to effectively manage the spirit. In Mars Pathfinder and Lunar Prospector, spirit drove the teams to work extra hours to get the job done, conversely, CONTOUR management controlled the spirit by making sure that people only worked 40-hour weeks. In projects with limited schedules and fixed launch dates, team members routinely work extra hours to guarantee project success. MCO was described by the interviewees as very high-spirited and committed to success. Noel Hinners stated, "There was not anybody who had any doubt that we were going to succeed." Management stated that motivating the team was the least of their concerns. But, by not managing the spirit and drive of the team, they ended up with too much of a good thing. Team members worked themselves too hard, resulting in lack of concentration at times, not enough time to think about the decisions they had made, and an extreme level of confidence. Ed Euler, MCO project manager, said that with such a highly motivated team that worked sometimes 100-hour weeks, they never had what he called "A'ha time." Noel Hinners defined "A'ha time" as, "We were so busy doing the work that had to get done, we did not have the luxury of just sitting back on a weekend or when you got home at night and just conjugating about what went on." Table 4 summarizes the spirit successes or faults in the four projects studied.

**Table 4: Cross-Case Analysis: Spirit**

| Mission | Spirit Style | | Interview | Archival Documentation |
|---|---|---|---|---|
| | Vision | Culture | | |
| **Mars Pathfinder** | Prove it can be done, do what others could not. | Mutual trust and respect; new way of doing business; personal ownership in the project. | "Mars Pathfinder had more spirit than any mission I've ever seen."<br><br>"The rest of the group has to be able to count on you—not just to rely on you to do your work well, but also be there when teammates needed back up. This meant keeping your word, meeting your commitments, and going public if you needed help or make mistakes." | Deliberately choose to do things differently; invite different perspectives<br>— *The Mars Pathfinder Approach to "Faster, Better, Cheaper"* |
| **Lunar Prospector** | Small project built into a large organization. | A feeling of identity with the hardware; a feeling of being part of something different; have fun or get off the project. | "Things that we did were unheard of, all goes into my saying that nobody believed we could do this."<br><br>"People I run into today say that LP was the best team and the best project they had ever worked on." | The change of the LP team dynamics with the change in Project Management was nothing short of miraculous. Energy and motivation were realized.<br>— http://appl.nasa.gov |
| **CONTOUR** | Do what others cannot; doing something different. | Overconfidence from past success; because of the Mars 98 failures, felt excessive pressure to not make the same mistakes. | "We were extremely mindful of the issues that happened on the spacecraft right before us, and with the Mars failures and the Mars Observer failure, we were making damn sure that we were not going to repeat the same problems that they had. But something else got us."<br><br>"A lot of sole searching as far as what was really needed in certain areas…I think at that stage there were some low points." | Enormous cost constraints threatened the project and possible cancellation after the Phase A/B Study. |
| **MCO** | "Follow the Water;" doing something different and challenging. | Sense of urgency; and excessive pressure to be successful. | "The team spirit was so good that it probably blinded us to the amount of work and stress that was existing on the project."<br><br>"It was very difficult for people to understand the environment that the NASA administrator had established. The axe he was holding over everybody. It was a challenge we accepted, and we paid the consequences." | The fixed launch date put tremendous pressure on project personnel, not allowing any "think" time.<br><br>— "The Failures of the Mars Climate Orbiter and Mars Polar Lander: A Perspective from the People Involved" |

### *6.2.4 Adaptation*

There is a fundamental difficultly with NASA BFC projects when attempting to define their Novelty, Technology, Complexity, and Pace. The shear fact that a project is attempting to explore the universe or launch into space can define the project as no less than high-tech; the level of risk and integration associated with such missions define their complexity no less than a system; the technological challenges and requirements of space exploration make them no less than a breakthrough; and the celestial mechanics or “launch windows” imposed on a BFC mission from their inception make them no less than blitz-critical. It appears from this research that a BFC mission should be defined and managed as a high-tech, system, breakthrough, blitz-critical project.

Figure 3 represents a summary of how the projects were managed based on the NCTP model. The successful projects not only applied the right project typology, but also the right approaches for that typology, while the projects that failed lacked a framework that would allow them to apply the correct project management to project type approach. Connecting the NCTP classification with a straight line to form a diamond gives a representation of the level of risk associated with a project. The greater the area of the diamond, the greater the degree of risk. Figure 3 also represents how each of the projects differed in their level of risk, and how the projects that failed, assumed a lower level of risk. The green lines represent the correct project classifications. The red dashed lines represent how the projects were managed. While there is not a linear relationship between the area of the diamond for correct and incorrect project risk, it does represent a difference in the degree of risk. To further explain this, Table 5 offers an overview of the actual and required project adaptation for each of the projects followed by a detailed explanation.

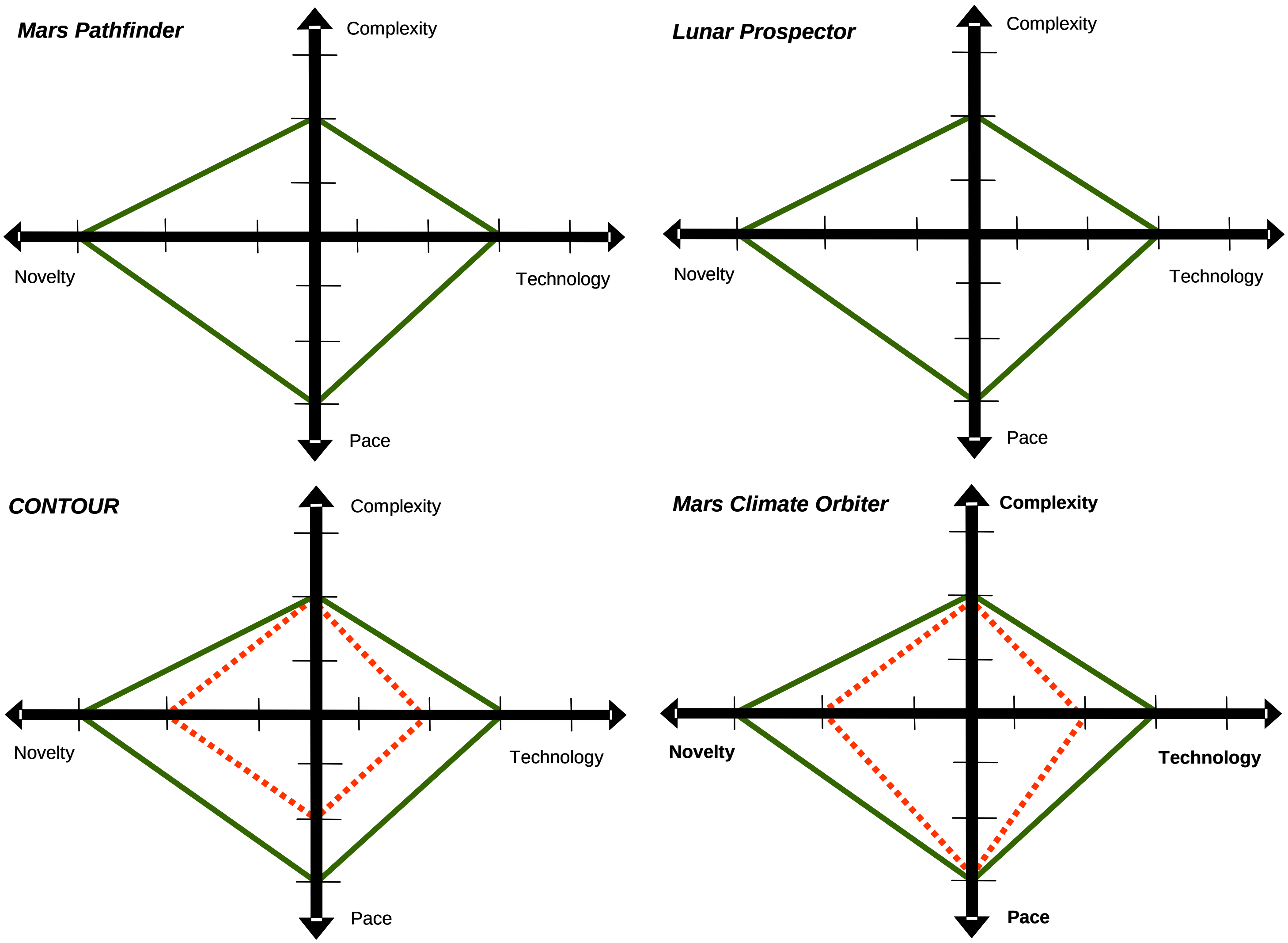


**Figure 3: NTCP Model – Case Analysis**

**Table 5: NCTP – Required and Actual**

| Mission | Novelty | Complexity | Technology | Pace |
|---|---|---|---|---|
| **Mars Pathfinder** ***Required/ Actual*** | **Breakthrough** Introduced to the world a new way of landing on Mars, and more significant, a robotic rover to traverse the planet. | **System** Complex collection of interactive elements and subsystems, it functioned as one unit to meet its operational needs. | **High-Tech** While most of the technology was COTS, a significant portion of the technology was new to planetary exploration. | **Blitz-Critical** Schedule, cost, and technology had limited margins with a fixed launch window. |
| **Lunar Prospector** ***Required/ Actual*** | **Breakthrough** New use for existing technology that had not been seen before; it pushed the boundaries of cost-effective space exploration. | **System** Complex integration of scientific instruments and spacecraft subsystems. | **High-Tech** Although most of the technology was COTS or borrowed from other proven spacecraft, it was innovative in its application. | **Blitz-Critical** Schedule, cost, and technology had limited margins with a fixed launch window. |
| **CONTOUR** ***Required*** | **Breakthrough** Integration into a new product with first-time-used systems; no one in history would bring a spacecraft this close to a comet. | **System** A systems project that relied on the integration and complexity of that integration to develop a spacecraft. | **High-Tech** Significant improvements were made to the technology to develop CONTOUR from its original design. | **Blitz-Critical** From project start, they were under pressure to meet specific launch opportunity with a strict schedule. |
| **CONTOUR** ***Actual*** | **Platform** Management believed they were building upon the success and technology of past missions. | **System** Integration testing was performed late in development, resulting in an inadequate understanding of the uncertainty of the system. | **Medium-Tech** Approached as a non-revolutionary improvement to past missions, thus assuming a lower level of uncertainty. | **Fast-Competitive** A belief that events such as integration and testing could occur late; team members for most of the project life cycle worked 40-hour weeks. |
| **MCO** ***Required*** | **Breakthrough** Integrated mature technology with a new and untested spacecraft. | **System** A complex interaction of subsystems and elements that would function in Mars' orbit and with the MPL. | **High-Tech** Much of the technology was developed prior to the project's inception, but MCO was the first of its kind. | **Blitz-Critical** Time was critical for project success and delays would only equal cancellation. |
| **MCO** ***Actual*** | **Platform** Cost constraints resulted in fast prototyping that compromised testing and reviews. | **System** Cost constraints limited control of subsystem integration and the absence of end-to-end verification and validation. | **Medium-Tech** Pressures to push the boundaries of BFC affected costs, testing, reviews, communication, and technical skills. | **Blitz-Critical** Schedule, cost, and technology had limited margins with a fixed launch window. |

Table 5 shows that for Mars Pathfinder and Lunar Prospector the required and actual approach were equal. For CONTOUR and MCO cost constraints and pressures to be successful in a BFC environment resulted in management making heuristic decisions on what to cut back to save costs. These items became important to the success or contributed to the failure of the two projects. Ed Euler, MCO project manager, stated that during the preproject development process and during the project the pressure of meeting the cost and schedule goals resulted in increasing risk and “knowingly cutting proven engineering practices to meet the cost and schedule demands.” For CONTOUR, critical redesigns at the end of the Phase A/B study created what Ed Reynolds defined as “doing a big rocket mission on a little rocket.” Table 6 shows a comparison between key factors in successfully managing a breakthrough, system, high-tech, blitz-critical project through SPL and root causes of failure as defined by the CONTOUR and MCO’s Mishap Investigation Board (MIB) Reports.

**Table 6: Root Causes in the Mishap Investigation Reports compared to SPL**

| SPL | CONTOUR MIB | Mars Climate Orbiter MIB |
|---|---|---|
| Considerable design, development, testing, and redesign; prototypes usually used during development. | Reliance on analysis by similarity; inadequate systems engineering process. | Inadequate systems engineering processes; improper verification and validation processes. |
| Frequent communication through multiple channels. | Inadequate communication between key systems. | Inadequate communication between project elements. |
| Manager with good technical skill; many professionals and academicians on project team. | | Inexperience of key personnel and no training; limited knowledge of spacecraft characteristics. |
| Tight and formal control of technical, financial, and schedule issues; reviews with customers and management. | Inadequate review function; significant reliance on subcontractors without adequate oversight, insight, and review. | Improper independent reviews. |

Novelty

**Mars Pathfinder:** Mars Pathfinder was a breakthrough product that introduced to the world a new way of landing on Mars, and more significant, a robotic rover to traverse the planet. No exploration robot has ever traversed a planet in the history of space exploration. Mars Pathfinder opened new possibilities to space exploration with a foundation built on a limited historical record of similar past projects. Because of time constraints, development was quick and prototyping almost seemed parallel with assembly. Mars Pathfinder maintained a flexible approach to development while using intuition, excessive testing, and a learn-as-you-go mentality. While keeping a strict eye on the project objectives, schedule and cost, they were flexible with changes to stay focused on success. With such a fast development pace, Mars Pathfinder made sure they kept their customer educated about the potential risks and ultimate success.

**Lunar Prospector:** Lunar Prospector was a breakthrough product. Lunar Prospector put existing technology to new use, in itself a breakthrough in the aerospace industry, and pushed the boundaries of cost-effective space exploration. While there was much to be learned from Apollo, these early lunar missions only opened 20 percent of our understanding of the Moon, and little had been accomplished in lunar exploration since Apollo. Therefore, Lunar Prospector was based largely on scientific fundamentals, with limited experience in similar products and history of trial and error. This meant fast prototyping, keeping a close, honest relationship with its customer, and late design freezes.

**CONTOUR:** CONTOUR was a breakthrough project. No one in the history of space exploration had brought a spacecraft as close to a comet as was planned for CONTOUR. Almost all of the technology they were using existed, was previously tested, or was being tested on NEAR and Stardust. Although APL had been successful with recent missions, not one successful mission had been repeated. Each mission, even if using similar, proven technology from past missions, had some degree of unproven technology and was a new venture. CONTOUR was no exception. There was still a lot to be learned about how to perform an Earth swing-by and rendezvous with a comet. Traveling to a comet incorporated a lot of calculated risks, intuition, and trial and error. CONTOUR would require fast prototyping, late design freezes, and constant interactions with its customers.

In many respects, CONTOUR was very new because this technology was being packaging into a new product with a new, first-time-used, noncoherent DOPPLER navigation system and the SRM had to be integrated into the spacecraft to perform the scheduled Earth swing-by maneuvers. This novelty in technology alone defined CONTOUR as a breakthrough project, but it was managed as a platform project. Without a framework to understand the right management style, management believed that they were building upon the success and technology of past missions (NEAR and Stardust) and approached this project as a derivative project. This gave the perception that CONTOUR would be a next generation in existing technology. Few projects in space exploration can be defined as platform projects (e.g. Expendable Launch Vehicles – Delta II, Atlas).

**Mars Climate Orbiter:** MCO was a new-to-the-world product that developed a new use for a product that NASA had not seen before. That defined MCO as a breakthrough project. As the first in a series of Mars missions, MCO was to integrate some mature technology into a new and untested spacecraft. Although NASA had been successful with recent missions to Mars, not one successful mission had been repeated. Each mission to Mars, even if using similar, proven technology from past missions, had some degree of unproven technology and was a new venture to the Red Planet. MCO was no exception. With only a few successful missions to Mars (Mariner, Viking I and II, Mars Global Surveyor, and Mars Pathfinder), there was still a lot to be learned about how to enter into Martian orbit. Traveling to Mars still incorporated a lot of calculated risks, intuition, and trial and error. MCO would require fast prototyping, late design freezes, and constant interactions with its customers.

Unfortunately, the cost constraints of MCO forced it to be managed and designed as a platform project. Using some proven technology and the history of NASA and JPL's successful missions to Mars, the strategy for MCO was that of a new generation in an existing product family. MCO had minimal technological success to build on. While MCO used some of the proven technology from the Mars Observer and Mars Global Surveyor, only the Mars Global Surveyor had been successful. Fast prototyping was compromised by inadequate testing and streamlined reviews. For example, the navigation software system was the most novel and uncertain of all the systems on MCO but received no more testing or review than any other system. In addition, the interaction with customers was less than optimal and was sometimes defined as "confusing."

Complexity

**Mars Pathfinder:** As a complex collection of a spacecraft, lander, rover, and all of its elements and subsystems, Mars Pathfinder was a system project. While JPL led the effort for Mars Pathfinder, it relied heavily on subcontracts with other institutions to deliver the scientific instruments. With Mars Pathfinder's unprecedented public exposure, its customer base spanned from industry to government and the public to the scientific community. As a systems project Mars Pathfinder was a complex project that required extensive planning, sophisticated computer and software tools, a complex contract with many internal and extern subcontracts, tight and formal control, strict financial and schedule requirements, reviews with customers and management. It was JPL's ultimate responsibility to guarantee integration and performance within the project budget, time, and quality constraints. While Mars Pathfinder followed NASA's strict requirements for documentation, great attempts were made to minimize the level of documentation to reduce time requirements. With Mars Pathfinder's high profile, the level of oversight was not limited to JPL, but stretched through the ranks of NASA. The level of bureaucracy was far above that of any assembly project.

**Lunar Prospector:** Lunar Prospector was a system project. As a complex integration of scientific instruments and spacecraft subsystems, Lunar Prospector was led by a main program office, Ames Research Center, directing a prime contractor, Lockheed-Martin. There were several other subcontractors to produce the scientific instruments with a mix of in-house and external development. While Lockheed-Martin managed the project, Ames was ultimately accountable for the spacecraft. Though documentation was kept minimal, the level required for any complex NASA project is extensive. Lunar Prospector was managed with a pure project structure, with tight control over the project and extensive reviews with the customer. Lunar Prospector had multiple key customers from industry, government, the public and the scientific community that were all vested in the project’s development and success. As a systems project, Lunar Prospector was a complex project that required extensive planning, computerized tools and software, hundreds or thousands of activities, tight and formal control, financial and schedule requirements, and reviews with customers and management.

**CONTOUR:** CONTOUR was a system project that understood the integration and complexity of that integration to develop a spacecraft. CONTOUR management approached the project with a formal and bureaucratic style mixed with some informal relationships with subcontractors and customers. It required tight and formal control on technical, financial and schedule requirements supported by many internal and external subcontracts. APL led the spacecraft development, Cornell University led the science, and other institutions were subcontracted to develop the scientific instruments. Multiple key customers from industry, government, the public and the scientific community were dependent on CONTOUR’s success. As a systems project, CONTOUR was a complex project that required extensive planning, computerized tools and software, tight and formal control, financial and schedule requirements, reviews with customers and management, and extensive documentation.

While much of the development occurred in-house at APL, a significant portion of the scientific development occurred outside to APL.  This geographic separation between major systems and management (principal investigator and project manager) restricted real-time, face-to-face communication.  While CONTOUR understood the subsystems of the spacecraft very well, a lack of framework to define unique project characteristics resulted in performing integration testing late in the development, thus not giving them a full understanding of the uncertainty of the system.  In addition, being a heavily matrixed organization, team members were not able to cut ties with their parent organizations to fully commit to the project.

**Mars Climate Orbiter:**  As a very complex interaction of subsystems and elements performing multiple functions, MCO was a system project.  In addition to its own complexity, MCO was designed to work with the MPL when it arrived at Mars.  MCO had multiple key customers from industry, government, the public and the scientific community that were all vested in MCO’s development and success.  As a systems project, MCO was a complex project that required extensive planning, computerized tools and software, hundreds or thousands of activities, tight and formal control, financial and schedule requirements, reviews with customers and management, and extensive documentation.

MCO was managed with its main contract under JPL and the Mars Surveyor ’98 office, and with several smaller subcontracts to complete the development.  The control of MCO was formal with standard reviews, but not tight.  Management worked to empower the subsystem engineers and therefore did not play an integral role in overseeing the project integration.  This was reflected in reviews and control of technical, financial, and schedule requirements.  Reduced involvement in these areas because of cost constraints resulted in limited control of the subsystem integration and the absence of adequate end-to-end verification and validation through reviews. While much of the project was treated as a system, certain subsystems with high levels of uncertainty were managed as assembly projects (e.g., navigation). Key people were balancing time with multiple projects and working the same type of subsystem for each project, while the process that each project was using was different. This was compounded by a lack of communication and transition between phases and subsystem operations. Inheritance from past systems was assumed to reduce the uncertainty, but it did not reduce the uncertainty of integration. Key to any system is an understanding of the impact change and risk have on any subsystem. To treat any part of a system as an assembly is to treat the entire system as an assembly.

Technology

**Mars Pathfinder:** Mars Pathfinder was a high-tech project. While most of the technology was commercial-off-the-shelf, there was a significant portion of the technology that was new to planetary exploration. As a product, Mars Pathfinder was the first of its kind; integrating the technology in a way that had never been done before. Mars Pathfinder required long periods of design, development, testing, and redesign with multiple design cycles that had to start before the project started. With the extensive testing that was required for a high-tech project like Mars Pathfinder, in-depth technical reviews were mandatory to make a project of this complexity successful. In conjunction with these reviews, communication had to be frequent and active. The complexity and communication demands required management to possess good technical skills and be intimately involved in the project. They also had to recognize the unique challenges of Mars Pathfinder and be flexible to extensive testing and design changes. Therefore, design freezes had to be scheduled as late as possible.

**Lunar Prospector:** Lunar Prospector was a high-tech project. As a product, Lunar Prospector was not revolutionary but maintained a simple design using proven technology with only a few new iterations of those technologies. Although most of the technology was commercial off-the-shelf or borrowed from other proven spacecraft, it was innovative in its application. With a simple design (by NASA standards), the project still involved long periods of design, development, testing, and redesign and multiple design cycles that had to start before the project to make a project of this complexity successful. In conjunction with these reviews and testing, communication had to be frequent and active. Good technical skills, intimate involvement, and active communication from management were mandatory for Lunar Prospector. They also had to recognize the unique challenges of Lunar Prospector and be flexible to extensive testing and design changes. Therefore, design freezes had to be scheduled and as late as possible. Lunar Prospector management had a clear understanding of the complexity of the technology they were dealing with and applied the right level of design constraints to the project to ensure success.

**CONTOUR:** CONTOUR was a high-tech project. The technology was mostly proven but being was applied in a new way. Significant improvements were made to the technology to develop CONTOUR from its original design, with minor modification to bring it together to function as a complete system. CONTOUR required long periods of design, development, testing, and redesign with multiple design cycles that had to start before the project started. In-depth, technical reviews were mandatory and had to be supported by frequent and active communication. The complexity and communication demands required an intimately involved management team with good technical skills. Management also had to recognize the unique challenges of CONTOUR and be flexible to extensive testing and design changes; therefore, design freezes had to occur as late as possible.

Without a NASA-specific framework for distinguishing CONTOUR's unique technology characteristics, CONTOUR assumed a lower level of uncertainty in the technology that they were using for the mission and managed the project more like a medium-tech project. This resulted in approaching the technology as a nonrevolutionary improvement to past missions when the application of the technology was very much the first of its kind. Development and testing of the integration of the Solid Rocket Motor (SRM) was limited and did not receive extensive review. Communication was not as frequent with subcontractors and key contributors as was needed for a high-tech project.

**Mars Climate Orbiter:** MCO was a high-tech project that used a mixture of existing and new technology. Much of the technology on MCO had been developed prior to the project's inception and building an orbiter spacecraft was not new. But MCO was the first of its kind. MCO required long periods of design, development, testing, and redesign with multiple design cycles. With the extensive testing that was required for a high-tech project like MCO, in-depth, technical reviews were mandatory, and in conjunction with these reviews, communication had to be frequent and active. Management had to possess good technical skills and be intimately involved. Recognizing the unique challenges of MCO, they also had to be flexible to extensive testing and design changes with scheduled design freezes.

MCO, more than any other project, was under extreme pressure to push the boundaries of BFC. These pressures, constraints, and challenges limited MCO's ability to fully recognize its technological challenges, thus MCO was managed more as a medium-tech project. There were not enough testing, reviews, communication, or technical skills to manage a high-tech project. Many of these key elements to managing a high-tech project were reduced to meet cost and schedule constraints, while some were just overlooked. The dependence on inheritance systems (e.g., navigation) eventually contributed to the failure of MCO. While inheritance allowed for the reduction in time, cost, and uncertainty in development, it did not reduce the need for extensive testing and review of the systems integration. MCO was treated as a "just like Mars Global Surveyor" spacecraft, and without a good understanding of the uncertainty, limited action was taken to reduce the risk. Testing, verification, and validation were reduced, and design freezes were not fixed. Because of budgetary constraints, management left no room for error or flexibility for design changes.  In-depth, technical reviews were streamlined and nominal.  Insufficient resources were allocated for independent peer reviews, resulting in not aggressively seeking experts in the field and not having peers as an integral part of the project.

Pace

**Mars Pathfinder:** Mars Pathfinder was a blitz-critical project.  With most deep-space projects, schedule, cost, and technology have limited margins.  Because of celestial mechanics, the launch window for a Mars mission only comes around every 24 to 26 months.  Once a launch date is specified for a project like Mars Pathfinder, adjustments in the schedule are measured in days, not months or years, and any significant delay in the schedule means cancellation.  In addition, Mars Pathfinder was under a 3 year development requirement from project start to launch.  This was unprecedented for a project of this size and complexity.  To be successful, Mars Pathfinder had to find new ways of doing business and work around some of the standard policies and procedures.  Mostly hand-picked team members, worked very closely with each other with a high-spirited, dedicated attitude.  Problems were resolved quickly with direct lines of communication to management and project managers that were intimately involved in the project in both monitoring and working.

**Lunar Prospector:** Lunar Prospector was a blitz-critical project.  All Discovery Program missions are under a contained development time, and any delays in that would mean cancellation of the mission.  As a pure project, the team was specially assembled because of their unique and valued capabilities, and team members were only retained because they brought value to the project.  When a crisis arose, it was dealt with in a quick and effective manner.  People were open in any crisis, realizing the end goal was more important.  With a shortened development time, many bureaucratic policies were lifted and procedures were kept to the core minimum.  Project managers were very involved in the project from beginning to end and were never afraid to “pick up a wrench” to guarantee project success. In addition, management up the chain never questioned the status of the project. They were kept informed while allowing the project team the freedom to get the project done.

**CONTOUR:** CONTOUR was a blitz-critical project. From the time the project got the green light, they were under pressure to meet a specified launch opportunity with a strict schedule. Time was critical for project success, and delays meant project failure. The project team had to be specifically picked for CONTOUR and they were considered a special group trying to achieve a rapid solution to a vital project. Procedures had to be shortened, made simple, and nonbureaucratic, while top management had to remain highly involved and constantly supportive.

The huge success of BFC at the time of CONTOUR built a confidence in Discover-class missions and gave the appearance that they could be managed as fast-competitive projects. While management understood they were under a constrained time factor, they believed that the project could be accomplished with team members maintaining a 40-hour workweek. In addition, not having access to a framework to determine the project risk led management to believe that events such as integrations and testing could occur late and less frequently in the project. The consequence was that there was not the sense of urgency as seen in successful BFC projects.

**Mars Climate Orbiter:** MCO was a blitz-critical project. Time was critical for project success, and delays would only equal failure. Attempts were made to hand-pick a special project team for MCO that would try to achieve a rapid solution to a high-profile project. The team truly felt the pressure of MCO’s project schedule, sometimes working 100-hour weeks to stay on schedule. Procedures had to be shortened, made simple, and nonbureaucratic, while top management had to remain highly involved and constantly supportive.

### *6.2.5 Project Focus*

All of these projects could be defined as strategic projects, and Table 7 indicates how these projects could be defined as either high or low in the Strategic, Operational, or Inspirational dimensions. Mars Pathfinder was attempting to prove that BFC was a viable management solution to performing low-cost, high-return space exploration for NASA. Lunar Prospector, the first competitively selected Discovery-class mission, was showing that BFC could be performed under a solicitation, peer-reviewed format. CONTOUR would lay out a foundation for Cornell University and APL to build a sustained reputation in space science. MCO would be the first in subsequent scientific missions to Mars and show reliable repetition in Mars exploration. For CONTOUR and MCO, the focus on the project was more operational. They believed they were building on past success, both in how the projects were managed and the technology. Not recognizing the strategic significance of the projects, minimized the projects' strategic focus, which may have contributed to the projects' failure. While the inspirational focus on the projects was variable, Mars Pathfinder and MCO had extremely high-spirited projects. The spirit of Mars Pathfinder was more managed than was MCO. Lunar Prospector and CONTOUR both had a high sense of spirit but not a high focus on spirit. While this may not have appeared to have a significant impact, that lack of focus was detrimental to CONTOUR when the spirit most needed to be managed after the project was hit with potential cost and schedule overruns. Therefore, the level of spirit appears not to be as important as managing the spirit.

**Table 7: Project Focus**

| | **Strategic** | **Operational** | **Inspirational** |
|---|---|---|---|
| **Mars Pathfinder** | HIGH | LOW | HIGH |
| **Lunar Prospector** | HIGH | LOW | LOW |
| **CONTOUR** | LOW | HIGH | LOW |
| **MCO** | LOW | HIGH | HIGH |

## 7. CONCLUSIONS

This investigation addressed two hypotheses: (1) NASA projects require a unique model or framework for project management and (2) Strategic Project Leadership (SPL) provides a fundamental framework for analyzing, planning, and managing NASA projects. As will be described, in the projects that failed, it was not a fault of the talent, but the lack of a framework that could help understand the fit that is needed between the project management style and the risks of these programs. It is believed from this case analysis that the projects that failed were forced to work under constraints that were impossible to achieve under the combined requirements of “better, faster, cheaper” and high project risk. While SPL provides a fundamentally unique and applicable framework for NASA projects, which may have helped in the projects that failed, it is still not an exact fit.

**Hypothesis 1 – NASA projects require a unique model or framework for project management:** NASA’s current policy documentation on program and project management, NPD 7120.4B and NPD 7120.5B, outlines the policies and processes of project initiation, approval, planning, and execution. Both documents mention the need for tailoring the agency’s processes to program and project characteristics and leave much of this interpretation or tailoring to the project manager. However, no formal document makes a distinction among different project types or how to tailor project management to project characteristics. In December 2003, Sherry Bucshmann, NASA Office of the Chief Engineer, stated in a presentation to the NASA/USRA Workshop of Research Topics in Program and Project Management that NASA has identified the need for a project categorization scheme that should be reflected in the new release of NPD 7120.5C.

Currently, NASA uses Technology Readiness Level (TRL) to classify a project based on its stage of development (see Table 8). This classification is based on a technology readiness in relation to being acceptable for launch. While TRL may give some indication as to a technology’s developmental state, it does not correlate to any specific project management principles or guidelines.

**Table 8: Technology Readiness Level**

| TRL | Definition |
|---|---|
| *Level 1* | Basic principles observed and supported |
| *Level 2* | Technology concept and/or application formulated |
| *Level 3* | Analytical and experimental critical function and/or characteristic proof of concept |
| *Level 4* | Component and/or breadboard validation in laboratory environment |
| *Level 5* | Component and/or breadboard validation in relevant environment |
| *Level 6* | System/subsystem model or prototype demonstration in a relevant environment |
| *Level 7* | System prototype demonstration in a space environment |
| *Level 8* | Actual system completed and “flight-qualified” |
| *Level 9* | Actual system “flight-proven” through successful mission operation |

For processes in project development, NASA teaches the Visual Process and Vee Model in its program and project management training (Forsberg, et.al., 2000). More recently, NASA has begun to adopt the Department of Defense’s Spiral Development for its Exploration Program. While all of these principles and practices have proven to be successful, they are focused on process issues and are not all used agency wide on all projects.

The projects investigated revealed that NASA has constraints that are inherent in all of its space exploration projects, such as the harsh environment of space, launch window opportunities, and the NASA culture. All the project managers interviewed said they had to modify required project management principles and practices to be successful. In the projects that failed, the absence of a framework to define the project left project managers with an inability to clearly identify the constraints of the project. For all of the projects, the project managers used heuristics to make determinations on what to cut to meet time and budget constraints. For the two failures, these heuristic decisions resulted in costly failures. A framework may have revealed the project could not have been accomplished under the specified constraints or practices. Perrow (1999) states that while a decision may appear perfectly rational, the operator may be using it in the wrong context. An effective framework, while it may not guarantee success, can provide practitioners with the tools so they can rely less on heuristics. While it is clear from this investigation that NASA needs a unique framework for program and project management, the exact principles to define that framework are not clear. This investigation is viewed as the foundation for the development of that framework.

**Hypothesis 2 – Strategic Project Leadership provides a fundamental framework for analyzing, planning, and managing NASA projects**: The projects studied represented a maturation of BFC, and Perrow (1999) states that as one becomes more comfortable with a technology (in this case BFC), one is more willing to take the risks that may ultimately lead to failure. In the case of BFC, NASA continued to push projects to be better, faster, and cheaper and Dan Goldin later stated that NASA pushed the “envelope too far.” In *The Challenger Launch Decision: Risky Technology, Culture, and Deviance at NASA*, Vaughn (1996) adds to this argument as she claimed that a disaster's roots are found in the nature of an institution’s life. NASA is an institution that was founded on taking high-level risks. Therefore, it could be concluded that BFC was destined to fail over some period of time. Could a framework have obverted or delayed the failure in BFC? SPL defined NASA projects well and provided a fundamental framework for planning and managing projects. While NASA’s policies and procedure are written to be adaptable to many project types, the key principles for various project types are not identified. Applying SPL to the four projects studied, showed that a fundamental framework in planning and managing different projects could reveal that a project may not be able to be successful under its constraints. In the projects that were successful, SPL correlated to the characteristics of the project as described by the case studies. In the projects that failed, SPL showed the deficiencies ultimately responsible for failure. The application of a framework such as SPL in the project planning phase could have identified the approach deficiencies that precluded success.

While SPL has proven to be successful in its application to many different types of projects in various technology areas and has worked well in defining the NASA projects in this study, it is not an exact fit. Some areas of SPL that need further development to be effectively used as a fundamental framework for analyzing, planning, and managing NASA projects are strategic focus, pace, novelty, organization, process, and tools.

**Strategy**: One of the most difficult questions for all of the interviewees to answer was “What is the competitive advantage of your project?” They were quick to say that NASA projects do not have a competitive advantage because they are government-funded. This mentality had a direct impact on the project manager’s approach to the strategic focus. For all of these projects, the competitive advantage was more defined by the project’s value. SPL would have to be refined in the area of strategic focus to be more applicable to NASA projects with an emphasis and refinement of project value.

**Pace**: There should be a distinction between blitz and critical. While the projects studied were considered blitz because of their time constraints, and critical because of their launch window opportunities, this would not be the case for all NASA projects. A type of NASA project that was not studied in this investigation was a human exploration project. Human factors in space exploration add an extreme level of risk and consequences for failure to a project. Many of these types of projects are critical but are not blitz.

**Novelty**: Novelty is related to a product’s uniqueness to the market. Even though NASA products could make their way to the market, they are not designed or developed for traditional market applications. Also, novelty is defined based on a comparison to the market history. NASA projects are rarely repeated and thus are almost always unique to the market (breakthrough). From inside the organization, some NASA projects may not always be viewed as breakthrough projects, but often the technology or its application is still novel. SPL may need a fourth alternative in classifying a NASA project's novelty between platform and breakthrough.

**Organization, Processes, and Tools:** While the elements of organization and processes helped define the four projects with respect to adaptation, there was not enough conclusive evidence to distinguish key factors that define a NASA project. In addition, no unique management tools were identified that were not commonly used in many projects throughout industry. These are key areas that could use further investigation to determine if there are unique characteristics to NASA projects.

### 7.1 Relation to Project Management

This investigation showed that leadership, strategy, spirit, and a framework were important to the success of NASA BFC projects. However, there is still a need to understand how these results correlate to the discipline of project management of complex systems. For leadership, the case studies showed that project managers need to be effective leaders, efficient managers, and technically competent, as well as take responsibility for the vision, its execution, and the business results. This conclusion is not unique to BFC or NASA—other studies have shown that leaders in complex systems projects must be competent both technically and socially (Katz, 1997).

For strategy, the case studies showed that the presence of a strategic approach may have contributed to a project's outcome. The importance of strategy in project management is well stated in the literature, but as Shenhar (2004) has stated, project strategy is typically the missing link between business strategy and the traditional project plan. This investigation concluded that the project managers were perceived as leaders and this was important for the projects success. Shenhar and Dvir suggest that a more strategic approach is needed for projects that must be managed for better business success (Shenhar, 1999a; Shenhar and Dvir, 2004). While the importance of strategy was present in the four projects investigated and is applicable to all project management, the strategic approach for a NASA BFC or government project may be unique.

The importance and expectations of behavioral attitudes of a project have been extensively studied with respects to project culture and spirit (Cooke and Rousseau, 1988; Organ, 1990; Morehead and Griffen, 1998; Greenberg and Baron, 2000). By managing the culture, some have theorized that managers can influence behavior and increase productivity (Deal and Kennedy, 1982; Peters and Waterman, 1982; Kanter, 1983). While this is evident in the project management literature, it was also shown in the case studies as the projects that failed did not adequately manage the spirit. More important, understanding the culture/spirit for the project framework has an important impact on project success (Gallivan, 1997).

A framework, in this case SPL, for analyzing, planning, and managing a project has been shown valuable to project management. Currently, project frameworks are designed for a limited project typology. Shenhar has theorized a unique framework that can be used for effectively managing all types of projects. This research showed that framework could effectively be used to define NASA projects. While these projects may have had unique characteristics, they are still representations of project typologies. Therefore, there is validation in the results of how these projects were classified to non-NASA projects in the same classification. Unfortunately, these four projects only represented one classification in over 200 potential outcomes in the SPL framework.

### 7.2 Research Limitations

Despite the revealing conclusions of this research, it was not without limitations. While the sample set used in this investigation was well defined, it was also this well-defined sample set that may limit the ability to correlate the results to other NASA programs and the project management of complex systems. The sample set covered only unmanned space programs at three NASA centers. NASA's programs and projects cover a multitude of technology developments at 10 NASA centers. Each of these centers brings a unique culture and way of doing business that could reveal variations in the results of this research. This sample set represented only one project type in the over 200 possible project scenarios as defined by SPL. This can cause limitations in generalizing the conclusions to other programs and projects, not only in NASA but across the discipline of project management. This research stated that without a framework, the projects that failed were unable to properly identify a strategic approach. These projects were viewed in retrospect; therefore, the framework was imposed upon the project. While this allowed for a more extensive data collection pool, further research would have to validate the effectiveness of the SPL model for strategically managing a project. A retrospective view also can create some bias in the analysis as some interpretations or conclusions could already have been made by the interviewees based on popular opinion and not objective analysis.

## 8. RECOMMENDATIONS

"FBC was reviewed extensively by the MPIAT and found to be an effective concept for guiding program implementation, if properly applied."

- Mars Program Independent Assessment Team, 2000

From its inception in the early years of Apollo, NASA has prided itself on pushing the boundaries of science and engineering and knowing how to manage these types of projects. Any organization that pushes the boundaries must be willing to accept the consequences of costly, visible failures. When BFC was instituted within NASA, the idea was to show that NASA could work on the edge of not only science and engineering, but also management. However, pushing the management boundaries requires a careful adaptation of risks, resources, and procedures, and projects must clearly assess the complexities and uncertainties of the task. While NASA said "do projects better, faster, cheaper," it was not clear how to do it.

As has been shown, some failed projects were forced to work under constraints that were impossible to achieve under the combined requirements of "better, faster, cheaper" and high project risk. These projects needed a framework and defined principles that could help assess project risks and select the right approach to the right project. There is no question that NASA projects are unique and have distinctive constraints; thus the principles for managing these types of projects should be unique as well. As well, there is no question that as an agency NASA has a vision and a legacy of taking on unique and unprecedented projects. The most revealing outcome of this investigation is that NASA needs a NASA-specific framework for understanding and classifying its projects. Its technological challenges are unique; thus should be its project management practices.

The following is a summary of specific recommendations (in nonranking order) for NASA project/program management based the analysis of the four BFC projects:

1. **Develop a NASA-specific framework for distinction among projects, and develop the unique project management characteristics that are required for each project type** – Incorporate this framework and its guidelines in NASA's procedures documentation (such as NPD 7120.5) and training. Understand the technological complexity to apply the right management approach.
2. **Build a specific project strategy for each project that will focus on creating value and competitiveness. Build a policy that supports the strategy and know its impact** – The project strategic focus must be tied to the vision and objectives, and there must be the right balance in policy to support the strategy.

3. **Build the project spirit, starting with a vision that will be exciting and inspiring, and build the project culture to support the vision** – High-spirited teams are a blessing to project managers, but not managing the spirit can lead to overworked team members. Project managers have to manage the spirit to make sure their teams have the drive and energy from project start to project end.
4. **Design to capabilities, not cost** – Projects that design to cost ultimately fail, or exceed budget and schedule. In a project with an unmovable deliverable date, none of these factors can be compromised. Designing to capabilities can reveal whether a project can even be completed for the time and money specified.
5. **Technical reviews should be in-depth, independent reviews, with active communication with experts outside of the review** – Peer reviews and access to experts is one of the single most important factors to project success. They provide an unbiased, external, critical review of the project and its technical progress. The use of peers to assess a project's development should be an integrated part of project management processes and procedures.
6. **Document the process for success** – Documentation is the storyline of a project's process, and the process for success as well as failure should be documented. When a project fails, it is usually well documented and aggressive corrections are made to avoid future mistakes, but rarely are the factors of success documented.

### 8.1 Future Research

This research was viewed as the fundamental development for determining a NASA-specific framework for program/project management with correlation to project management of complex systems. Therefore, future research to further develop the initial findings of this investigation should focus on:

**Examine other NASA programs** – This research focused on unmanned space programs. NASA made its mark in space exploration with human space exploration, which raises the level of risk and complexity with a project that is unmatched by most standards. In addition, all NASA projects are not “cutting edge.” Further work should focus on NASA programs that fit into other dimensions of the SPL framework.

**Validate SPL as a tool** – Once SPL has been refined to fit NASA programs, it should be validated by practitioners (project managers, senior executives, and decision makers) as an effective management tool.

**Evaluate projects pre- and post-project** – This investigation looked at projects after completion. Further analysis needs to be performed to see how SPL is as an effective model for guiding a project’s success.

**Further investigate the SPL elements and principles for complex systems** – This research could not make conclusive statements about how NASA projects (or complex systems) correlated to all of the SPL elements and principles. Further research should determine if there are unique characteristics for NASA projects (and complex systems) for other SPL elements and principles.

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# APPENDICES

# APPENDIX A – MARS PATHFINDER

# Strategic Systems Innovation

# A Case Study of

# Mars Pathfinder

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## Executive Summary

In 1993, Congress approved a plan proposed by NASA's Space Science Enterprise for better, faster, cheaper planetary missions called the Discovery Program. To show Congress that it could be done, NASA selected two charter missions - one at the Jet Propulsion Laboratory (JPL) and one at the Johns Hopkins University Applied Physics Laboratory (APL). Mars Pathfinder was chosen at JPL as a scientific mission set out to broaden the understanding of Mars and show that Better, Faster, Cheaper could be done successfully.

As a product Mars Pathfinder was a single vehicle (lander), with micro-rover and several instruments designed to demonstrate a low cost system for cruise, entry, descent and landing on Mars. Additional objectives included the deployment and operation of various scientific instruments: stereoscopic imager with filters on a pop up mast, alpha proton x-ray spectrometer (APXS), and atmospheric structure instrument/meteorology package. As a project Mars Pathfinder was to design, test, and develop a lander and rover to launch and safely land on the surface of Mars, at the time one of the most complex planetary exploration projects in space science history. With three years for development and a total cost no greater than $280 million (including the launch vehicle and mission operations) Mars Pathfinder was to demonstrate a simple, low-cost system, at a fixed price for placing a science payload on the surface of Mars at 1/15 the cost of Viking (Viking cost $2.8 billion in 1997 dollars). Mars Pathfinder was a breakthrough product that introduced to the world a new way of landing on Mars, and more significantly a robotic rover to traverse the planet. As a system of a complex collection of interactive elements and subsystems, it functioned as one unit to meet its operational needs. While most of the technology to accomplish this was commercial-off-the-shelf, there was a significant portion of the technology that was new to planetary exploration that made it a high-tech project. As with most deep space projects, schedule, cost, and technology have limited margins, making Mars Pathfinder a blitz-critical project.

On July 4, 1997, Americans across the country were glued to their television to see the first pictures come back from Mars, forever marking this as one of NASA's most celebrated, historic, and accomplished days in its history. A whole new generation was being introduced to the Red Planet through television and the Internet. Mars Pathfinder shattered records for web site hits, peaking at 1 million in a day. From its start, Mars Pathfinder had objectives that gave it unmatched constraints and science objectives that would return an unparalleled amount of data to the largest science community associated with a NASA mission. With all of Mars Pathfinder's interest and success, it is not the landing on Mars that marked its success (Viking I and II accomplished this in 1976 and 1978 respectively), it is the means by which it was accomplished that made it unique, innovative, and electrifying.

To be successful the Mars Pathfinder team had to do business differently from traditional and standard operating procedures. They worked to develop a unique culture centered around leaner staff, reduced overhead, empowered team members, a willingness to do things in new ways, and a management team that believed in a team of capable, self-directed members. To build this cultural rules were lifted, and authoritative structures were minimized. The team was hand picked with many being experts in their field, but most of all these people had to have the ability to be generalist and multi-disciplined. These types of people were picked from a skill set of different ages and experiences, but all brought with them a level of energy and creativity to carry the project from beginning to end. The leadership was committed to the goal and all actions were in line with the goals of launching every day. This meant having a clear vision and making sure that that vision was part of every action. Mars Pathfinder was successful at being on time, on budget, and on target, and management valued the people that they empowered every day.

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**Participant Observation**

Academy of Program and Project Leadership Advanced Project Management training course. June 11-22, 2000.

**Background**

January 1993 marked the start of one of NASA's most accomplished success stories in the last 20 years, Mars Pathfinder. What would occur over the next five years (project start to completion) would be a project that would receive press coverage, congressional accolades, and public interest comparable to the early Shuttle years or Apollo. Although most people were not aware of Mars Pathfinder until it landed on Mars, from its landing to completion, Mars Pathfinder contained the public interest. On July 4, 1997, Americans across the country were glued to their television to see the first pictures come back from Mars, forever marking this as one of NASA's most celebrated, historic, and accomplished days in its history. A whole new generation was being introduced to the Red Planet through television and the Internet. Mars Pathfinder shattered records for web site hits, peaking at 1 million in a day. With all of Mars Pathfinder's interest and success, it is not the landing on Mars that marked its success (Viking I and II accomplished this in 1976 and 1978 respectively), it is the means by which it was accomplished that made it unique, innovative, and electrifying.

Long before the Sojourner Rover would traverse the surface of Mars, NASA was developing the Mars Environmental SURvey (MESUR) project (Mars Pathfinders locus of innovation). The MESUR project had an original design to drop weather stations around the surface of Mars. Early in the project budget constraints threatened to cut the project, so NASA Ames Research Center (ARC) stepped forward with a reinvented MESUR and claimed they could do 16 or 24 small landers for a less significant budget of $200 million. The NASA Jet Propulsion Laboratory (JPL) did not believe that it could be done for such a reduced budget. JPL performed a counter study that peaked the interest of NASA Headquarters, but also stated that if JPL was to do such a project they had to run it. JPL was known for its planetary exploration expertise, so what resulted was a clash between JPL and ARC for the rights to develop the MESUR project. In the end, JPL won. The first thing JPL did was to make it clear that the project could not be done for $200 million. Therefore, JPL proposed that before MESUR get started, a test project needed to be initiated, so MESUR became MESUR/Pathfinder. Pathfinder was a proof-of-concept that would demonstrate that NASA could land on Mars cheaply. At the time, there were two contractors that were looking at the MESUR System (Rockwell and Hughes). They were performing a Phase B (concept) study looking at the 16 or 24 lander system. When Pathfinder was added there was not enough time to finish the MESUR study before Pathfinder was to start, so JPL kept the Phase B study going during the time that Pathfinder was being defined. But, at some point during the Phase B study, it became clear that the MESUR concept was going to be put off.

With the inevitable delay in MESUR, an alternative was sought. The European Space Agency (ESA) had been studying a similar concept to MESUR for a long time. This was a mission called Mars Net. In about 1994, the Mars Science Working Group recommended that instead of doing MESUR as a US only mission, JPL should collaborate with ESA's Mars Net, which would put an orbiter around Mars and be able to pick up the signals from the landers. Negotiations from this collaboration became quite extensive. At the time, the Europeans had a sizable seismometer community, so they wanted seismometers along with weather stations on the landers. Seismometers are large, require a lot of power, and are big consumers of data. In addition, they require a constant power stream because Mars' quacks are unpredictable; hence, they need to be on at all times. Therefore, ESA was demanding bulkier landers than those envisioned for the original MESUR project.

With the joint ESA/NASA collaboration, the Mars Net project became InterMars Net because it would be an ESA orbiter with NASA landers. ESA was quite persistent that NASA provide the landers with all of the ESA instruments along with all of the instruments that the NASA scientists wanted to carry. On top of that, the Europeans were going to provide an Arion 4 rocket as a launch vehicle, which limited capacity. NASA claimed that in order to get all the instruments on the landers, the landers had to be much larger than planned. An agreement with ESA over mass could never be reached, so the number of landers was cut to three. In the end it would cost more to work with ESA on the modified landers then it would if NASA did their own landers. In about 1998, it became clear to JPL that InterMars Net would not work. Ultimately, InterMars Net was not selected by ESA, so the project was dropped. That meant the end of MESUR; therefore, all that was left was Pathfinder.

During the same time as the initial development of MESUR, NASA and the science community began to look at the big missions that they had on the books. They recognized that when Galileo finished its primary mission, they would not have any actual science data coming from space until Cassini reached Saturn in July 2004. That was a period of seven years where there was absolutely no data. So NASA started a small group consisting of representatives from NASA and the science community to look at what NASA could do to offer more opportunities. At the same time, there was a significant out-cry from the science community that those scientist that were on the larger missions had career longevity in obtaining science data because there was a policy at that time that gave data protection rights for the scientist on those projects.

So in the early 90's, the Office of Space Science (Code S) at NASA began looking at how to solve this issue. When Dr. Wesley Huntress became Associate Administrator of Code S in March 1993, he was a strong advocate of finding a way for NASA to provide more frequent opportunities for space science. At the same time, Congress became aware of this issue and asked NASA to develop a program for smaller missions that would allow more frequent opportunities.

In April 1992, Code S submitted a report to Congress with the basic framework for the Discovery Program. These basic mission constraints missions were:

1. $150 million maximum development costs.
2. 3 years maximum development time.
3. Launch on nothing larger than a Delta II

In 1993, Congress approved the plan proposed by Code S. To show Congress that it could be done, Code S selected two charter missions - one to JPL and one to the Johns Hopkins University Applied Physics Laboratory (APL). Because of its constraints to be a cheaper and smaller mission, Pathfinder was chosen at JPL, which became Mars Pathfinder.

**Mission Description**

While not all NASA projects are defined by the same mechanism, most planetary projects such as Mars Pathfinder do follow a usual scoping. This is not a defined process but has become very standard. A science advisory group typically defines the project scope for a planetary mission. For Mars Pathfinder, this was the Mars Science Working Group (established for the Mars Program to provide direction and strategy). The group lobbies a program office (e.g. Mars Program Office) and the program office goes to NASA headquarters to request a mission that they would like to fly. They specify to NASA Headquarter the amount of money that this would require and the science constituents it would satisfy. NASA Headquarters then determines if they will fund the project, and then at project inception the scientific goals are set (observations, measurements, time needed to collect data, quality of data). These scientific requirements then drive the spacecraft design. As with Mars Pathfinder and many planetary projects, what typically happens over the course of the project is that the realities of building a spacecraft and having it operate under the specified conditions are much harder than envisioned in the beginning. As with Mars Pathfinder, the scientific goals, while originally ambitious, became modest. As one manager stated, “Even with a lot of experience you always find yourself hard-pressed to meet all the science goals.” And the reason for that may be as one manager states, “You’d think they might learn after a while and propose less-lofty goals, but again you’re in this vicious cycle of, the less-lofty goals you propose, the less likely it is that NASA Headquarters is going to sign-off on the mission. So naturally what happens is you start off with this nice grand scope and by the end of the project you’ve whittled that down somewhat.”

To overcome this dilemma, Mars Pathfinder management credits “smart project managers” working diligently at the beginning with the scientific community to understand what parts of the science goals were the most important. One scientist stated, “You can tell an experienced planetary scientist from someone who’s not. Because someone who’s not will say, ‘Oh, everything’s important. You don’t do this and the mission’s not worth flying.’ And they say that to everything.” The reality as Wayne Lee, Mars Pathfinder Engineer, stated is that if “…you don’t back off early enough, you wind up with design headaches just before launch.”

From its start, Mars Pathfinder had four objectives that gave it unmatched constraints and science objectives that would return an unparalleled amount of data to the largest science community associated with a NASA mission.

The Major Objectives of Mars Pathfinder were:

1. "Faster, Better, and Cheaper" with three years for development and cost no greater than $150 million.
2. Demonstrate a simple, low-cost system, at fixed price for placing a science payload on the surface of mars at 1/15 the Viking price tag (Viking cost $2.8 billion in 1997 dollars).
3. Demonstrate NASA's commitment to low-cost planetary exploration by completing the mission for a total cost of $280 million including the launch vehicle and mission operations.
4. Demonstrate the mobility and usefulness of a micro-rover on the surface of Mars. (www.jpl.gov)

The Science Objective of Mars Pathfinder were:

1. Surface morphology and geology at meter scale.
2. Surface mineralogy and elemental composition of rocks, soil, and surface materials.
3. Magnetic properties and soil mechanics of the surface.
4. Atmospheric structure as well as diurnal and seasonal meteorological variations.
5. Rotational and orbital dynamics of Mars.

An unbelievable 2.3 billion bits of information, including more than 16,500 images from the lander and 550 images from the rover as well as more than 15 chemical analyses of rocks and soil and extensive data on winds and other weather factors were sent back to Earth from a lander that outlived its design by three times and a rover by 12 times. All of these accomplishments were


value added returns, for nobody planned for this level of success. What was planned and made Mars Pathfinder unlike any mission in NASA history was that it was accomplished with a total budget of $270 million in a three-year timeframe – start to launch (See Table 1). Mars Pathfinder launched atop a Delta II-7925 launch vehicle from Cape Canaveral Air Station in Florida on December 4, 1996. Once on its seven-month journey to Mars, it went through four trajectory corrections to maintain its flight pattern with only minor difficulties early in the mission (two of the spacecraft' s five Sun sensors needed adjustment). For the majority of the flight, all critical spacecraft subsystems functioned as expected. On June 30, 1997, the flight team commanded the spacecraft to switch into its entry, descent, and landing mode. After a much-anticipated trip to Mars, Mars Pathfinder passed into the sphere of Mars' gravitational influence on July 3, 1997. Over the next six hours, Mars Pathfinder would go through one of the most innovative and accomplished planetary landings in space history (see Table 2 for the detailed landing sequence).

| | |
|---|---|
| **1992** | |
| | Mars Pathfinder is born from MESUR/Pathfinder |
| **1993** | |
| **January** | Project Starts |
| **May** | In-house Review |
| **July** | Design Review |
| **1994** | |
| **September** | System Critical Design Review |
| **1995** | |
| **May** | ATLO Readiness Review |
| **June** | ATLO Start |
| **1996** | |
| **August** | Launch Readiness Review |
| **December 2-25** | Launch Window |
| **December 4** | Launch, at 1:56 a.m. EST from Cape Canaveral, FL |
| **1997** | |
| **May** | Surface Operations Readiness Review |
| **July 4** | Landing on Mars, approximately 10 a.m. PDT |
| **August** | Planned Mission Completion |
| **September 27** | Lander Batteries Fail, Last successful day of transmission |
| **October 7** | Last Signal |
| **November 4** | Press Conference to Announce End |
| **1998** | |
| **March** | Mars Pathfinder Mission is declared officially complete |

**Table 1: Project Milestones**

Upon hitting the Martian surface, Mars Pathfinder would bounce 15 times (maximum height 15 meters) before the air-bag cushioned lander came to rest just 20 kilometers from its targeted landing site. Approximately 90 minutes after landing the first data was received by the flight team that the lander had fully deployed its petals. The first transmission of the lander's low-gain antenna was received on time with information about the health of the spacecraft and rover; the spacecraft's orientation on the surface; data about its entry, descent and landing; and a first look at the density and temperatures of the Martian atmosphere. On the same day, Pathfinder transmitted via its high-gain antenna the first images from the lander's camera. These images not only revealed a beautiful mosaic of the boulder-strewn Ares Vallis (an ancient flood plain in Mars' northern hemisphere), but that the airbags had not fully retracted. This was obstructing the opening of one of the ramps the rover would deploy on. After capturing some images of the landscape, the lander spent the rest of Martian day one (Sol 1) retracting the airbag so the rover could roll out off the ramp. A second problem was with communication between the lander and the rover. This was attributed to the modem on the lander, but was fixed on the second day. On the night of July 5, the Sojourner Rover (named after Sojourner Truth, the Civil War, African-American crusader) extended her rocker bogies and rolled off the Pathfinder lander. This marked a historic moment in space exploration with the first unmanned planetary rover. Sojourner spent the rest of the day using its alpha proton X-ray spectrometer (APXS) to take 10 hours of measurements. Over the next two and a half months, Sojourner collected data on 15 rocks - including those nicknamed Yogi, Scooby Doo, and Barnacle Bill. It also performed technology experiments designed to provide information that would improve future planetary rovers.

| **T minus 34 minutes to landing** |
|---|
| ▪ Release of the cruise stage. |
| **T minus 4 minutes to landing** |
| ▪ Entry into Mars' upper atmosphere |
| **T minus 2 minutes to landing** |
| ▪ Deployment of the 11-meter diameter parachute |
| **T minus 8 seconds to landing** |
| ▪ Release of the heat shield<br>▪ Release of the lander from the backshell<br>▪ Descent of the lander on a 20-meter tether<br>▪ Acquisition of altitude information by the radar altimeter<br>▪ Inflation of the airbags |
| **Moments before landing** |
| ▪ Firing of the rocket-assisted deceleration engines<br>▪ Cutting of the tether<br>▪ Free-fall of the lander to the Marian surface |

**Table 2: Landing Sequence**

The last successful data transmission cycle from Pathfinder was completed on September 27, 1997, Sol 83. The final signal was received October 7, and for the next seven months the Pathfinder team attempted to contact the lander. Then in March 1998, the Pathfinder mission was officially concluded. Based on an assumption that the lander was not working after the signal was lost, it is believed that the rover went into a contingency mode within a few days. This meant that it either was left circling the lander repeatedly or standing in place, awaiting instructions.

In the end, Mars Pathfinder used 250 full-time, 150 part-time (lander), and 30 full-time rover personnel to launch, land, and operate Mars Pathfinder. It was launched an unprecedented 47 months after start date and landed on the surface of Mars 55 months after start date. Once on the surface the scheduled one-month operation became four months with an eventual project completion 69 months after project start date.

### Technology Description

Mars Pathfinder was a conglomeration of both commercial-off-the-shelf components and new technologies (see Figure 1 for a listing). With each component being evaluated for its contribution to performance, risk, and cost. Although Mars Pathfinder used some existing technology, it was a breakthrough in its technological innovation of landing and operating on

New Technology

- Free-ranging micro-rover with on-board autonomous navigation
- Rocker bogie suspension
- Solid-state X-band power amplifier
- Radiation-hardened Loral RS6000, 32-bit flight computer
- Airbags adapted for Mars atmosphere
- Image data compression

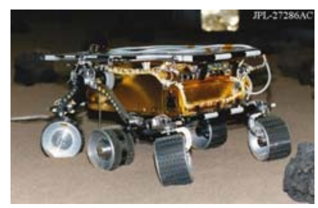
Existing Technology

- Rocket assisted deceleration rockets and altimeter (DOD)
- Transponder (Cassini)
- Star Scanner (Magellan)
- Sun sensors (Adcole Corp.)
- Aeroshell and Parachute Design (Viking)

**Figure 1: New and Existing Technology**

Mars. As a system (rover, lander, Earth) it was a collection of integrated software and hardware systems that could be classified as a high-technology project.[1]

The lander was controlled by a derivative of the commercially available IBM 6000 computer with a 32-bit architecture, which was capable of executing 20 million instructions per second. The computer stored flight software as well as engineering and science data on 128 megabytes of DRAM. Three solar panels provided 1,200 watt-hours of power per day on clear days. At night, it maintained power on rechargeable silver zinc batteries with a capacity of 40 amp-hours. The lander carried a camera on a mast to survey the surroundings with a 14-degree field-of-view in both horizontal and vertical directions (256 by 256 pixels). The rover, Sojourner, weighing in at 15.5 kilograms (on Earth) was equipped with three cameras (a forward stereo camera system and a rear color imaging system). Sojourner was powered by a 0.2 square meter solar array with backup from lithium thionol chloride D-cell sized batteries. Three radioisotope heater units containing plutonium-238 were used to give off about 1 watt of heat each to keep the rover's electronics warm. The rover wheels and suspension used a rocker-bogie system that was unique in that it did not use springs. Three motion sensors along the frame could detect excessive tilt and stop the rover before tipping. In addition, the rover performed technology experiments for future rovers: terrain geometry reconstruction from lander/rover imaging; basic soil mechanics by studying wheel sinkage; path reconstruction by dead reckoning and track images; and vision sensor performance. Aside from the technology experiments, the rover carried the alpha proton X-ray spectrometer to measure the elemental composition of the rocks and soil.




NASA-JPL

To accomplish these technological innovations Mars Pathfinders team was not limited to just engineers and scientists from JPL. The imager for Mars Pathfinder was developed by a team lead by the University Of Arizona with contributions from the Lockheed Martin Group, Max Planck Institute For Aeronomy in Lindau, Germany, the Technical University Of Braunschweig in Germany and the Ørsted Laboratory, Niels Bohr Institute for Astronomy, Physics and Geophysics in Copenhagen, Denmark. The alpha and proton spectrometer portions were provided by the Max Planck Institute, Department of Chemistry, Mainz Germany, and the x-ray spectrometer portion was provided by the University Of Chicago. Other contributors or participants on the Mars Pathfinder project that were not with JPL were from Ames Research Center, Oregon State University, Cornell University, Risoe National Laboratory, U.S. Geological Survey, University of Tennessee, Applied Physics Laboratory, Princeton University, Malin Space Science Systems, Inc., and DLR Institute for Planetary Exploration.

[1] Shenhar, A.J. 2001. One Size Does Not Fit All Projects: Exploring Classical Contingency Domains. Management Science. March, 47(3):394-414.

## Strategic Project Leadership

### <u>Strategy</u>

#### *Objectives*

Mars Pathfinder maintained simple objectives centered on cost, schedule, and an attainment of some “modest” scientific objectives. In the end it would be the scientific community, user of the billions of bits of data returned from the mission, and congress, ultimate funder of Mars Pathfinder and any future missions, that would judge it’s success. As customers to Mars Pathfinder, the scientific community would use the mountains of data to advance the scientific understand of Mars and our solar system, support graduate students, and advance careers. For congress, it would build faith in NASA’s ability to do low cost space science missions, and build support for future funding. All the management on Mars Pathfinder believed that in order to achieve the project objectives they had to be constrained. Although the objectives for Mars Pathfinder were modest, the means by which these objectives were achieved were not. The innovation of Mars Pathfinder did not lie in the mission objectives, but in the how.

#### *Competitive Advantage /Value*

It is difficult for a government project to define a competitive advantage. Usually they are supported by a congressional or administrative push. In some cases they are developed from a scientific community pull. In either case there is usually little competition, but there can be a significant value, to congress, the agency, the public, or the scientific/engineering community it supports. For any project like Mars Pathfinder, the competition that exists is before the project starts. What typically happens is principal investigators team up with various engineers and scientists at specific NASA centers to collaborate and write a proposal to NASA Headquarters. There may be as many as thirty other groups preparing proposals to meet the same requirements. John Wellman, Science Instruments Manager, said that there is definite competition, because their will always be another center that thinks they can do it better. This can become severely competitive. As Wayne Lee said, “It brings out the best in terms of designs and ideas.”

For Mars Pathfinder, the competitive advantage, as Donna Shirley, Rover Project Manager, saw it, was partly skill and partly political, but once the project started there was little competitive advantage and a lot of value. Prior to the start of Mars Pathfinder, JPL was in competition with ARC for the rights to develop Pathfinder. Therefore, the competitive advantage JPL had in the competition with ARC was that they had success with similar projects and they had a reputation as the planetary center. Before Mars Pathfinder, JPL had a project to attempt to recover a lander on Mars in 1971, CSAD (Capsule System Advanced Development). It showed how to land on Mars very cheaply, and it used some of the same technology proposed for Mars Pathfinder. In addition, JPL had landed probes on the moon, were building small rovers, and had such a head start with their rover technology (e.g. Rocky 4) that no other center could come close. It was evidence that JPL could be successful with Mars Pathfinder. ARC on the other hand had not done anything since Pioneer, and Pioneer was a simple mission compared to other JPL successes. The other difficulty for space science missions is that there are usually few missions before it to compare against. For Mars Pathfinder it was Viking. Although the comparison was almost incomparable in the level of constraints, it was nonetheless compared in terms of project cost and scientific return.

Once Mars Pathfinder was initiated, the competitive advantage transitioned into the value of Mars Pathfinder. Most members of the Mars Pathfinder team felt that the value of Mars Pathfinder fell on the fundamental objectives and the primary customers. For instance, the first objective was to demonstrate NASA's ability to do a cost-constrained, high-performance mission with a fixed budget and schedule. Mars Pathfinder was much cheaper than anything like it in the past and it carried an excitement that was unmatched. This had great value to NASA in their ability to demonstrate to Congress, the American people, and their own administration that it could be done. Therefore, it was clear that the value to NASA, the public, and congress were intertwined. The second objective was to demonstrate the technology that could land safely and cheaply on Mars. Mars Pathfinder was a great success in the press, and at the time this was a great relief for an agency that was being viewed negatively in the press because of one of its largest projects (International Space Station). The third was to demonstrate the mobility and the fourth was to do science. Brian Muirhead, Mars Pathfinder Payload Manager and later Project Manager, emphasizes that the values match the objective in this ranked order.

***Business Perspective (Success Dimensions)***

"Develop a plan, then improvise."

– Brian Muirhead, *High Velocity Leadership: The Mars Pathfinder Approach*

Mars Pathfinder developed a plan early on based on a detailed schedule and worked hard to maintain that schedule. Traditionally within NASA the standard mechanism for running planetary flight projects and performance metrics is a system called "earned value." Earned value is based on a cost per task performance standard. For example, if a project has one hundred different tasks (or items to procure), and each task/item has an estimated value or cost, these tasks or procurements will be completed by a certain point in time. As each one is completed, a monetary credit for completion is given and that is graphed against how much money has been spent thus far to see where a project is on the curve. But as one engineer stated, "It sounds good in theory until you really try to do it in practice. You realize that for something that is supposed to be a valuable metric it is only useful to the highest-level managers somewhere looking to appease somebody that might have to talk to Congress or make sure you're over budget or under budget. At the planetary flight projects level they kind of roll their eyes over earned value. You sort of do it because you have to, but you sort of build a gut feeling of how it's really going."

As with any project, Mars Pathfinder viewed success at many different levels and thus in many different ways. For Mars Pathfinder, success was measured from the perspective of NASA, the public, and the science community. NASA measures its success by the attainment of project goals. For example, NASA headquarters will give a project a list of success metrics they have to accomplish for the mission to be successful, but as one engineer stated, "What happens is that in order to keep expectations down and to play down the risk of some sort of anomaly happening during the mission that degrades its performance from the theoretical maximum, the success criteria that headquarters set are actually fairly low." For Mars Pathfinder the rover was to last seven days, and it lasted almost 83 days on the surface. Usually the success metrics set by NASA headquarters are set so that unless a major disaster occurs, they can easily be achieved. As one engineer so colorfully put it, "It is like when you take a test and you hope you get a B on the test knowing darn well you'll get an A, so when you only get a B+, you feel good about yourself." Therefore, Mars Pathfinder started with defining the success objectives in the mission, which were discussed and changed throughout the development phase of the mission, in terms of what would constitute a successful demonstration of the rover and data return. There were two bounds on these success dimension: (1) the lower bound: land on the surface of Mars safely and (2) the upper bound: land safely and send back at one panorama, get the rover to function on the surface of Mars, and use its instruments to collect data on a rock. Within these bounds planning decisions were made on the basis of risk, budget, and schedule.

From the public standpoint, success is how well is it received in terms of the news media, website hits, and the sheer amount of publicity that is generated. One engineer stated that, “Although NASA Public Affairs likes to think of the more long-term metrics of success in public engagement: educating teachers and getting information to schools to teach them about space, all it really comes down to is, were the people excited at that point in time?” Mars Pathfinder received an unprecedented amount of media coverage. On the day of landing, all major television stations maintained 24-hour coverage, and every major publication (newspaper and magazine) printed stories on this historic event. The web site set up by JPL received 7 million hits, shattering all records for web hits in 1997.

Publicly, Mars Pathfinder was a great success because it was so engaging. Scientifically its success was modest and questionable. Compared to Mars Global Surveyor, which flew near the same time, it was far from a scientific success. The scientific community, a significant customer and stakeholder in the project, would be left with a reduced amount of data and some of the data tagged speculative. The alpha spectrometer had not been properly calibrated resulting in data that was very ambiguous. Neither the Germans nor the University of Chicago tested the instrument in a $CO_2$ rich atmosphere (Mars is 95% $CO_2$). The instrument works by distributing alpha particles, and these particles are either absorbed or re-radiated by the rock. However, if introduced to carbon and oxygen atoms in between the stream, it alters the flow of the particles. The instrument has been repeatedly recalibrated after the fact to reevaluate the results, but to no avail. Therefore, all of the data from the alpha spectrometer is suspect. That was the most innovative and new science instrument being flow on Mars Pathfinder.

As for Mars Pathfinder and many NASA projects, a real measure of success is: did it generate enough excitement such that Congress recognizes it as a success and get funded next time. Thus, by getting funded next time, you’re able to offer the science community more-ambitious projects. To measure the success of Mars Pathfinder is also to measure its success with the science community. Was the mission conducted long enough to allow the science community to gather enough data? On missions such as Mars Pathfinder, the amount of data should last the science community really fifteen or twenty years. For example, Wayne Lee stated that he knew people that had received their Ph.D. analyzing data from the Viking-era missions in 1976.

While Mars Pathfinder worked towards a self-measurement of success that appeared to be straight forward, it was what Mars Pathfinder benchmarked itself against that was harder to define. As with many NASA project post-Apollo, it is really hard for project teams to benchmark themselves against something. Rarely is there anyone to beat or is anyone doing anything even remotely similar. As with Mars Pathfinder, they ultimately benchmarked themselves against what they promised, deliver it on schedule, within budget and with a level of quality data. One benchmark that can be defined is ‘Did we do better than last time?’ This is an interesting benchmark because sometime there is no last time and in every case you always try to do better than last time. Rarely are missions with NASA repeated identically with the expectation of achieving identical results.

### ***Strategic Focus***

“If you don’t make quantifiable progress toward the goal of launching every day and you let very many days slip by, you won’t get there.”

- Donna Shirley, *Managing Martians*, p. 139

Wayne Lee states that most projects have very little strategic focus. He explains that in the Space Shuttle Program there is a program office looking after the long-term goals and that the missions are building on top of each other. In the planetary programs it’s a little different holding programs together because of the fact that launch opportunities do not occur every two or three months like the Space Shuttle.  For example, a sustained Mars program, which has the most-frequent launch opportunities, would only have a launch window every 26-27 months (due to celestial mechanics). Lee sees this as a challenge in sustaining the interest and support of Congress and the American public.   Because the opportunities are so limited it becomes hard to get Congress and the President to commit to a ten-plus year Mars program. What has occurred over the last ten years in the Mars Program with launches every two or three years is unprecedented.  This has not occurred since the Sixties when the Cold War fired much of America's space innovation.  Since then, it has been a mission (project) by mission (project) effort.  The large programmatic efforts have been restricted because funding limits and agency strategic changes.  As Wayne Lee emphasized, "Before, if you were lucky enough to get one mission funded, you counted your blessings with that. The programs were almost impossible to sustain because by the time you got to the second step of the program it was already dead because priorities had changed. Because of this trend, planetary projects have had a very project-centric view on strategic goals. It has mainly been very tactical. How do I get my project to work tomorrow?"

This nonstrategic focus that Lee refers to had to change for Mars Pathfinder to be successful. Simply, the strategic focus for everyone was to land a spacecraft on the surface of Mars for a budget less than, as Brian Muirhead puts it, "the largest blockbuster movie at the time, *Waterworld*." The added challenge was that it had to be accomplished on a fixed cost, spacecraft plus rover, of about $200 million and within three years.  Given these programmatic constraints and the added technical challenge, the strategic focus needed to be one that could allow people to get through this really tough challenge.  Donna Shirley believed this was simplicity.  She stated, "Modesty, simplicity were really the strategies of Mars Pathfinder."  All of the managers believed in this strategy and Shirley emphasized it simply as, "Keep it simple stupid."  But, that did not mean that the project was not challenging.  Mars Pathfinder was going to demonstrate something that had not been done before under these kinds of constraints. Therefore, Brian Muirhead believed they needed a strategic focus that said, "Take risks, don't fail."  That was the behavior that management stressed to the team.  With a reduction in structure and policy, people were allowed to think outside the box and challenge themselves and the project.  This behavior, Muirhead believes, was critical to turning the Mars Pathfinder competitive advantage into a successful project.  To create this relentless pursuit of the competitive advantage or focus, management fostered a focused vision for the project and made sure that this vision was part of everyone's approach.  Mars Pathfinder team members believed in the project vision and thus became self-directed to achieving the strategy.  There was a clear linkage between the strategy, vision, and objectives.  This made sure that as long as team members understood the objectives and were committed to their success, they were committed to the vision and the strategy. Management used regular weekly meetings and advice from a peer review committee to stay focus on the project strategy and objectives.  Everyone felt accountable and committed.

More specifically, Mars Pathfinder management identified specific events and actions that allowed Mars Pathfinder to maintain a strategic focus toward success:

- **Reduced Requirements**:  Many requirements were pushed back to drive cost and reduce risk.  They felt that this could not be accomplished without a "capabilities driven" project.  They believed the capabilities of the people, hardware, designs, and architecture would drive the project to success.
- **Hand-off Top Management**:  In order to give Mars Pathfinder management the ability to push back requirements and allow people to think differently, they believed top management had to stay hands-off.  Giving them the freedom to do what they felt needed to be done, even if it meant breaking the rules.
- **Getting people to think differently**: Mars Pathfinder was unlike any project that anyone on the project team had worked on before.  Mars Pathfinder management said that breaking the traditional mindset of how projects were done was an ongoing challenge.

- **Managing risk**:  Risk was seen as a distracter to maintaining focus.  When time is critical, there can be no time for stopping to adjust for unplanned risk.  To manage risk Mars Pathfinder:  attempted to understand risk early and develop a mitigation strategy; avoid risk with qualified parts, materials (COTS where needed), and process; rigorous testing, and rapid prototyping.
- **High Reliance on the People**:  By removing much of the structure, Mars Pathfinder believed the people became the foundation of the project and thus critical to its success; therefore, this meant a foundation built on people's knowledge, communications skills, and commitment.
- **Parallel Processes with more Peer Reviews**:  Reviews from technically qualified and experienced peers was seen as on of the most significant factors in contributing to Mars Pathfinder's success and maintaining focus.
- **Co-location**:  Mars Pathfinder felt this allowed management to express the strategic focus on a constant basis in real-time.
- **End-to-End Design**:  People worked the project from beginning to end.  Mars Pathfinder believed this kept people focused on the success of the project because they knew they would be there in the end; success or failure.

**Project Spirit and Leadership**

"Leaders have to reassure their people that they share the same goals for the final products."
– Brian Muirhead, *High Velocity Leadership: The Mars Pathfinder Approach*, p. 39

***Organizational Culture***

Due to the shear nature of the constraints placed upon Mars Pathfinder, they felt they had to invent new ways of doing business, and that became part of the culture. A willingness to take risks, but make sure that they were able to manage those risks. As John Wellman stated, "The overall project had taken on a fairly challenging goal, so I think there was an understanding that we were willing to take some risks on this project that we might not ordinarily be taken on some missions." And by virtue of this, an atmosphere was created where people felt or were continuously reminded of the common elements of the vision. The management was very conscious of the costs and schedule constraints and worked very hard to make decisions that would reflect these constraints. Team members recognized this need, but were not afraid to admit and correct bad decisions. They saw management working with them and not for them. They believed that they all had to finish this project together. For example, as Brian Muirhead put it, "It wasn't one subsystem saying: 'Screw you. I'm going to worry about my budget.' Everybody worried about everybody else. There was a sharing. You know you talk about a really great team holding each other responsible as much as you hold yourself. And that's what we did." Each member of the Mars Pathfinder team held every other member responsible and accountable for his or her actions.

They each had a deeply rooted, common commitment, purpose and goal. They were very diverse and offered different ages and areas of expertise in science and technology. They expressed care and concern for both the individuals and the project. They had a well-balanced task-orientation as well as people-orientation, but always remembering the super-ordinate goal of the mission. Since they were so accountable for each other, they were relatively self-managed with leadership there to provide continual support and direction only as needed.

Brian Muirhead best describes the culture of the Mars Pathfinder organization like this:

> There was a real sense of people. We structured it in such a way that the people that were going to be there at landing were there during the design. So we made sure that people followed all the way through. So people knew they were going to be there on landing day. And that was the key part of our strategy for keeping the cost down. We didn't build or do a lot of documentation. We relied on the people's knowledge and experience to be there. So it really did grow into the tightest, most high-spirited group of people I've ever worked with. If you ask any member of the Pathfinder team, they will say the most special part of it was the relationship they had with the other members of the team. And so it was again, that's the definition of a high-performance team. That's having a personal commitment to the other members of the team making it. And again this showed up at the management level and it became just part of the culture all the way through.

People were more concerned with being honest and meeting the goal, than trying not to "rock the boat." The team enforced "lieutenants," these are people who will tell you if you are off target or just plain wrong. There was also no time for social loafing. While they recognized that each individual contribution to the group effort was significant, almost without exception, they "let go" of any member who wasn't doing the job or contributing to the team effort. Every member of the team valued their input, took personal ownership of their responsibilities and understood how each member played a role in the overall success of the mission. Members of the team had mutual trust and respect for one another and had to be fully competent in his or her domain. Donna Shirley stated, "The rest of the group has to be able to count on you- not just to rely on you to do your work well, but also be there when teammates needed back up. This meant keeping your word, meeting your commitments, and going public if you needed help or make mistakes". There was a healthy balance between being task-oriented and being people-oriented. The idea was to be hard on the issues and soft on the people. That protected the relationships, but allowed them to get at the heart of any problems or issues.

***Project Spirit***

“Mars Pathfinder had more spirit than any mission I’ve ever seen.”
– Wayne Lee, personal interview

When it comes to the project spirit of Mars Pathfinder, Donna Shirley likes to give the example of the atmosphere in the control room at the day of landing for Mars Pathfinder compared to orbit entry for Mars Global Surveyor (MGS). “I have a video I use that shows the Pathfinder on landing day in contrast to the MGS team on orbit entry day. The Pathfinder team is leaping up and down, cheering, and hugging. The MGS team applauds, puts on red hats and passes out peanuts. This total reflects the personalities of Tony Spear to Glenn Cunningham (MGS Project Manager). Glenn Cunningham is very organized, non-emotional, business like, good manager. He picked his team to basically reflect his personality: very thorough, lots of reviews, follow the rules and make it all work. Tony is totally emotionally driven.” Although both projects are considered success, this example is a unique representation of the open spirit of Mars Pathfinder.

Mars Pathfinder believed nurturing and fostering a team spirit; therefore, rituals, ceremonies, and slogans played a key role in team development. Some of these events centered on naming. The first of these was the naming of the rover. A contest was held which allowed schoolchildren across the country to write essays of what the rover should be named. Donna Shirley believed that a lot of kids at a lot of different schools had fun doing it, and it got the public involved in Mars Pathfinder. The person that won the contest was a schoolgirl from Connecticut who was flown out to see the launch. Donna Shirley took a lot of criticism from NASA Headquarters for naming the rover without going through the normal NASA Public Affairs Office procedures. A second naming event was the naming of the rocks the rover encountered. The first rock the rover came to was named Barnacle Bill. It was named Barnacle Bill because it had barnacle-looking substances on it and so it was sort of tongue in cheek. But that created some problems when this information was released at the press conference and the reasoning for naming the rock Barnacle Bill was associated with it appearance and an old raunchy drinking song. This did not go over well for the straight-laced NASA. Matt Golombek, Project Scientist, stated that even with the minor obstacles the naming of the rocks was a source of fun for the scientists. Now it was not rock 3021A, they became Barnacle Bill, Yogi, Scooby-Doo, Matterhorn, and others. Wayne Lee stated that Mars Pathfinder “found ways to take things out of the rigor of the everyday process of NASA’s very straight-laced organization and put some humanity and some fun into the process.” Other naming activities were nicknames. David Gruel, who created the landing operations simulations, was called the Gremlin, and the seven ladies that worked on the wiring that tied the spacecraft together were called the Seven Dwarfs. Donna Shirley also believed that just as the Apollo program had a motto *man, moon, decade*, so should Mars Pathfinder, so she coined *soil, rock, lander*.

Another key activity that was entertaining for the team, and would later become critical for Mars Pathfinder’s success was the creating of test cases for the operations simulation. An Entry Decent and Landing (EDL) group created what they call the “Mother of All Simulations,” which was used to design the whole EDL system. When hardware was delivered for this simulation, it was a big deal. The team invited the whole project team to come to the place where the hardware was delivered. Everybody gathered around, took pictures, and later copies of the pictures were distributed amongst the team.

The abundance of time spent together, the relatively small number of members in the group, the challenge and constraints posed by external factors and those who did not believe in their potential success, all these forces contributed to the team's strong cohesiveness. They all lived in close proximity and worked, and talked and played together daily. They had a great sense of pride and team spirit. Good communications and co-location helped build the team, as did an atmosphere of open communication and shared space help build human relationships. Tony Spear, Project Manager, and some of the other managers, every so often would declare a happy hour and at four o'clock on Friday members of the team would go out for drinks. This activity became a festive event that helped develop camaraderie. John Wellman stated that there was even a group that got involved in a once a week trail hike. This continued for a year and a half over the life of the project. At the end of the project about ten of the regular hikers climbed Mt. Whitney.

***Policy to Support Strategy and Spirit***

Traditionally at JPL projects function as line organizations, people in specific line organizations will not perform tasks outside of their line organization. Mars Pathfinder believed that that had to change, the policy had to change. They felt that anyone from any organization, as long as they had the right mind-set, could do any job. For the first time ever, navigators whose job was to track data from outer space and perform the mathematics to calculate the spacecraft location were working in the test beds. By doing so, they got a new-found appreciation of how the spacecraft operated, and as Wayne Lee stated, "I think were able to do their jobs better." The traditional policy would have never permitted these crossing responsibilities. Wayne Lee believes that if you get the right quality person, you can train them to do most tasks, and in an interdisciplinary environment this becomes very efficient and helpful.

In addition, the co-location of much of the staff allowed for the crossing of line organizations and as one manager described, "I think the fact that everybody was there as an integrated cohesive unit as a team, doing something new, really contributed to the high-level spirit that I was able to observe on the mission. That was something very unique." The idea of co-location fostered less formal and more immediate interactions between management-levels. John Wellman described it, "You know, I'd be sitting in my office and Tony Spear, the project manager would yell in the hole, 'Wellman, get in here!' And I'd walk into his office and next thing you know we'd be in a meeting. So it wasn't a matter of scheduling it for a week from Tuesday, it was pretty immediate." Mars Pathfinder believed that co-location allowed them to solved problems in real time rather than scheduling or waiting for the monthly reviews or the weekly status meetings to get the work done. Wellman contributes this more than anything else to keeping the project on a tight schedule. Mars Pathfinder also contributes co-location to developing an intimate team.

Brian Muirhead said that you have to have a policy (or lack of policy) that will allow you the freedom to be creative about how you do your job. He believed that is really the hallmark of being successful, and if you do not have the freedom to be creative and the constraints are really impossible, you will probably not succeed.

***Leadership***

The management was instrumental to the overall success of the Mars Pathfinder mission. Mars Pathfinder leadership believed leaner staffs, minimal overhead, empowerment of the people and a willingness to do things in new ways. From the beginning, the leadership believed in their team and believed they enjoyed work as naturally as play. They believed they were capable of self-direction and could be motivated and responsible enough to achieve the mission's goal. Manager Brian Muirhead clearly states the key factor to the success of the project was the people. They consistently exhibited their commitment to the goals and all of their actions were in line with the goals. They believed in being an example to the rest of the team and believed leadership begins at the top, and so does team spirit. The leadership had a clear vision, and backed up its words with actions.

The Mars Pathfinder management understood that different circumstances called for different types of leadership. As Donna Shirley believed that sometimes you have to let your team rely on their own abilities; the management team also believed that, as Brian Muirhead states, "…a manager must confidently reach into a project to move it forward." They empowered the employees by giving them access to information that normally only a leader would have. Individuals became more empowered to make decisions when they had access to information necessary to make those decisions. The leaders used whichever style best fit the situation that arose during the project. At times they were participatory, or delegating, selling, or telling. For the most part, they were participating. The leadership primarily provided support and direction. If the circumstances dictated, the leadership was there to make a final decision and move with it. They believed the most successful leaders learn to channel their energy, focus it, and use it to energize their people. The Mars Pathfinder leadership understood they were dealing with a talented team and did not need to micro-manage. The manager is there to help the people and guide them in becoming a cohesive unit, and at times must confidently reach into a project to help move it forward towards the achievement of the goal.

The leadership on Mars Pathfinder worked to create an atmosphere of trust and openness between the employees and management, and the team felt that the management team reflected a very tight, focused group. They believed in making the people, not the policy, responsible to the organization. This instilled a sense of belonging in the team. Younger people dominated the leadership for Mars Pathfinder with a can-do spirit. They believed that things could be done differently and the way things have always been done is not always conducive to getting the job done effectively. As one engineer stated, "Sometimes the older engineers who may become line managers get very set in their ways, and believe you have to do things this way because that's the way we did things before." One engineer felt that when you get a lot of managers working in a collocated environment you don't always have to report back to the line because you're not sitting with your line manager everyday; therefore, "you're able to bend the institutional rules a little bit and get things done efficiently in this can-do spirit kind of way."

Management for Mars Pathfinder carried a level of respect from the team as well. As Wayne Lee stated "You never want to get project managers who have never been in the rubber-meets-the-road situation. They have never faced the pointed edge of the sword. Yes, they can shuffle viewgraphs around but they're not really gonna be that effective." The team members of Mars Pathfinder felt respect and confidence in the management. As one engineer put it, "If you went up to a manager and asked if you could do such-and-such because we're having a hard time with math and schedules, budget, the project manager understood and said I was in your position before, I understand why you need to sacrifice this."

***Team Empowerment***

Mars Pathfinder believed that the people not the management or the technology made the project; therefore, the team was empowered to be decision makers. Brian Muirhead states that because the project was moving fast and the budget was so tight, they really did rely on people's individual effort or contribution. This instilled a sense of ownership and responsibility in the team. People felt the responsibility and personal integrity. Everybody believed they had a key part in the success of the project, whether they were a technician on the floor tightening a bolt or someone working on the simulation of the entry, descent and landing. As Brian Muirhead said, “Everyone understood that we were one failure away from disaster.” Brian Muirhead believed that if people feel like they own it, you’re going to get the performance.

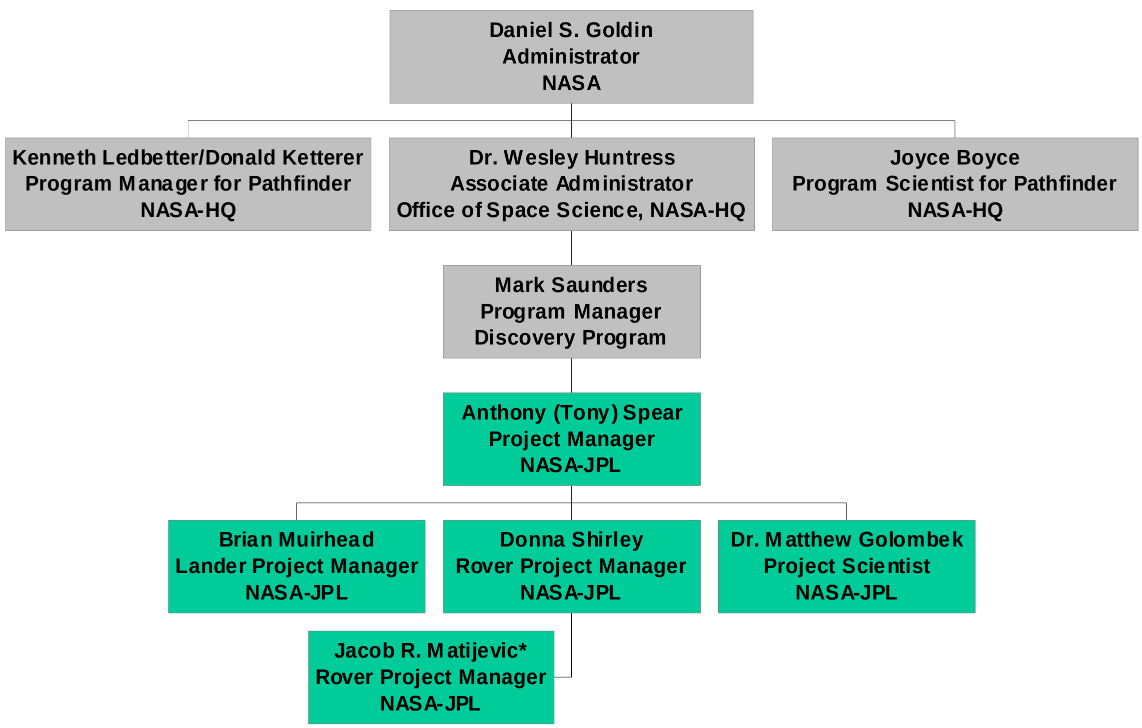
Mars Pathfinder had to make decisions rapidly and they were breaking new ground in some areas; therefore, management felt that people at all levels had to be empowered to do creative thinking, make decisions and follow up on them in order to move the project at a much faster pace than was normal. Donna Shirley described it by saying, “When you are managing really brilliant people, at some point you find it is almost impossible to command or control them because you can’t always understand what they are doing. Once they’ve gone beyond your ability to understand them, then you have to make a choice as a manager. You can limit them and the project by your intelligence (which I think is the wrong way), or you can trust them and use your management skills to keep them focused on the goal”.

Mars Pathfinder management believed that knowledge was key to empowerment. They felt that individuals became empowered to make decisions because they had access to information once available only to managers. Therefore, they made sure that individuals had access to as much information as possible.

## Organization

### *Project Organization*

With many NASA projects, they can become huge bureaucratic monoliths. Wayne Lee states that in many NASA projects people are empowered to do their own tasks, but you are not really empowered to help make strategic decisions. Mars Pathfinder tried something very novel and unique to most of NASA. It employed some of the traditional characteristic of the skunk works paradigm. At JPL, traditionally projects were set up as line organizations with project members reporting and sitting with their line management. Project integration would have to overcome multiple management lines and locations. Mars Pathfinder recognized these as limitations in order to achieve their constrained objectives. As one engineer stated, "The only way that people from different lines interact together is almost never." To overcome this the Mars Pathfinder management secured an entire building and they brought everybody from those line organizations into that building and relocated everybody into one location (about 200 or 300 people). They covered two floors of the building, creating a tight close-knit atmosphere where everybody was readily available. As Wayne Lee stated, "You just had to walk down the hall to resolve a problem and that was a very efficient way to do things."




* Replaced Donna Shirley when Mars Pathfinder landed on Mars

**Figure 2: Project Organization**

### *Structure*

Mars Pathfinder believed in keeping the team small and thus keeping the organization flat. It was about eight project element managers who worked directly for the project manager with a team underneath them. There was almost no hierarchy, and in most areas the group was only one deep with no one person backing up an engineer or scientist. The team was designed to be small so it could function not as a group, but as a “high performance team.” There was a reliance on a small core team with individual subsystem engineers to bridge interfaces, improve the understanding of the overall system and establish relationships with the JPL technical divisions and aerospace community. They believed that a flat organization could empower the people who were doing the work. The challenge as Donna Shirley put it was that “…with flat organizations you can have inexperienced people trying to do the work with no one coaching them or mentoring them.” Donna Shirley believed that if you have a team of more that seven people it is going have a completely different dynamic than a team that is seven or smaller. People are able to avoid becoming decision-makers in teams of more than seven. Therefore, the teams within the project structure were kept small.

The co-location and flat organization allowed for issues to be addressed real-time and across functional areas. John Wellman stated that as manager for the payload, when he had a problem down in the lab, he would go down there and roll up his sleeves and pitch in with whatever needed to be done.

### *Team Assembly*

“Build a team of different ages and experience.”
- Donna Shirley, *Managing Martians*, p. 148

Mars Pathfinder management believed as Brian Muirhead put it, ”Build a team of generalist, people who are not limited in scope to the confines of the work they were trained in or are most experienced at, but who have the interest and ability to work beyond the limitations of their resume’.” They tried to put together the best technical team that they could with a combination of experience and inexperience. Since Mars Pathfinder was not considered a large project, by NASA standards, people were consumed by the bigger projects. Therefore, experienced personnel were hard to come by. The team was dominated by youth. Brian Muirhead even commented that he “felt like the old man at 42.” Most of the people on the team had not done the job they were assigned to do, it required learning the job as they went along. Some saw this as helpful in that it did not limit their perspective. Mars Pathfinder had to take a multi-discipline team and innovate. Donna Shirley described it as, “You get the best people you can, and then you mush the organization around to fit the people.”

With the limitation of not being able to select from a large talent force, Brian Muirhead learned that it is best to work just a few people short of enough. Without the draw from the line organizations, which usually dictated the number of people required for a job, Mars Pathfinder was able to select only the number of people they felt was appropriate. Because of this, Mars Pathfinder would find people within JPL that had the energy, the drive and then do their best to nurture them along. Sometimes this meant having a relatively inexperienced staff, but as they demonstrated their abilities they were assigned more significant responsibilities. Brian Muirhead believed in making people stretch by putting them in jobs they were not “qualified” for by experience, but that he felt they could handle. To support this he found strong “lieutenants,” people who would tell you when things were off target or just plain wrong. Someone like Tom Revilini who was responsible for the airbag system was a perfect example of a typical Mars Pathfinder team member. At the time no one had ever successfully built an airbags system for landing before. Because of the immense engineering difficulty with trying to model the system through computer simulations, it had to be done empirically. The time and effort to design the airbag system empirically took a lot of energy and drive of the individual in charge. Brian Muirhead described Tom this way, "You could have had a really brilliant person, but they couldn't have done a job like that. Tom's a pretty sharp guy, too, but it was his energy that really pulled that job off. And I think overall we had a lot of really smart people that came to Pathfinder."

When selecting members for the Mars Pathfinder, team management wanted people that were going to be with the project from beginning to end. This meant being able to reduce the turnover of key technical personnel, and the ability to identify qualified staff early and foresee any organizational problems. Mars Pathfinder management realized that this poised a risk of staff burnout and limiting someone's career mobility. Although management had to look hard for people to fill some unique positions for Mars Pathfinder, in some cases it was almost self-selected. A lot of people came because they heard about the project. At the time, people at JPL were contrasting Pathfinder to Cassini, a major 'flagship' mission with very formal classic project architecture. When people heard about the kinds of opportunities people were getting, the kind of responsibility and authority they had, people were asking to be part of the project.

While youth and inexperience seemed to dominate Mars Pathfinder, it maintained a level of experienced scientists and engineers to keep the project focused and directed. Wayne Lee best described it as, "I think a lot of the older engineers probably are among the smartest people within NASA, primarily because they had to learn their skills in the days when we didn't have computers. Nowadays, all engineers grow up going through college with computer simulations. It's actually pretty bad because what happens is you get somebody fresh out of college that has no intuition and you tell them, well how did you find that answer. 'Well the computer told me.' Well how do you know the computer's right? They don't know how to think for themselves."

### ***Responsibilities***

In order to manage how responsibilities were allocated with Mars Pathfinder, management put the power in the team. Mars Pathfinder practiced what they called "Soft Projectization." It became an institutional idea where rather than having the line organization responsible for the delivery of a subsystem, they had a Project Element Managers who came out of the line organization and reported directly to the project manager. This project element manager was then responsible and accountable for their subsystem; in addition, they took complete ownership of the delivery of a particular subsystem. The empowerment of the Project Element Managers became a very efficient way to manage Mars Pathfinder.

By empowering the Project Element Managers with the responsibility of ownership for their subsystem, management wanted people in this position who were technically competent and could be close to the action of their subsystems. One of the reasons for this was so when problems came up, the time to resolve any issues could be limited. Management felt that this was critical during a compressed schedule.

But just as the team was empowered with the responsibility to make decisions, management felt they were just as responsible for making sure the engineers and scientist got the help they needed. John Wellman felt that when the science instruments had to be calibrated, and those operations had to be staffed around the clock, he would take a shift along with the engineers and scientist to make sure the work got done on schedule. Although this is a common occurrence on many project, Mars Pathfinder believed that it happened to a greater degree with their project.

### *Top Management Involvement*

Mars Pathfinder believed that commitment begins at the top. They saw top management as a champion for Mars Pathfinder and important to sustaining its success. The commitment of Mars Pathfinder was received from the director of JPL but the project received its true champion in Wes Huntress, Space Science Associate Administrator. Wes wanted to see the Discovery Program be successful, so he selected Mars Pathfinder because he believed it could be successful. With Wes' support, it kept the mission going and gave the project a funding profile that could be worked.

Mars Pathfinder believed top management should be kept informed but has a limited involvement. Mars Pathfinder believed that they were successful because they were left alone. Mark Saunders, Discovery Program Manager, believed that and made sure that Mars Pathfinder had that freedom. They did not get a lot of help from others. As Brian Muirhead said, "A lot of people kind of stood back and said 'Oh my God, those guys are scary.'"

### *Professional Advice and Reviews*

To perform reviews they relied a lot on outside consultants. This was something Tony Spear believed in and made a significant part of the budget. Many of the Mars Pathfinder team felt that the project was over reviewed, and felt that the formal reviews (PDR, CDR) that are once a year are enough to achieve success. But, everyone on the team did understand that the true value in the review was the preparation. Tony Spear worked hard to make sure that the outside review board was a formal, very competent board that would work to keep the team honest. The board members consisted of technical people with recent, directly applicable, subsystem experience. These reviewers were selected based on their knowledge of what questions to ask, how to probe issues, and when an answer was satisfactory. Brian Muirhead said this was important because as they prepared for those reviews they knew they were going to be pretty tough; therefore, being able to understand the system and be able to communicate it well was critical.

### *Organizational Problems*

"Only when there was a dispute of a problem that the team could not solve, they should turn to me."

> - Donna Shirley, *Managing Martians*, p. 149

While problem-solving was common, conflict was not. However, when conflict did arise it was usually handled within the team. Only when there was a dispute of a problem that the team could not solve, did they turn to management. One of the biggest or the toughest problems as Brian Muirhead stated was with individuals. He believed that some people do not always fit into an organization either because they do not have the skill, the drive, or the attitude. An example of this was a story that Brian Muirhead tells,

> "There was early on one guy who was our parachute lead guy, who I just didn't trust. And we had to get rid of him. And so probably over the course of the project we changed out about 10 percent of the staff, just for reasons of they didn't – well, most of the time it wasn't a matter of skill, they just didn't fit in with the environment. You know, they liked more formalism or they just weren't willing to commit, make that personal commitment to pulling this project off on the schedule within the cost."

Even with its problems, Mars Pathfinder believed that there was a culture in which, when a problem came up, it was communicated quickly so all elements of the project were aware of it. This applied to organizational problems and resource problems.

***Training***

Aside from regular training that team members had received through the course of their career, no one received any training outside of on-the-job training during the course of the project.  Most everyone on the project had a four year degree and some advanced. Few had any formal management training.  Once the project was started, it was rapid-paced, and there was no time for training.  For some this meant some pretty quick learning, reviewing archival test results (e.g. Viking), and getting out and meeting the people who did know how to design certain systems. Therefore, the technical learning became on-the-job or real-life crash courses.

## Processes

### *Project Phases and Reviews*

For Mars Pathfinder, at the project level the managers looked at three basic milestones: Critical Design Review (CDR); the start of Assembly Test and Launch Operations (ATLO); and the launch date. CDR is when the design is believed to be set and ATLO is when it is believed that spacecraft assembly is ready. The launch date for a planetary flight project remains fixed because of the alignment of the planets, so that cannot be changed. Therefore, from project inception, the project end date is set. The only two options are to cancel the project or delay it by years. For Mars Pathfinder everything followed on a set schedule from CDR to ATLO to launch date. Management gauged their progress and risks against meeting these three major milestones. These major milestones drove Mars Pathfinder through development. Brian Muirhead said that the biggest challenge in development was getting to the launch pad within budget. Management knew that if they blew the budget the project would be canceled. Everyone on the team felt this perception. Brian Muirhead took it upon himself to make sure that the schedule was maintained. He used it to track people and a way of controlling costs.

Clark and Oberhettinger state in their report on the NASA Lessons Learned Database that,

> A JPL study of in-flight problems on Voyager I and II, Magellan, and Galileo revealed that 40% would likely have been identified by better technical penetration in reviews of the detailed designs performed well before launch. An additional 40% (for a total of 80%) might also have been found by similar in-depth reviews. Because of this JPL adopted the informal peer review process in order to ensure that technical personnel qualified to adequately interrogate the designs obtained the appropriate level of penetration.

This commitment to the design reviews was attributed to reducing the uncertainty. Management for Mars Pathfinder felt that they received more reviews than, "anybody even had any right to even think about." Mars Pathfinder was submitted to about a hundred peer reviews on all of the subsystems in addition to the standard preliminary design (PDR) and critical design reviews (CDR). Although, the amount of internal review within JPL was not as high as compared to a flagship class mission (e.g. Cassini), there was still a fair amount of review from the headquarters side.

Aside from the formal PDR and CDR, Mars Pathfinder placed a lot of emphasis on informal reviews comprised of in-depth discussions of requirements and designs. Mars Pathfinder saw the formal reviews at a verification of the project status and attainment of milestones while the informal reviews featured detailed value-added engineering analysis, problem solving, and peer review. The formal reviews were used as the gates in the development process. But, as Brian Muirhead stated, "they aren't crisp gates." Traditionally the preliminary design is complete at PDR, which gives approval to go into detail design. Then when the CDR is completed, approval is given to go into fabrication. For Mars Pathfinder this traditional approach could not work. Brian Muirhead stated that this not only did not work on Mars Pathfinder, but also would not work on most projects today; "there are just too many parallel threads." Therefore, the CDR becomes the point when a fair amount of the design has been completed, and hardware has already been committed in other areas. Brian Muirhead describes it as a "rolling wave," or a "moving target." For Mars Pathfinder the schedules drove when you needed transition and not the design reviews.

### ***Communications***

"To make it work, you have to design your communications system just like you design everything else and manage it."
- Donna Shirley, personal interview

Communications were critical to moving Mars Pathfinder successfully forward in its project development. Many of the Mars Pathfinder team attributes things like co-location, email, hallway conversations, and focused meetings to their communications success. Brian Muirhead placed a lot of value on face-to-face communication and thus attempted to co-locate as many of the Mars Pathfinder team as possible. This created an environment where decisions could be made in real-time or by walking down the hall or to the next floor. Many critical, timely decisions were made when two people crossed paths in the hall. Donna Shirley shared this belief, but believed that co-location, although important, became impossible as the team began to grow and not everyone was full-time. Donna Shirley felt that in the BFC modality, Mars Pathfinder was the smallest team that could have full-time people, and in a BFC world, collocation becomes impossible because you will be limited on full-time people. Donna Shirley stated that the rover team was not co-located at all, and that she was the only person in the Mars Pathfinder area. She overcame this with weekly meetings, emails, and making people come together to put the rapid prototypes together. Electronic communication (e.g. email) was a major contribution to the Mars Pathfinder team overcoming any co-location issues, as there was a fair amount of email traffic.

Another valuable communication mechanism was meetings, but not how many or when they occurred but how they were conducted. Meetings were kept short (sometimes only 15 minutes), to the point, and offered the opportunity for team members to address issues or concerns. Some meetings had nothing on the agenda, but all meetings included a set of questions that were the framework for the meeting and centered on budget, schedule, and major programmatic issues and changes. Some of these questions included:

- What are we going to accomplish today?
- Does everybody know what they are supposed to do?
- Does anyone have a communication problem with anyone else?
- Are there any other issues?

Decision-making meetings were kept small, where the number of people making decisions was relatively small, to prevent the room from sub-dividing into smaller groups. Donna Shirley had weekly status reports and regular Monday morning meetings to keep everyone focused and Brian Muirhead had two leadership meetings per week: (1) management (2) systems.

Another mechanism by which communication was fostered was in the development of documentation. Mars Pathfinder made the person who generated a document (e.g. requirements, change-control processes, drawings) be the owner of it, and when there was a change needed to the document, that person had to be part of the interface to make the changes. This required a lot of face-to-face and direct communication between all affected parties. Brian Muirhead described that "Sometimes there's an intermediary, like a systems guy who's kind of the glue, the between two subsystems, say between mechanical and attitude control or those which have significant relationships such as propulsion and attitude control. Rather than have a systems guy between them, we let those two organizations really work out the issues between them." This is why Mars Pathfinder searched for people that had a systems mentality.

***Resource Management***

In some respects Mars Pathfinder followed the standard approach to resource estimation at JPL: (1) the initial budget for the project is defined by headquarters, (2) then a bottom-up layout of the schedule and staffing, (3) and then a bottom-up costing. For Mars Pathfinder, this quickly showed that there were not adequate reserves for the project. This triggered some major reevaluation and descoping very early on in the project in order to get the baseline, estimated costs low enough to get adequate reserves within the cost cap. This resulted in decisions such as not using a rocket-assisted descent, and lessening a very ambitious science payload. From this point, reserves were then distributed out to the subsystems and Tony Spears kept some additional reserves at the overall project level. Each subsystem manager had to keep track of his or her own budgets and schedules with an informal earned-value system to track performance.

During the project, Mars Pathfinder believed that resources were part of the entire project and not the sole possession of any subsystem. Donna Shirley stated that Mars Pathfinder believed in the sharing of resources whenever possible. One way to do this was through a barter system. This was done routinely between the rover and lander projects (e.g. mass). Another was relinquishing parts of a budget from one subsystem to another to guarantee project success. In some cases subsystems willing transferred funds or reserves to support other subsystems. Brian Muirhead described it as, “Most of the time subsystems, once they have a budget, they guard it jealously. And if they have any extra money in there you don’t see it. When they have a problem of course they’re coming to you for reserves. But there were actually times when projects with subsystem elements like propulsion said, ‘You know I don’t need this two or three hundred thousand dollars this month. You guys over in the electronics area, I know you’re struggling. Here, you can have it.’ Ground system guys gave the flight system guys money, which is unheard of.” John Wellman stated that he ended up transferring nearly two million dollars of reserves – out of a total of $15 million for his whole effort – to the spacecraft to help solve problems. This was the situation in many of the subsystems. The data systems team relinquished some reserve early on to help solve technical problems on the spacecraft side. As Wellman continued to state, “I won’t say it was cheerfully done always, but those kinds of adjustments were made without a lot of recrimination and it was done successfully.”

Mars Pathfinder did not believe in being restrained about setting up reserves. Mars Pathfinder maintenance of large reserves when it was initially started was recognized as critical to solving problems. Therefore, when problems were identified the team tried to assess the cost impact and then a change control board did the allocation of reserves to those problems, with first-level managers sitting on this board. Three reserves were established that they believed were critical to their success: budget, schedule, and mass. The Mars Pathfinder team had a commitment to the cost and schedule constraints of the project. As stated before, these constraints and the commitment to those constraints was part of the culture and vision. Therefore, people were willing and encouraged to share and give resources.

Aside from the Mars Pathfinder resource management and subsystems, universities developed the science instruments for Mars Pathfinder. To maintain budget, when the science experiments/instruments were selected they were cost-capped. This meant that they were unable to spend any more money than they proposed to accomplish the task. John Wellman believed that the science principle investigators (PI) recognized that their credibility and ability to propose for future missions rested on their ability to demonstrate that they could deliver on cost and on schedule. Historically, once a winning proposal was granted to a university, the negotiation efforts with the projects were started and budgets were a moving target. For Mars Pathfinder, the science content and the budgets were frozen early, allowing for success later in the project.

### *Reducing Uncertainty*

"If you can't afford the time or the money to build with the goal of perfection, then test the hell out of every piece of hardware and software."

- Brian Muirhead, *High Velocity Leadership: The Mars Pathfinder Approach*, p. 74

Every team member of Mars Pathfinder will say that the key to reducing the technological and requirements uncertainty was to freeze design early and test. To freeze the design process early, Mars Pathfinder pressed for very early deliveries. Rather than do extensive trade-off studies and analyses, Mars Pathfinder moved rapidly from prototyping to the engineering model stage. If it worked, the design for the flight was chosen and an extensive amount of test time scheduled to drive out any problems.

Brian Muirhead felt that testing was even part of the vision. He explains, "We were going to test this thing very aggressively, end to end, as many times as we can, testing every aspect of it because it's a single-string machine. You know one failure in one part or one component could take out the whole mission. And everybody knew that." Mars Pathfinder had a significant amount of risk associated with it simple because it was a single-string spacecraft; there was no backup. The lander that was built was the only one, and the rover only had some back-up parts. That's where the testing came in. Mars Pathfinder put in twice as many hours testing the spacecraft as anybody thought was needed. All of the management felt that rigorous and extensive testing was even part of the culture.

An example of this was The Gremlin. David Greuel (a.k.a. The Gremlin) was tasked with creating scenarios for operational readiness tests. During test, The Gremlin would set up pathological cases in The Sandbox (Mars surface simulation) of the test bed area. And the team would have to use the telemetry and the imaging they got from the Rover to figure out the problem and figure out how to get out of it. This would entail going through a sequence of activities just like it could occur during landing. This would mean that the software and hardware was simulating what the spacecraft would see, and the team was in their operational readiness conditions. They were at the consoles and they were driving the rover just like they were on Mars. Tests were performed on real clock time with communications delays from Mars. One test started at two o'clock in the morning and worked twenty-four hours a day for five days. This became invaluable. The first time this was performed the team crashed and burned.

Mars Pathfinder dealt with challenges that not all planetary missions encounter, landing on Mars. Most missions that are designed come within close proximity of a planet, but landing is very hard. One of the biggest challenges is that you cannot test that under realistic conditions on Earth. Gravity and atmospheric density are almost impossible to reproduce. It would require a significant amount of money to test anything under the same conditions it would encounter on Mars. This required a heavy reliance on computer simulation and testing at the assembly level. For example, the testing of the O-shell to handle the heating, the parachutes to handle the dynamic pressure and deployment, the rockets for the final deceleration, and the airbag for impact were all tested individually, but tied together with computer models to optimize for end-to-end solutions. With limited budgets many worst-case scenarios could not be performed for fear of damaging any equipment that was too costly to replace. Therefore, in many situations, especially with the entry, decent, and landing phase, probabilistic solutions were found. As Wayne Lee described, "We did tens of thousands of Monte Carlo runs to come up with a suite of performance parameters that would give us a high probability of success and allow each of the components to work. As John Wellman described, "There was less of a sense of "Let's consider seven options for this one" and spend a month studying them all, but it was a matter of having to choose the one or two and proceeding on that course. If we picked the wrong directions we'd have to go back and make a change of direction later on, but we couldn't afford to agonize over lots of decisions for long periods of time and still stay on schedule."

### *Systems Engineering*

Mars Pathfinder believed they had a reasonably strong system engineering effort. To ensure this people were devoted to working across subsystems. Brian Muirhead believed that every one of his project element managers was a systems engineer and a very tight team. Because the project management had a system engineering mindset, people were not afraid to be a systems engineer or think like a systems engineer. Brian Muirhead purposely sought people for his management positions that had the mentality of systems engineering. He considered himself a systems engineer. Therefore, there was a short path between systems engineering and management, and everyone shared the system ownership as well as the programmatic issues that went along.

Besides assuring the management had a systems engineering mentality, Mars Pathfinder took an innovative approach to the requirement documentation to make sure that systems engineering mentality was intertwined throughout the life of the project. Brian Muirhead explains,

> "We had a younger systems engineers who was kind of the guru for the requirements documents; we grew him in that role. Now typically when the requirements document's are done, you get rid of those guys and bring on the test guys. What we did is let this guy, follow through. He did the requirements; let's see him be the lead tester. That's a job he hasn't done before, but again he grew into it and was very, very efficient. He knew how this thing was supposed to work. So he became the test director. Then he moved on into operations to become one of the flight directors. So it was a great growth opportunity, again part of the culture."

Mars Pathfinder believed that having people work "cradle to grave" also reduced the uncertainty. Mars Pathfinder also believed that by allowing people to all phases of the projects development addressed many of the issues associated with integration. They had a very carefully planned integration test activity, which of course went though many iterations and modifications, but all components saw a lot of test time with the spacecraft. Mars Pathfinder was a very well tested system when it launched. Brian Muirhead lived by the motto: "You test as you fly, you fly as you test."

### *Risk Management*

"Well the way you take risks and don't fail is you have enormous license to do things differently."
- Brian Muirhead, personal interview

This statement by Brian Muirhead was a large sense of the vision that the management instilled in the team. They wanted a new way of doing business, technically and programmatically, which would allow them to get the job done. Design it, build it, and operate it within the specified constraints, because they believed it could never be done by the traditional techniques. Therefore, risk was a significant factor. Not only was a high level of risk inherent in the project because of the technological challenges, but also on the way the project was to be managed. Donna Shirley stated that with risk management the project used many of the standard techniques and a lot of testing, but credits Tony Spear with really doing a good job with Mars Pathfinder. Mars Pathfinder built things early and then tested them. They had the system integrated and going into test with 40% of their resources still left. When they found things they were able to fix them. As Donna Shirley explained, “Other missions like Cassini, do systems engineering on the front end with a lot of requirements and create a big paper trail. Tony could not afford that. We had requirements documents, but they were not as large as other projects. Most of our decisions were made by rapid prototyping. As you put something together you test it; it either works or it doesn't, and then you write your documents based on the testing.”

### *Customer Involvement*

Mars Pathfinder believed that you rely on customers, not executives, for setting a project’s strategic direction; although, in some instances these were the same. Mars Pathfinder had three customers: NASA, the Science Community, and the Public. Any NASA project has itself as a customer. This usually is NASA Headquarters or the Program Office for which the project is being funded. Donna Shirley described it as, “If you have a commercial customer, you have to do market research or you have to find out what is selling. In the case of government projects there is really not any money changing hands, so you have to represent the person that represents the taxpayers. In this case is was Murray Hurshbine (Program Manager at NASA Headquarters).” NASA Headquarters was the most heavily involved customer in terms of monitoring on a monthly basis, keeping track of progress, performance against schedule, budget, and risk. Therefore, there was a direct involvement.

The second customer was the scientific community that the project supported. The role of the scientific community for Mars Pathfinder was viewed as an important customer. Mars Pathfinder was very aware that not only did they have to land on Mars and have a functioning spacecraft that could transmit pictures, those pictures and the other scientific data had to have scientific merit to justify a reasonable scientific program and to generate real scientific results. Unlike past NASA missions the scientific data from Mars Pathfinder was readily available to the scientific community almost in real-time.

With the public it was the scientific knowledge, the excitement and that sense of participation that made Mars Pathfinder a success. As Mars Pathfinder approached launch, there was a heavier involvement from NASA and JPL Public Affairs Offices. These offices coordinated getting the press kits together, arranging the viewing sites, keeping the press involved, and running the press conferences; this continued through the cruise phase and landing. The pictures coming from Mars Pathfinder were available to the public within a few hours of when they arrived on Earth.

One philosophy that Mars Pathfinder believed with every one of their customers was to be truthful with them in the front end. Eliminate any surprises and let them know exactly what to expect, good or bad. Mars Pathfinder had working groups that worked through scenarios to determine possible outcomes. It was made clear in all the press materials of the risks and the overall risk of the mission. The facts, as they knew them, were communicated over and over to the customer.

### *Contractor Involvement*

For Mars Pathfinder, some of the science experiments were contracted to universities chosen through a NASA Announcement of Opportunity (AO). This meant a formal solicitation and a review of proposals. Particularly this is how the camera team was chosen (Peter Smith, et.al. of the University of Arizona). Other experiments were dictated by the Science Working Group (e.g. Tommy Kanamu, et.al. University of Chicago, the alpha proton X-ray spectrometer).

In the case of both of the contracts with the universities, they were cost-reimbursable contracts that were monitored in a more collegial method. For example, if the University of Arizona was supposed to do a particular job and certain capabilities resided at JPL that could be performed better, the work was moved and that task was taken out of their contract (money included). This went both ways. Contracts became guidelines and not hard and fast rules.

## Tools

For Mars Pathfinder there were no unique tools used to manage the project. The one tool that was used by Mars Pathfinder, is used by many NASA space science projects, and unique to NASA is Earned Value Management (EVM). EVM is a standard NASA way of running planetary flight projects and performance metrics. EVM is based on a set of project tasks, and each task has a cost to complete and/or items to procure. Each task and procurement has a schedule for completion, and as each one is completed a monetary credit is assigned. These credits are then graphed against how much money has been spent thus far on the project to determine where project progress follows on the curve.

### *Knowledge Management*

Mars Pathfinder felt that documenting the development of Mars Pathfinder was critical to be able to empower the team. Although documentation was an obligation of the contract, Donna Shirley felt that documentation is only a representation of reality, as much as you can make it, and performance specs are largely just predictive. Therefore, the ability to capture knowledge and manage it was only as good as you made it. One tool used to assure that knowledge was documented and transferred was through a project library. A hard-copy library was maintained with all critical documents (e.g. engineering drawings, test reports). These documents were kept lean. For example, the Level 3 Requirements Document for the flight systems was only about a half-inch thick, compared to the Level 3 Requirements Document for Galileo or Cassini that are volumes thick. A librarian maintained this library. Another big portion of the knowledge for Mars Pathfinder was managed by the knowledge of individuals. It was the responsibility of the team to be the keepers and sharers of knowledge.

### *Learning Process*

Mars Pathfinder management felt that lessons learned and the capturing of lessons learned were a valuable tool for project success. Mars Pathfinder believed in lessons learned from start to finish. For example, with Mars Pathfinder and Mars Global Surveyor (MGS), after the failure of Mars Observer (the precursor to MGS), Mars Pathfinder decided that they were not going to overload the science. Thus, Mars Pathfinder maintained a modest science mission to assure mission success. For Mars Pathfinder, they also used seasoned engineers and scientist to learn from past projects. The value in getting lessons learned from people is as Donna Shirley stated, "…nobody has time to read them, specially on a BFC project. The only way to use lessons learned is to have the people that learned them or to go through the documentation. The way it is documented now, it is almost impossible."

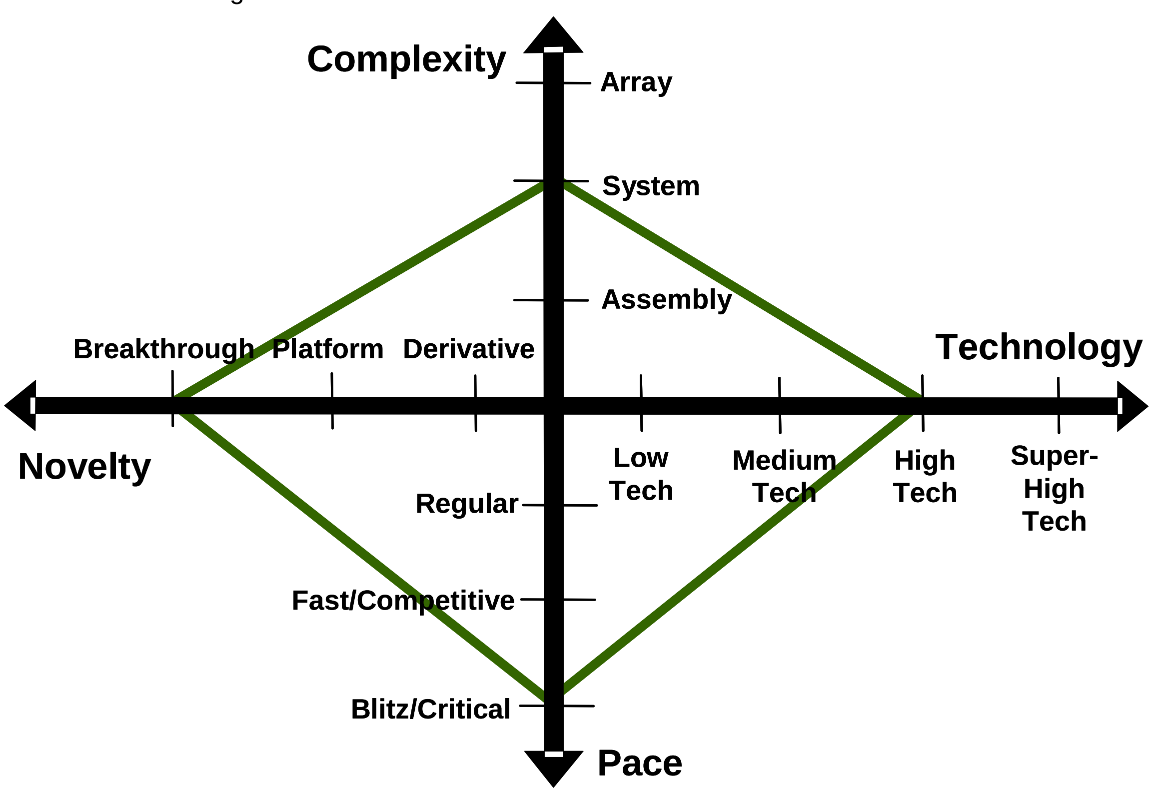
During the project, Mars Pathfinder captured lessons learned as they went through the project. For example, after the launch, the project team had a lessons learned activity that produced a two-inch thick summary of the lessons learned at subsystem and system level. At the end of the mission, a second lesson learned document was created. This document has since been passed on to other projects. Also, during the cruise period, team management prepared a comprehensive summary of the lessons learned. They emphasized the importance of innovative management techniques, concurrent engineering/teaming practices, and spacecraft architecture. To relay these lessons learned, senior project staff hosted information transfer seminars on Mars Pathfinder lessons learned for all of JPL.

The difficulty with lessons learned as Wayne Lee stated is that it is a "pull system." You have to pull them from the people and the documents. Donna Shirley stated that another problem with lessons learned at NASA is that learning is about one project long. Wayne Lee expressed that a video lessons learned tool would be much more valuable. Wayne Lee explained it as, "…just like we're talking here, if you could get a video of a conversation with some key person in a project who was like a propulsion subsystem lead telling you about his trials and tribulations, that would sink in. A half-hour of the "Best of Crises" from propulsion, what worked and what didn't would sink in. Because hopefully you'd capture the guy's emotions and the pain and the excitement."

**Adapting Project Management to Project Type**

Mars Pathfinder was very much a strategic project. Although NASA had been to Mars before with the Mariner and Viking Programs, Mars Pathfinder was going to do it in new ways and prove that it could be done better, faster, and cheaper. The philosophy of 'better, faster, cheaper' was virtually unproven in NASA and would open up new ways of doing business for an agency that prided itself on being on the forefront of space exploration. Mars Pathfinder would only be the beginning of what NASA would hope to be a long-term exploration of Mars and a new way of doing business. The task outcome for Mars Pathfinder was a tangible product of a spacecraft, lander, and rover with an intellectual activity. Mars Pathfinder required a significant creative effort for a product that had never been produced before. Since it had never been done before, it required new ideas and the imagination of experienced, talented people. As an external project Mars Pathfinder would be supplying data and excitement to two of its customers, the scientific community and the public. Based on the public perception of Mars Pathfinder, it would be defined as an external project, but a deeper analysis of the project would define it as an internal project. While Mars Pathfinder's defined project objectives were scientific, it had a larger objective, and that was to show that NASA could safely land on Mars under the philosophy of 'better, faster, cheaper.' When defining project success and making strategic decisions, Mars Pathfinder was most concerned with their internal customer… NASA.

The NCTP Model below represents the analysis of Mars Pathfinder in respects to its Novelty, Complexity, Technology, and Pace. Connecting the NCTP classification with a straight line to form a diamond, gives a representation of the level of risk associated with a project. The greater the area of the diamond, the greater the degree of risk. While there is not a linear relationship between the area of the diamond for correct and incorrect project risk, it can represent a difference in the degree of risk.



*Novelty*: Mars Pathfinder was a breakthrough product that introduced to the world a new way of landing on Mars, and more significantly a robotic rover to traverse the planet. No exploration robot has ever traversed across a planet in the history of space exploration. Mars Pathfinder opened new possibilities to space exploration with a foundation built on a limited historical record of past projects similar to Mars Pathfinder. Because of time constraints, development was quick and prototyping almost seemed parallel with assembly. Mars Pathfinder maintained a flexible approach to development while using intuition, excessive testing, and a learn-as-you-go mentality. While keeping a strict eye on the project objectives, schedule and cost, they were flexible with changes to stay focused on success. With such a fast development pace, Mars Pathfinder made sure they kept their customer educated about the potential risks and ultimate success.

*Complexity*: Mars Pathfinder was a system project. As a complex collection of interactive elements and subsystems, it functioned as one unit to meet its operational needs. While JPL led the effort for Mars Pathfinder, it relied heavily on subcontracts with other institutions to deliver the scientific instruments. Mars Pathfinder had multiple key customers from industry, public, government, and the scientific community that were all vested in Mars Pathfinder's development and success. As a systems project Mars Pathfinder was a complex project that required extensive planning, computerized tools and software, hundreds or thousands of activities, tight and formal control, financial and schedule issues, reviews with customers and management, and extensive documentation. It was JPL's ultimate responsibility to guarantee integration and performance within the project cost, time, and quality constraints. While documentation was minimized with Mars Pathfinder, the level of documentation required for any government project was par with any systems project. With Mars Pathfinder's high profile, the level of oversight was not limited to JPL, but stretched through the ranks of NASA. The level of bureaucracy was far above that of any assembly project.

*Technology*: Mars Pathfinder was a high-tech project. While most of the technology was commercial-off-the-shelf, there was a significant portion of the technology that was new to planetary exploration. More significantly the way the technology was integrated had never been done before in space exploration history. As a product, Mars Pathfinder was the first of its kind; integrating the technology in a way that had never been done before. Mars Pathfinder required long periods of design, development, testing, and redesign with multiple design cycles that had to start before the project started. With the extensive testing that was required for a high-tech project like Mars Pathfinder, in depth, technical reviews were mandatory to make a project of this complexity successful. In conjunction with these reviews, communication had to be frequent and active. The complexity and communication demands required management to be of good technical skills and intimately involved in the project. They also had to recognize the unique challenges of Mars Pathfinder and be flexible to extensive testing and design changes. Therefore, design freezes had to be scheduled and as late as possible.

*Pace*: Mars Pathfinder was a blitz-critical project. With most deep space projects, schedule, cost, and technology have limited margins. Because of celestial mechanics the launch window for a Mars' mission only come around every 24-26 months. For a project like Mars Pathfinder, once it starts down the path toward a specified launch date, adjustments in the schedule are measured in days and not months or years, and any significant delays in the schedule mean cancellation. In addition, Mars Pathfinder was under a three-year development time from project start to launch. This was unprecedented for a project of this size and complexity. To be successful, Mars Pathfinder had to find new ways of doing business and work around some of the standard policies and procedures. Mostly hand picked team members, worked very closely with each other with a high-spirited, dedicated attitude. Problems were resolved quickly with direct lines of communication to management and project managers that were intimately involved in the project in both monitoring and working.

### Success Factors

It is difficult to find deeply rooted faults in Mars Pathfinder. Management clearly understood what their objectives were and what it would take to accomplish those objectives. They understood the scope, technical uncertainty, and pace of the project, and what managerial practices were needed to make Mars Pathfinder a success. Keys to Mars Pathfinder's success were:

- Strategy
  - Modest and Attainable Objectives
  - Clearly defined success dimensions
  - Understanding of Competitive Advantage and Value
- Spirit
  - Deeply rooted, common commitment, purpose, and goals
  - Reduction in policy
  - Team empowerment
- Project Organization
  - Accountability
  - Flat organization
  - Maintaining core workforce
  - People worked project from beginning to end
  - Co-location
  - Organizational problems were managed quickly
  - Limited top management involvement
- Processes
  - Peer reviews
  - Formal reviews viewed as rolling gates
  - Adequate resources
  - Testing to reduce uncertainty
  - Customer/Vendor Involvement
- Tools
  - Project library and librarian

Mars Pathfinder understood the importance of project success and management knew of the importance of Mars Pathfinder to be successful. To secure project success, objectives were defined that were modest and attainable. Objectives were set for Mars Pathfinder that only unless there was a catastrophic failure, would they not be achieved. Tertiary objectives were set but success was not measured on obtaining these objectives. These objectives, while modest and attainable, were clearly defined and success was easily measured against these dimensions. While the competitive advantage of Mars Pathfinder was not clearly defined to the project team, management understood exactly what was the competitive advantage of Mars Pathfinder. Management worked very hard to define the value of Mars Pathfinder and transfer this to the project team through the spirit. Fostering in the team a spirited belief in why Mars Pathfinder was unique and could benefit NASA and the scientific community. Team members developed a deeply rooted, common commitment to the project and its success. There was an understanding that they were doing something different, and a successful project would have significant value to their customers.

To develop this can-do spirit in Mars Pathfinder, management had to reduce some of the policies that would restrict people from thinking outside the box, or looking for alternative processes to meet mission objectives. A reduction in policy, lifted many bureaucratic structures that would have diluted the high-octane spirit of Mars Pathfinder. By reducing the policy and thus the structure, management moved the responsibility to the people and empowered the people to be the decision-makers and shepards of their processes. This created a high level of accountability, and made the people an intimate part of the project. People felt that they were the project and not the processes. Mars Pathfinder maintained a flat organization, and thus accountability could not be passed or spread throughout the organization, and problems could quickly be identified and resolved. Maintaining a flat organization meant a limited workforce; therefore, people worked the project from beginning to end. People followed a system through the development process, and were held accountable for that processes/system. Because of their ability to be co-located or located in close proximity for real-time, face-to-face, focused meetings, issues could be resolved in real-time. Mars Pathfinder was given many liberties to be successful, and to allow the project those liberties there was a limited involvement from top management. While Mars Pathfinder kept top management informed, they did not interfere with Mars Pathfinder management to do what they had to do to guarantee project success.

Reviews are a part of all projects but Mars Pathfinder saw reviews as a critical part of project success. Management saw reviews as so important that significant resources were allocated toward reviews and serious thought was given to who would sit on the review committees. Mars Pathfinder had two types of reviews: informal (peer) and formal (phase) reviews. The informal reviews were seen as very critical to gaining insight from very capable and experienced technical people. These reviews were not held as standard points in time, but at more random points throughout the project lifecycle. While the formal reviews were held at there standard phases throughout the project, management saw these reviews as rolling gates. Therefore, the project did not stop or slow down as one of these reviews was approaching. The project would continue to proceed into the next phase well before the review would occur. By relying on the technical expertise of the informal reviews Mars Pathfinder could proceed forward with a significant level of confidence.

To reduce uncertainty, significant testing was performed throughout the project. Management understood when to freeze certain phases, move to the next phase, and test. Testing was performed not as a quantity activity but as a quality activity. The objective of testing was not to test a system over and over, but in every possible scenario.

Mars Pathfinder understood who was their customer and believed the best customer is listened to and well informed. While attempting to make sure that all of the customer's requests were met, they clearly defined to the customer the limitation and risks of Mars Pathfinder. Likewise, the contractors were viewed as a critical part of the project's process; therefore, they were in many cases made part of the project decisions.

Unique to Mars Pathfinder was to establish a project library to file all project documentation. This library allowed for a centralized location for documented knowledge. Management saw this as such an important tool that they designated a project librarian to manage the library.

**Recommendations**

Despite the success of Mars Pathfinder, no project will ever be considered a flawless success. Mars Pathfinder was has its faults in areas such as strategic focus, training, and documenting processes.

**Recommendation 1 – Policy to support the strategy:** At the time of Mars Pathfinder, BFC was just a developing concept. NASA told the Mars Pathfinder management to just make it happen. To make BFC cheaper happen, Mars Pathfinder was given the authority to reduce or eliminate certain policies. While this helped them be successful, in the end, there was not a clear linkage between the policy and the project strategy. Management understood the strategic focus with a relentless pursuit of the competitive advantage and value of the project. Although Mars Pathfinder was successful in instilling the strategic focus into the project team through the spirit and vision, without a policy to support this focus, it allowed no mechanism to formally transfer this throughout the project or to other projects. While other projects attempted to repeat what Mars Pathfinder had accomplished, it was the people and not the policy that made the project. Without a documented policy to support the strategy, the success of Mars Pathfinder was tied into the people.

Mars Pathfinder was under extreme pressure to be successful, because of this pressure there was less emphasis put on capturing how Mars Pathfinder was managed in the processes. Therefore, it became difficult to capture and transfer the success of Mars Pathfinder to other projects. Mars Pathfinder was successful because of the people, not the processes or the tools. Mars Pathfinder was successful without following many standard procedures and doing things differently. But, it was not a breaking-the-rules mentality that attributed to its success; it was the management's vision and the team believing in that vision. Mars Pathfinder could have been successful under other management models, but it was the right mix of people that made the project successful.

**Recommendation 2 – Provide appropriate training:** Mars Pathfinder relied on knowledgeable team members and on-the-job training. This worked for Mars Pathfinder because they had the right skill mix of experience, but this is not a practice that can be relied upon for other projects. Being able to select the right skill mix assumes that there is an unlimited supply of experienced capable people to choose for a project. Some managers for Mars Pathfinder believe that the most talented people were not always available. Although this may be a true statement for every person working on the project, Mars Pathfinder did have people that were willing to leave their current project to come to work for Mars Pathfinder. If a project is not as high profile as a Mars Pathfinder, people are not always lining up at the door to join a project. In addition, this unique skill mix cannot be attributed to a formal or informal project training system. The team members of Mars Pathfinder received no formal or even informal training to prepare them for the project (managerial or technical).

**Recommendation 3 – Fully document the processes, even the process for success:** Mars Pathfinder worked to maintain what they called a flat organization. Maintaining line organizations that were only two people deep, and functional groups that were 7-10 people. While this allowed for more direct lines of communication and problems to be solved quickly, it left Mars Pathfinder very vulnerable to a reliance on individuals and not teams or documentation for sources of information or success. This structure adds a level of risk when information and knowledge are tied to the people. Sustaining a level of knowledge sharing, Mars Pathfinder was a co-located project. While this was the perception of many, it was not the perception of some of the management. The difference in the perception of co-location can better be described as a difference in definition. If Mars Pathfinder is defined by co-location as everyone being in one building, then Mars Pathfinder was not co-located. The rover team was in a different building. If co-location is defined by the team's ability to easily access other team members in a face-to-face environment, then Mars Pathfinder was co-located.

# APPENDIX B – LUNAR PROSPECTOR

# Strategic Systems Innovation

# A Case Study of

# Lunar Prospector

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**Executive Summary**

Lunar Prospector was the first competitively selected mission in the NASA Discovery Program, developed to produce frequent, low-cost missions to explore the solar system. Lunar Prospector was a spin-stabilized spacecraft designed to map the surface composition and magnetic field of the Moon and begin investigating some of the 80% of the moon's surface features, structure, and composition not investigated during Apollo.

As a product, Lunar Prospector was a single vehicle (orbiter), and several instruments designed to demonstrate a low cost system for orbiting the Moon and expanding its scientific knowledge. Additional objectives included the deployment and operation of various scientific instruments: neutron spectrometer, gamma ray spectrometer, magnetometer/electron reflectometer, doppler gravity experiment, and alpha particle spectrometer. While much of the technology was known, its application and what Lunar Prospector was planned to accomplish made it different than anything that had been done before.

As a project Lunar Prospector was to design, test, and develop an orbiter that would obtain scientific data and demonstrate the philosophy of 'faster, better, cheaper.' With a development time of almost three years and a project cost which included development ($34 million), launch vehicle ($25 million), and operations ($4 million), for a total of $63 million, Lunar Prospector was chartered with being the first competitive selected Discovery Program mission to demonstrate 'faster, better, cheaper.' Lunar Prospector involved 75 to 100 people from NASA Ames Research Center, NASA Goddard Space Flight Center, NASA Jet Propulsion Laboratory, University of California – Berkley, University of Arizona, Lockheed-Martin, Lunar Research Institute (Alan Binder, Principle Investigator, left Lockheed Martin to establish the Lunar Research Institute), and Los Alamos National Laboratory. As a project Lunar Prospector could be described as a high-tech project. Much of the technology was proven from previous spacecraft, but had not been incorporated in this configuration. The complexity of the project could be described as a system. As is the case with all deep space missions, they are a collection of interactive elements and subsystems that must perform a wide range of functions under extreme conditions. The pace of the project was a blitz-critical project. While many of the characteristics point to a fast-competitive project, it is the inflexible launch date that moves deep space missions like Lunar Prospector into a blitz-critical mode. Time and budgets become fixed and any error in either of these areas meant cancellation for the project.

Lunar Prospector ended on July 31, 1999, when the spacecraft was jettisoned into a crater near the south pole of the Moon as part of an experiment to confirm the existence of water ice. The mission ran for 19 months and successfully completed all of its objectives. The data collected has allowed for the construction of a detailed map of the surface composition of the Moon and results have been ten times better than ever planned. The information gathered was far more comprehensive than any data ever collected.

Lunar Prospector was successful because they understood well before the project started that simplicity would be the key to project success. Lunar Prospector was well defined with a clear understanding of the scope, technical uncertainty, and pace. This guided management toward design constraints that kept Lunar Prospector on budge and on time. Lunar Prospector determined their strategy early with customer-defined objectives that were simple, attainable, and valuable. A focused, unspoken, and common commitment from a co-located team laid a foundation for limited top-management involvement and a dedication of people from project start to finish. Lunar Prospector understood the value of informal and formal reviews, how they related to when to freeze designs, how they impacted requirements, and that only a good test program can reduce uncertainty.

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**Background**

Return to the moon… this is exactly what Lunar Prospector (LP) attempted to accomplish, but under a budgetary and time constraint not comparable to any mission in the history of the National Aeronautics and Space Administration (NASA) or aerospace. What Lunar Prospector was designed to accomplish under a minimal budget, was many magnitudes surpassed to any mission of any kind. Despite an extensive amount of data collected from the Apollo program, a large part of the Moon remained and remains uninvestigated. It was not until Apollo 15 (the program ended with Apollo 17) that true science was conducted on the surface of the moon. A majority of this science was conducted around the equator and only resulted in a 20% edification of the moon's surface features, structure, and composition. In 1992, the Lunar Exploration Science Working Group (LExSWG) confirmed this limitation in lunar data in a culmination of working group reports entitled "A Planetary Science Strategy for the Moon." The LExSWG stated that the following sets of measurements must be collected to better understand the Moon and its role in our celestial universe. The scientific objective dictated by the LExSWG were:

1. Determine globally the elemental and mineralogical composition of the surface.
2. Determine globally the surface topography and gravitational field.
3. Map globally the distribution of surface magnetic anomalies and measure the magnitude of the induced dipole moment.
4. Obtain a global image database along with selected coverage in stereo and color.
5. Measure the microwave brightness temperature as a function of wavelength.
6. Measure globally the composition, structure, and temporal variability of the lunar atmosphere.

In 1994 Clementine, designed to space qualify lightweight imaging sensors and component technologies for the next generation of Department of Defense (DoD) spacecraft, addressed objective 4; therefore, it left five of the six objectives open for Lunar Prospector. Of the remaining five, Lunar Prospector chose to embark upon four (1-3 and 6). Although Clementine addressed objective 4, it was not part of Clementine's strategic intent. Clementine, a $75 million Pentagon spacecraft, was designed to track missiles and test "Star Wars" sensors. Despite this, Deputy Project Manager, Stewart Nozette, convinced the Ballistic Missile Defense Organization that the Star Wars sensors could provide valuable scientific information about the Moon. He proposed that Clementine use its Bislatic Radar Experiment to beam radio waves into the dark regions of the South Pole of the Moon, into lighted regions of the South Pole, and other places on the Moon for comparison. Then in April 1994 on Orbit 234, the spacecraft revealed what many scientists theorized and hoped, ice on the Moon's surface. Despite what Paul Spudis, Lunar and Planetary Institute, declared "an amazing discovery," there was still much speculation in the scientific community over the interpretation of the data. This extensive debate raised many more questions and opened the door for a mission such as Lunar Prospector.

As Alan Binder put it, "We went to the moon in '69 and early '70s and in thirty years we haven't been there. And this is a crime against humanity." When Alan Binder returned to the United States in 1983 from a ten year sabbatical in Germany, he recognized this gap in exploration and human curiosity, so he began conceptual developments for what would later become Lunar Prospector. He believed that NASA did not have the resources or drive to develop a return trip to the Moon; therefore, he pursued interest outside of the government. In late 1988, the Space Studies Institute (SSI) in Princeton and the National Space Society in Houston – which Binder was a part – simultaneously decided to do a mission, which became Lunar Prospector. Binder and Preston set up the Lunar Exploration Institute (LEI), which was a non-profit, tax-exempt Texas Corporation made up of volunteers. This team consisted of about thirty NASA and contractor engineers working at Johnson Space Center, and some of Binder's science colleagues that would define the payload, which would later fly on Lunar Prospector.  This development team set four simple goals for themselves before they ventured into this project:

(1) Prove that a mission can be done without huge NASA bureaucracy.
(2) Prove it can be done with a small group of competent people who know what they are doing.
(3) Prove it can be done inexpensively.
(4) Reawaken interest in the Moon.

Through volunteers, Binder and Preston were able to complete a Phase A study.  The SSI provided $75,000 for a Phase B Design Study.  Normal Phase B studies cost two or three million dollars, but Binder was able to get a small company made up of Hughes engineers to win the Request for Proposal (RFP) to perform the Phase B study.  With the Phase B dollars secure, this placed this small company in charge of designing the spacecraft, SSI in charge of the money, and LEI in charge of the science and engineering, building, and flying the spacecraft.  SSI was supposed to continue to find financial support for the project but failed.  This left Binder searching for money from many of the major aerospace companies (e.g. Boeing, Lockheed, Allied Signal), and Lunar Prospector stuck on the drawing board.

At the time, Binder’s biggest obstacle was that most aerospace companies were securing contracts for hundreds of millions of dollars and to support Binder’s Lunar Prospector would show that missions could be done for a lot less.  Binder and Preston continued to search for funding sources, even approaching Coke and Pepsi.  When Mike Griffin became Associate Administrator of the Space Exploration Initiative, now NASA Space Science Enterprise, he believed in Lunar Prospector and promised to secure funds to support the project.  But Griffin succumbed to political pressures from Congress and backed away from Lunar Prospector.

About this same time, NASA was beginning development of the Discovery Program, built on the Goldin philosophy of faster, better, cheaper.  In the early 90's, the Office of Space Science (Code S), responsible for all of NASA's programs relating to astronomy, the solar system, and the sun and its interaction with Earth, began looking at how to solve the issue of an over reliance on large missions for scientific data.  When Dr. Wesley Huntress became Associate Administrator of Code S in March 1993, he was a strong advocate of finding a way for NASA to provide more frequent opportunities for space science.  At the same time, Congress became aware of this issue and asked NASA to develop a program for smaller missions that would allow more frequent opportunities.

In April 1992, Code S submitted a report to Congress with the basic framework for the Discovery Program.  These basic constraints would be missions that were:

1. $150 million for development.
2. 3 years for development time.
3. Launch on nothing larger than a Delta II

In 1993, Congress approved the plan proposed by Code S. To show Congress that it could be done, Code S selected two charter missions - one to JPL (Mars Pathfinder) and one to the Johns Hopkins University Applied Physics Laboratory (APL) (Near Earth Asteroid Rendezvous).  Later missions would be selected under a competitive peer review process.

When the Discovery Program was announced Binder decided that the only thing left was to team with Lockheed Martin as the industry partner and try and win Discovery Program funding. LP was the first competitively selected mission from the Discovery Program.  The concept of using the competitive selection process for choosing missions for NASA has become routine in the planetary exploration projects. Ten to fifteen years ago this was not done. When LP was selected, the Discovery Program was still basking in the success of Mars Pathfinder and the soon to be successful Near Earth Asteroid Rendezvous (NEAR) missions. The Discovery Program was showing that missions could be done Faster, Better, Cheaper (FBC), and LP would only become another shining example of FBC. Lunar Prospector pushed the limits of FBC and raised the bar for FBC projects to come. During its initial reviews many felt that there was Lunar Prospector and then all the rest (30 proposal were submitted). The quality of the Lunar Prospector proposal was perceived as above all the other proposals in every category. Because of the work that Binder and others had completed before the proposal was submitted, they presented a complete mission from launch to mission end.

**Mission Description**

Lunar Prospector was a successful marriage between what Hubbard called “Alan’s science interest, my interest in small missions, and Lockheed Martin as the implementing organization.” From its selection to authority to proceed, it was about six months and then from authority to proceed to launch an unprecedented 22 months. Lunar Prospector involved 75 to 100 people from NASA Ames Research Center, NASA Goddard Space Flight Center, NASA Jet Propulsion Laboratory, University of California – Berkley, University of Arizona, Lockheed-Martin, Lunar Research Institute (Alan Binder left Lockheed Martin to establish the Lunar Research Institute), and Los Alamos National Laboratory. Its mission objectives were:

1. Obtain high quality scientific data about the Moon’s structure, composition, and resources.
2. Demonstrate that the philosophy of “faster, better, cheaper (FBC)” can successfully yield a rapid development, very inexpensive planetary science mission.
3. Create an innovative education and outreach program, which stimulates public interest in planetary exploration.

Project cost included development ($34 million), launch vehicle ($25 million), and operations ($4 million), for a total of $63 million. Many Lunar Prospector team members like to boast that the project cost one-third the budget of the movie Titanic. Lunar Prospector was a Principal Investigator (PI) led project with NASA oversight. The program/project management role was the responsibility of the Mission Office at NASA Ames Research Center (ARC). G. Scott Hubbard, NASA Mission Manager, Ames Research Center (ARC) and Sylvia Cox, NASA Deputy Mission Manager, from the ARC Mission Office would act as the single point to the PI/Industry Team. Alan Binder, Principle Investigator, Lunar Research Institute (at Lockheed Martin during development) and Thomas Dougherty, Project Manager, Lockheed Martin, who managed the science and daily operations, would lead the PI/Industry Team. Lockheed Martin was responsible the spacecraft development, launch and operation. See Table 1 for project timeline.

| | |
|---|---|
| **1983** | |
| | Lunar Prospector is born from Alan Binders conceptual design |
| **1988** | |
| | Lunar Prospector completes a Phase B design study |
| **1995** | |
| **February** | Lunar Prospector is selected for flight |
| **October** | Spacecraft and Instrument Construction Begin (design freeze) |
| **October** | Project Starts |
| **1997** | |
| **August** | Spacecraft and Instrument Construction Complete |
| **1998** | |
| **January 6** | Launch of Lunar Prospector is scrubbed at 2:28 GMT |
| **January 7** | Launch, at 12:30 GMT from Launch Complex 46<br>Cape Canaveral, FL |
| **January 11** | Lunar Prospector is captured into lunar orbit |
| **January 15** | Primary mission begins |
| **March 5** | Lunar Prospector discovers signs of water ice on both poles |
| **March 5** | First operational gravity map of the Moon is announced |
| **1999** | |
| **January** | Mission is extended an additional 7 months |
| **July 31** | Lunar Prospector impacts the moon at 09:52 GMT; ending the mission. |

**Table 1: Project Timeline**

LP launched from Launch Complex 46 of Cape Canaveral, Florida at 09:28 EST on January 6, 1998 aboard a Lockheed-Martin Athena II expendable launch vehicle. This was the maiden voyage, not only for LP, but the Athena II. At 09:32 EST, the payload separated and at 10:25 EST the spacecraft was put on its trajectory for the Moon (a 105-hour coast) by the Star-37 Trans-Lunar Injection stage. LP was scheduled for a one-year, polar orbit, with primary mission objectives of:

1. Determine globally the elemental and mineralogical composition of the surface.
2. Determine globally the surface topography and gravitational field.
3. Map globally the distribution of surface magnetic anomalies and measure the magnitude of the induced dipole moment.
4. Measure globally the composition, structure, and temporal variability of the lunar atmosphere.

The mission was declared official when the spacecraft switched on, 56 minutes, 30 seconds after liftoff. Shortly after this the spacecraft's five instruments – the gamma-ray spectrometer, alpha particle spectrometer, neutron spectrometer, magnetometer and electron reflectometer – were turned on. On January 11, at 07:20 EST, LP successfully entered (captured) into lunar orbit, and began its mission to globally map the Moon just a few days later. Figure 1 shows Lunar Prospector's trajectory from launch to lunar orbit insertion. With the primary mission beginning on January 15, 1998, Lunar Prospector spent one year mapping the entire surface of the Moon from a distance of about 100 kilometers. This phase produced data at a quality far greater than anything that had been produce before. The mission was extended for an additional seven months, starting in January 1999. Lunar Prospector is then lowered to an orbit 30 kilometers above the lunar surface to obtain higher resolution data. Originally, the mission was designed to end when the spacecraft ran out of fuel and crashed into the lunar surface. This changed when someone suggested crashing the spacecraft into the lunar surface as an experiment to confirm the existence of water on the Moon. The spacecraft was successfully directed into a crater near the lunar South Pole, thought a possible location for ice, but no water was detected in the resulting impact plume. Lunar Prospector impacted the moon at 5:52 am EST, July 31, 1999. The final targeting burn was commanded an hour earlier to target the impact to hit the permanently shadowed crater near the south pole, at -87.7 deg latitude, 42 deg longitude.

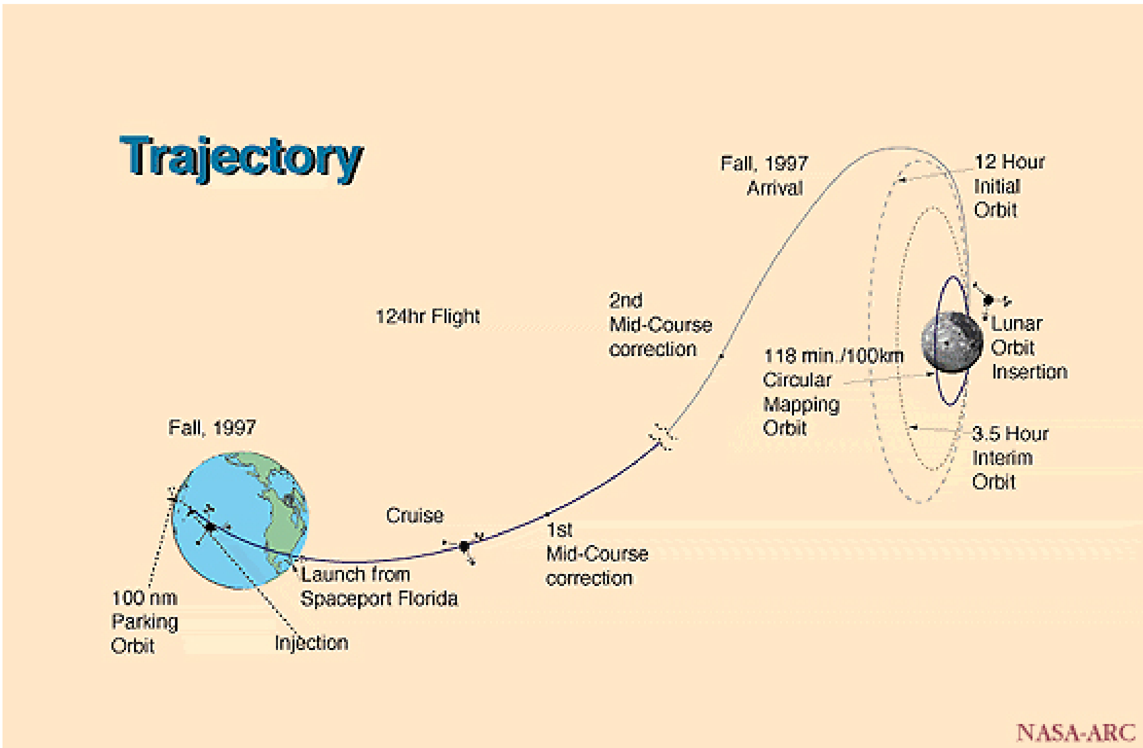



**Figure 1: Lunar Prospector's Trajectory Path**

**Technology Description**

Lunar Prospector was a new generation of planetary spacecraft. Although all of the technology was off-the-shelf or borrowed from other proven spacecraft, it was an innovation in systems engineering and management that made it possible. A medium-tech project structured around a blitz-critical project pace helped bring this system into reality under strict budgetary and time constraints. Lunar Prospector was a spin-stabilized spacecraft, 1.4 meters in diameter by 1.22 meters in height and weighing 2964.4 Kg, and built by Lockheed Martin Missiles and Space. Around the spacecraft were three radial instrument booms or arms (2.4 meters in length) for deploying the five scientific instruments. These five instruments performed six experiments to address the scientific objectives.

1. Neutron Spectrometer (NS) --Map hydrogen at several signature energies and thereby infer the presence or absence of water.
2. Gamma Ray Spectrometer (GRS) -- Map 10 key elemental abundances, several of which offer clues to lunar formation and evolution.

3. Magnetometer/Electron Reflectometer (Mag/ER) -- These two experiments combine to measure lunar magnetic field strength at the surface and at the altitude of the spacecraft and thereby greatly enhance understanding of lunar magnetic anomalies.
4. Doppler Gravity Experiment (DGE) -- Make an operational gravity map of the Moon for use by future missions as well as LP by mapping gravity field measurements from changes in the spacecraft's orbital speed and position.
5. Alpha Particle Spectrometer (APS) -- Map out-gassing events by detecting Radon gas (current outgassing events) and Polonium (tracer of recent, i.e. 50 years).

The five instruments, a cost-effective $3.6 million, were built on previously developed and tested hardware. Additionally, the spacecraft was designed and built on existing hardware. While most of the technology was off-the-shelf or from other missions, its application was considered a new generation in planetary exploration spacecraft. Making Lunar Prospector a breakthrough innovation. The engineering and science team worked very hard to match the design constraints to this existing technology.

Power was provided by solar arrays mounted on the outside of the cylindrical drum shaped spacecraft. The spacecraft maintained a polar orbit every 118 minutes and covered the lunar surface twice a month at a nominal altitude of 100 kilometers. The Moon rotated a full turn beneath the spacecraft every lunar cycle (~27.3 days). Lunar Prospector was designed for a one-year-long primary mission with an optional extended mission of six months at a lower altitude.

Lunar Prospector would return more relevant data per dollar invested then any mission in NASA history. This was accomplished with a scientific team that consisted of industry, government and academia. Lunar Prospectors scientific team was lead by:

*Alpha Particle Spectrometer, Neutron Spectrometer and Gamma Ray Spectrometer*
Alan Binder, Lunar Research Institute
William Feldman, Los Alamos National Laboratory
G. Scott Hubbard, NASA ARC

*Magnetometer and Electron Reflectometer*
Robert Lin, University of California, Berkley
Lon Hood, University of Arizona, Tucson
Mario Acuna, NASA Goddard Space Flight Center

*Doppler Gravity Experiment*
Alex Konopliv, NASA Jet Propulsion Laboratory

## Strategic Project Leadership

### Strategy

#### *Objectives*

"It's a matter of saying this is what we are going do and we don't change anything we build."
- Alan Binder, personal interview

Lunar Prospector objectives were designed to be simple, attainable, and provide a significant value to the science community. It was the science community that Lunar Prospector gave the most consideration to when establishing their objectives. Satisfying the scientific community became driving factor for the project objectives and

While not all NASA projects are defined by the same mechanism, most planetary projects do follow a usual scoping. For Lunar Prospector and other Discovery Missions it was slightly different. Typically, a science advisory group defines the project scope for a planetary mission. For Lunar Prospector, this was the LExSWG. The group lobbies a program office and the program office goes to NASA headquarters to request a mission that they would like to fly. They specify to NASA Headquarter the amount of money that this would require and the science constituents it would satisfy. NASA Headquarters then determines if they will fund the project, and then at project inception the scientific goals are set (observations, measurements, time needed to collect data, quality of data). These scientific requirements then drive the spacecraft design. What was different about Lunar Prospector is that there was a competitive selection process based on a solicitation. The Discovery Program does not specify mission objectives, but general mission constraints. Lunar Prospector's scientific objectives were defined my Alan Binder based on the LExSWG, but Lunar Prospector did not have to lobby to a program office for funding. As with many planetary projects, what typically happens over the course of the project is that the realities of building a spacecraft and having it operate under the specified conditions are much harder than envisioned in the beginning. Science missions will start with a certain payload and by the time they fly, they fly twice the original payload. As Alan Binder stated, "Most engineers do not like to build the same old stuff they always want to add some new toy." What was unique about Lunar Prospector was that the mission that was defined in 1988 was the mission that flew in 1998.

#### *Competitive Advantage/Value*

It is difficult for a government project to define a competitive advantage. Usually they are supported by a congressional or administrative push. In some cases they are developed from a scientific community pull. In either case there is usually little competition, but Lunar Prospector was subjected to stringent competition to be selected. The competition was in the initial proposal phase. There were 30 proposals that responded to the Discovery Program solicitation the year Lunar Prospector was selected, which included all of the science community that had the capability to propose a space science mission. Binder believed that Lunar Prospector's competitive advantage was a simple spacecraft and streamlined management. This translated to the best science per dollar of any other mission. Saunders believed that Lunar Prospector's ratio of science per dollar was not even comparable to the other mission proposed with Lunar Prospector. Hubbard stated that science per dollar was Lunar Prospectors competitive advantage. Lunar Prospector was a simple design with a simple mission profile. Nobody could compete with a spacecraft that cost $20 million and a five-instrument suit at a cost of $3.5 million. Lunar Prospector was a total of $63 million, and most NASA space science instruments cost around $10 million each. Management was kept to a minimum and managers kept a one-on-one relationship with engineers. This approach minimized the bureaucracy. Lunar Prospector worked to maintain themselves as a small company in a big company. Once the project started the competition was their schedule and budget. Like all Discovery missions, going over budget or schedule meant the project being canceled.

Once Lunar Prospector was initiated, the competitive advantage transitioned into the value. Lunar Prospector believed that its value had three customers: the Office of Space Science at NASA Headquarters and the Discovery Program, the sponsor; the scientific community, user of the data; and the general public. Obtainment of the project objectives means project success and provides value to the NASA customer in the form of return on investment. Lunar Prospector showed that low-cost competitively selected space exploration missions could be done. This was great value to NASA in seeking support of Congress and the general public. Additional value to the general public came in the form of education and outreach and excitement in science and technology. Finally, the value to the scientific community, definer of the project objective, came in the form of data for research.

***Business Perspective (Success Dimensions)***

Like all Discovery class missions, Lunar Prospector's success was measured on their ability to stay within budget and on schedule while maintaining the science objectives. Traditionally within NASA the standard mechanism for running planetary flight projects and performance metrics is a system called "earned value." Earned value is based on a cost per task performance standard. For example, if a project has one hundred different tasks (or items to procure), and each task/item has an estimated value or cost, these tasks or procurements will be completed by a certain point in time. As each one is completed, a monetary credit for completion is given and that is graphed against how much money has been spent thus far to see where a project is on the curve. Alan Binder said that the earned value system is fine for reporting to upper management, but has less value in the day-to-day operation of a project.

What is also the case with Discovery Missions that is not found in most projects is that there is very little leeway. Planetary missions are restricted based on a window of opportunity due to celestial alignment (launch windows). Lunar Prospector was no exception. Although launch opportunities to the Moon are much more frequent than a trip to Mars, NASA is very strict about their allowance for delays in Discovery missions. NASA was even more restrictive on Lunar Prospector, not allowing the normal fifteen-percent budget reserves. As Binder stated, "We had a schedule and we simply marched to that schedule. We knew how much money we intended to spend every phase, we kept to our schedule and those were our marks." Lunar Prospector had little choice but to stay on budget, within schedule, and meet their objectives. As Cox stated, "The cost constraints under which Lockheed (Martin) signed up for Lunar Prospector clearly forced the whole project to pay a great deal of attention to not growing requirements, not changing the science, not trying to make this fancier than it needed to be."

In the case of Lunar Prospector there was a set of Level I science requirements which was what the mission was mandated to accomplish. Although, there was a set of secondary goals of demonstrating how faster, better, cheaper could be successful. In the end, it was the science objectives that determined the projects success. Therefore, the data management plan very carefully spelled out data requirements of a specified quality. Lunar Prospector was a data purchase program. That meant that Lunar Prospector had a certain standard set of data requirements they had to collect. Even in their contract it did not specify the delivery of a spacecraft or launch vehicle; the requirements were to deliver scientific data. Therefore the success of the mission was totally quantified in terms of delivering the specific science data to meet the requirements of each of the instruments. What they produced was a factor of two or three better. So scientifically Lunar Prospector produced the promised product and better.

How these science objectives were defined was key to its success. Binder presented the science objectives to NASA with a strong understanding of the possible results because similar instruments had flown and their capability was known; in addition, Binder had worked for many years to get commercial or NASA backing for Lunar Prospector, so Lunar Prospector had already been honed down in its mission objectives. This meant that Binder was able to constrain the projected results to increase the probability of success. As Binder stated, “I don’t like to make promises that I can’t keep and scientists have a tendency to somewhat exaggerate what they are going in the hopes that they will convince someone. I intentionally kind of downplayed what I thought we could get. And interestingly enough my co-PIs did the same thing to me. They thought that they could do better but they weren’t going to tell me they could. So we went in there with a very realistic definition of what we could do and it turned out that our optimistic assessments were correct.”

Lunar Prospector worked towards a self-measurement of success that appeared to be straightforward, it was what Lunar Prospector benchmarked itself against that was harder to define. As with many NASA projects post-Apollo, it is really hard for project teams to benchmark themselves against something. Rarely is there anyone to beat or is anyone doing anything even remotely similar. As with Lunar Prospector, they ultimately benchmarked themselves against what they promised, deliver it on schedule, within budget and with a level of quality data. One benchmark that NASA attempts to define is ‘Did we do better then last time?’ This is an interesting benchmark because sometimes there is no last time (this was the case for Lunar Prospector), better has to be quantified, and in every case you always try to do better than last time. Rarely are missions with NASA repeated identically with the expectation of achieving identical results. Cox agrees that there is not formal or easily defined benchmark. She states that the whole management team benchmarked their decision process on their experience or perception of why they had been successful in the past. With little for Lunar Prospector to benchmark against, NASA wrote the contract with Lockheed Martin as an award fee contract. There was a clause in the contract and in the award fee plan that said that for every dollar of overrun the first two million dollars came out of Lockheed Martin’s fee. This became a very strong performance incentive for Lockheed Martin because the total amount of fee was at risk if the science was not successful. If Lunar Prospector launched and did not return science or did not make it to the Moon, the entire award fee was at risk and it could be demanded back.

***Strategic Focus***

When Binder was asked what the strategy for Lunar Prospector was he answered simply, “You are responsible, you’re responsible to me, no passing the buck, keep it simple, and do it on time. If there is a problem we sit down together and fix it right then and there. That was the whole strategy.” Binder lived by the motto: “Keep It Simple Stupid” (KISS), and this is how he ran Lunar Prospector. This meant no redundancy, modularity, backup or test model; it meant going “single string.” Binder’s philosophy on single string was that “if you know you’ve got a backup you’re not quite as careful in construction. If you have no backup you are damned careful about what you are doing.” Binder’s strategy could not have been reality without a reduction in the insight and oversight. Hubbard believed that this was critical to a focused strategy and keeping the team focused. Before Lunar Prospector started they had a series of meetings with the Program Manager, Principal Investigator, Project Manager for Lockheed Martin, and Senior Management of Lockheed Martin to lay out what they were going to try to do and how they were going to try and do it. These meetings were then extended to the project team to make sure that they understood the strategy and how it was going to be accomplished. There were strategic corrections throughout the project, but Lunar Prospector wanted to be very sure that people did not misinterpret faster, better, cheaper as being a license to be ‘sloppy.’ This meant defining the requirements early and sticking to them. With such a short development time and limited resources, Lunar Prospector believed they could not afford or allow requirements to grow. Lunar Prospector wanted to make sure that everyone understood that they should focus on things that were truly value-added or contributed to mission success and not on things that provided minimal value. Additionally, Lunar Prospector management built a strategic focus on a:

- **Clear Set of Requirements**: Requirements were not only clearly defined but people adhered to them.
- **Defined Roles and Responsibilities**: Team members and management know their roles and responsibilities from the beginning and there was neve any question.
- **Mix of Experience**: Experienced people at the top combined with energetic young engineers.
- **Willingness to do Things Differently**: Lunar Prospector was unique in how it was selected, managed, and developed. People were willing to try a different way of doing business.
- **Strong Sense of what was Mission Success**
  **Strong commitment from Top Management**: Consistent funding stream from top management, which did not waiver from the commitment.
- **Extensive Pre-project Definition**: A long history of studies and missions to the Moon, which gave a solid basis of the science requirements.
- **Focused Management Team**: The focus of all of the managers was on making Lunar Prospector successful. When problems arose, the management set aside differences to keep the project directed with a common goal of doing it appropriately and timely.

## Project Spirit and Leadership

"Things that we did which were unheard of, all goes into my saying that nobody believed that we could do this."

- Alan Binder, personal interview

### *Organizational Culture*

"You've got to change the culture, you can't do things this way if you're going to keep the old culture."

- Alan Binder, personal interview

For Lunar Prospector there was the culture of a small project built into a large organization. As a large organization, Lockheed Martin, has a tendency to manage projects from the top with a significant amount of top management oversight. For Lunar Prospector where the team was considered small compared to most planetary missions, people were involved from beginning to end of the project. Engineers that were involved in the design process were involved in the test program; launch integration and many of them were sitting at the consoles during launch. There was a feeling of real identity with the hardware and what they were trying to do and this instilled a unique feeling of being part of something that was different.

### *Project Spirit*

"People that I run into today say that LP was the best team and the best project that they had ever worked on."

- Sylvia Cox, personal interview

When Binder was asked about project spirit, he replied, "Without that we would have never had achieved anything." Binder believed and stated constantly that if you were not having fun you should get off the program and go somewhere else. Alan Maloney wrote at the end of his paper published in an engineering journal, "Alan, we all had fun." Lunar Prospector believed that project spirit was built on the people. Hubbard stated that one of the keys to Lunar Prospector was that the people involved brought a lot of experience and dedication to doing things in a different way. There was a common understanding of the challenge and a dedication from everyone involved. Binder also believed that understanding the history of the project was critical to project success and building project spirit. So one of the first things he did was to sit the engineers down and explain the philosophy, history, and what Lunar Prospector was trying to accomplish. Binder wanted the project members to feel committed to the project and think of it as a traditional aerospace contract. Although this task took much effort and received resistance from some of the engineer's, it became pivotal in build a foundation for the project spirit.

Lunar Prospector believed that the project spirit had to be experienced as much as it was felt. They developed project logo stickers and patches, which appeared on everything from notebooks to janitor's barrels. One of the most unique and clever project spirit activities was after the announcement was made that water was discovered on the lunar surface, Lockheed Martin project members put out a Lunar Prospector water bottle with a Lunar Prospector logo and some clever sayings on the side (e.g. Moonshine). NASA was in the developments of a slogan that would be the foundation of future planetary missions – Water, Life, Origins. Lunar Prospector gave that slogan and NASA hope that life could exists away from Earth. Project team members fostered these events, but as an organization Lockheed Martin did little to nurture a project spirit. When it was announced that Lunar Prospector was selected, Lockheed Martin did little to congratulate the project team, while Martin Marietta, winner of the other two Discovery proposals, through a large dinner party for all of the people involved. Throughout the project it was the project team and not the parent organization, Lockheed Martin, which fostered and nurtured the project spirit. Despite what rituals and ceremonies there were to foster a project spirit, most team members will tell you that it was the success of the mission and their knowing that they were a critical part of it that fostered and maintained the spirit.

### *Policy to Support Strategy and Spirit*

"Are you familiar with Lockheed skunkworks? Well this was a super skunkworks"
- Alan Binder, personal interview

When Hubbard was asked if Lunar Prospector has a policy to support the strategy he simply stated, "To a certain extent we were making it up as we went." The management of Lunar Prospector had a vision on how Lunar Prospector could be accomplished in a very cost constrained environment. Some of this was using existing Lockheed Martin policy directives and not writing an Ames plan or a NASA plan. By doing this Lunar Prospector was able to keep documentation to a minimum, and allow the team to concentrate on the project engineering. This allowed engineers to do what they loved, be engineers. Alan Binder believed that people were the keepers and the communicators of the knowledge, so he relied on people's tacit knowledge and open communication to keep the project moving and motivated.

To accomplish this, Lunar Prospector believed that to be successful they needed a team of good engineers and no bureaucracy. Binder stated from the start of the project that in order for Lunar Prospector to be successful they had to meet these two criteria. Lockheed-Martin said they would give Lunar Prospector the companies' best engineers and lift all the bureaucratic barriers, but Binder does not believe they did.

### *Leadership*

As a management team Binder and Dougherty worked each other's skills to move the project forward. Binder understood the technical thoroughly, and while Dougherty may not have understood the system as well, he managed the money and personnel, as Binder put it, "beautifully." Binder and Dougherty believed that management should be working managers. As Binder stated,

> I was not the manager who sat in my big soft chair somewhere and just wrote memos. I was down there, they know that they could come in and talk to me and tell me anything they needed to do and I worked with them – they did not work for me. Slowly but surely as the program went on even though these guys thought I was totally wacko for trying to do what they thought could not be done they began to see that it was working.

As the Principle Investigator, Binder was in charge of the science in addition to being the lead for the project. He set a standard of open communication, but made no doubts that he was in charge. As he stated, "I believe absolutely in dictatorships. You get nowhere by doing things by committee." Binder believed that in a FBC project an individual has to step forward and lead the project. They must be willing to take responsibility, make decisions and stick to their decision. If someone on the project cannot work in this environment then they should be removed from the project. The counter to this, Binder also believed that this person must be willing to take blame when something goes wrong. Binder believed that whoever is going to run the program has to be willing to standup and say they screwed up. If they are successful then credit will come to them, but they have to be willing to take the blame and as Binder stated, "very few people are willing to do that."

Dougherty believed in including people in the decision making process and then making a decision, telling them why he made that decision, and then moving on. He did not spend a lot of time on decision-making processes and rarely was any decision stalled for more than a week. Dougherty was a motivational manager and believed in instilling confidence in the team members so they would not doubt his decisions. Hubbard believed in working hard at the front-end of a project to establish the requirements and then let a capable team do what they are trained to do. He did not believe in micro managing. Hubbard believed that he should manage by delegation and hold people accountable to high-level requirements rather than detailed specifications. Hubbard believed that a significant amount of effort should be put up front to ensure the project go off to a proper start. This meant a certain degree of control and engagement in the contract process and the early definition. But once Hubbard felt it was clear that the project was heading in the right direction, he was hands-off and letting the project go where it needed to go.

***Team Empowerment***

"It was very much by delegation and holding people accountable to high level requirements rather than detailed specifications."

- Scott Hubbard, personal interview

Lunar Prospector worked hard to try and empower the project team. The shear virtue of NASA not inserting how Lunar Prospector was managed gave empowerment to the project team. Tom Dougherty brought a philosophy about management that made the people responsible in the decision making process. Management believed that you let people know their job and let them do it. With responsibility came accountability. If any person failed in their responsibility, they were responsible to fix it. Conversely, if they did a good job, they got the pat on the back they deserved. To do this Lunar Prospector believed in hiring competent people. People were put in charge of not just specific parts of a subsystem but whole subsystems. Cox stated that this was harder for some because "…they were used to maybe worrying about the component system and they had the whole power subsystem. They had to worry about the solar arrays and the solar cells and the power budget." Many of team members found the scope of their jobs almost intimidating. While some were able to step up to the challenge, others had trouble. This is where Dougherty's people managing skills became critical. He was able to adapt specific individuals to tasks they were capable of and motivate or intimidate people to take ownership. Cox says that Dougherty was successful because he looked at the individual and tried to motivate them to do the job he felt they were capable of doing.

Hubbard said that one of the keys to empowering the project team was having the ability to say, "No." He states that routinely a company such as Lockheed Martin is "accustomed to working for different customers and they would come and say ok Mr. Customer, Mr. DoD, or NASA what do you want us to do next? Or, what do you do about this? And we would say no, no, no. You don't get it we are holding you accountable for delivering a spacecraft that works. What do you propose to do about it? Give us your options and then you're proposed solutions and if it seems reasonable we'll go with it."

## Organization

### *Project Organization*

"He who defines the program, designs the hardware; he who designs the hardware, tests the hardware; he who tests the hardware, flies the hardware. It was a cradle to grave program."
- Alan Binder, personal interview

Lunar Prospector was small compared to most NASA sponsored missions, but this is one of the factors that made Lunar Prospector innovative. The contractor, Lockheed-Martin in Sunnyvale, California, has a workforce no more than forty or fifty people. NASA's main contribution came from the Ames Research Center (ARC) through two distinct groups: the mission office, which was responsible for managerial oversight for the project, two to three people; and the NASA project team, which was people actually working on the project, six people. In addition to the Lockheed-Martin contractors, there were co-investigators at various institutions around the country: Los Alamos National Laboratory, University of California-Berkley, University of Arizona, Goddard Space Flight Center, and the Jet Propulsion Laboratory.

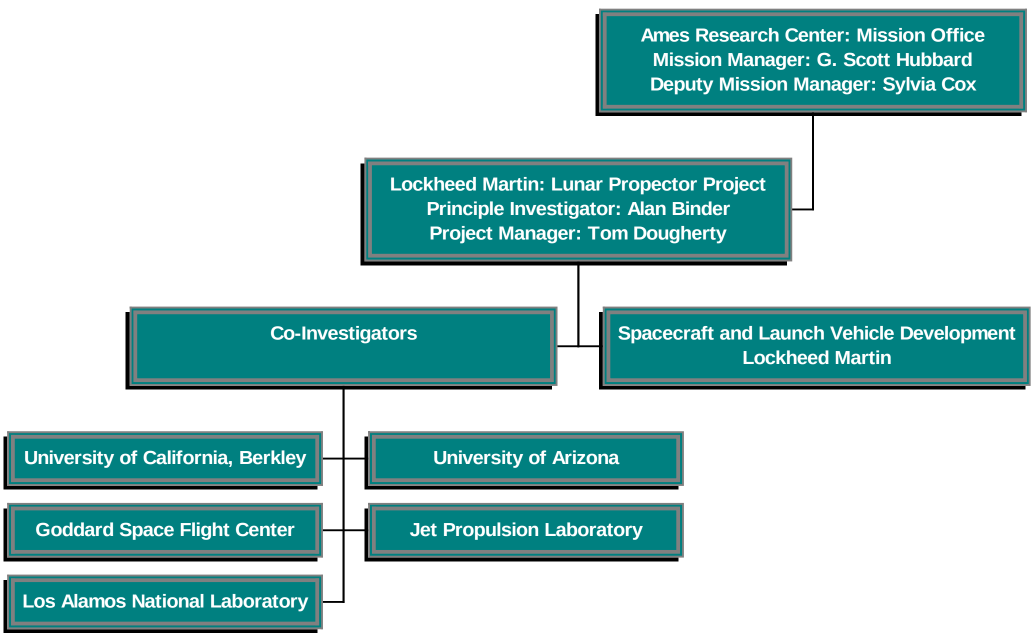



**Figure 2: Organization Chart**

### *Structure*

Lockheed Martin implemented the project under a NASA contract. The Project Manager within Lockheed Martin, Tom Dougherty reported to the Principal Investigator (PI), Alan Binder. At the start of the project, Lockheed Martin employed Binder. Later Binder started his own non-profit company, Lunar Research Institute. Normally the science PI is not from a company, but part of a university, so this was a unique situation. The PI is responsible for setting out the scientific requirements of the mission and the day-to-day project management responsiblity was with the Project Manager. The PI worked directly with co-investigators who would provide instruments and/or scientific analysis. Something that was unusual to this project was that Lockheed Martin was made the single prime contractor and they sub-contracted with all other parties involved (except other NASA agencies). This did create some bureaucratic issues, but they were overcome. The actual delivery schedules came from the Lockheed Martin's project office, and the contract between Lockheed Martin and the government to deliver a working spacecraft was the responsibility of ARC.

The organization was flat with lines of communication kept lean and accountability kept firm. To be successful, Dougherty believed that co-location was critical. One of the first things he did was get the team co-located. They were located in one building in what Lockheed Martin called a pod, which made everyone no more than 50 or 100 feet of anyone. Binder and Dougherty worked every single day with every single engineer in the trenches. Lunar Prospector had one engineer who was responsible for each subsystem. As Binder stated, "There was no passing the buck here, there was no saying some of my guys screwed up. He was it."

### *Team Assembly*

"You can't let people just keep their job because they are there warming the chair."
- Alan Binder, personal interview

Binder does not contest the critics that say FBC is hard. He says that you have to have competent, dedicated people who are led by someone who know what he or she is doing, and that is difficult to come by. With Lunar Prospector, Dougherty handpicked many of the engineers. Traditionally within Lockheed Martin people are selected from individual departments based on skill sets. This can take time because these people have to be requested and transitioned through a normal process of selection. Because Dougherty had years of experience with Lockheed Martin and an established network, he was able to select the talent needed to make Lunar Prospector happen. Dougherty also believed that you have to be able to manage those people's time, a valuable resource. When a person was not necessary or having work to perform, Dougherty would put them on another program for a week. He was able to strategically manage personnel to optimize budgetary constrains. Binder and Dougherty only had people working on the project who had something to do. For Dougherty is was a balancing act between people with minimal cost (usually junior people) and those with senior level experience. The co-investigators were picked on the basis of their track record in supplying instruments and knowledge about lunar science. The NASA (ARC) people were selected by Hubbard based on their work on other programs.

### *Responsibilities*

"People basically were given overall authority for a specific subsystem or a specific task and then they were expected to go do it."
-Sylvia Cox, personal interview

Lunar Prospector had one engineer in charge of each subsystem and they were the responsible person for that subsystem. Each person knew that their work was critical and that they were responsible for it and they could go to management without repercussion

For Lunar Prospector, people had well defined and specific responsibility and each person knew what was their responsibility. They were told very early in the process what was their responsibility and each person knew their work was critical and they knew they could go to management without repercussion. Management sat down with each specific area of the project and asked the individual responsible for that area to come up with milestones of what they felt would show they were making progress on a monthly basis. Then management negotiated with the individual the definition of those milestones. With this process they tailored for each subsystem in the project a way of keeping tabs on whether they were making progress on their path.  The whole delegation of work was the responsibility of the individual within the constraints of meeting the milestones.

***Top Management Involvement***

A combined program and project management from the Lunar Prospector Mission Office (LPMO) at NASA Ames Research Center (ARC) managed Lunar Prospector.  This office was responsible for being the single point of contact to the Principle Investigator and the Lockheed Martin (LMMS) Staff.  Lunar Prospector wanted to maintain lean management staff with clearly defined roles and lines of communication.  Hubbard believed that it was necessary to limit the detailed specifications given to the contractor and let them work from high-level requirements.  He believed that you find a contractor with a depth of experience and let them do their job.  In this case it was Lockheed Martin with over thirty years worth of development experience in the private sector.  Hubbard stated that judgments were made up front about risk areas and working the insight and oversight.  Hubbard termed this "programmatic oversight and technical insight."

Top management at NASA gave the project team of Lunar Prospector as much freedom as possible to accomplish the mission.  As Alan Binder stated, "NASA kept saying, 'Oh, my God; we don't like this we're never going to do this again,' because they had no control (personal interview)" NASA top management left the Lunar Prospector team alone, and felt that as long as things were moving along they would stay out of it.  This was true until it got close to launch and the reality of a possible failure became more realistic.  This was because Lunar Prospector was going to launch on an unproven launch vehicle that had never been used before.  Top management then became very involve with some extensive reviews.  Cox recollected, "Tom Dougherty had run the first Hubble servicing mission and he told me that by the time they got ready to go they had 25 independent review committees looking at them. He predicted that the closer we got launch the more reviews would come and the more nervous headquarters would become.  And he was absolutely dead on right."

***Professional Advise and Reviews***

"Simple and frequent review meetings allow quick responsiveness.  Not everyone must participate, but they must be available.  It can be done quickly and allow for quick feedback and continuous monitoring of cost and progress."

- Sylvia Cox, ASK Magazine

Great attempts were made to make sure that reviews were based on quality and not quantity. The numbers and lengths of reviews were kept to a minimum and Binder even changed the names of the reviews to minimize the attendance at these reviews to the critical minimum.  Doughtery believed that reviews were critical to project success, and stressed that reviews should be seen as opportunities and not a trial.  He believed that the review committee should be just as accountable with providing potential trades and solutions as the team was for meeting developmental objectives.  Reviews (formal or informal) were frequent and based on a systematic and simple monitoring system.  Doughtery implemented weekly subsystem reviews and everyone on the team had to make him or herself available to immediately solve problems.

Lunar Prospector was asked from the onset to have an independent (informal) review team.  Hubbard took this very seriously and hand picked a review committee that he believed NASA headquarters would have unquestionably confidence in.  To head the committee he got Jim Martin, Viking Program Manager, he also got a former Vice President at Martin Marietta, and representatives from other NASA centers to get across agency support and input.  Hubbard got a very high level, extremely experienced set of reviewers to participate in this review team.  The annual reviews with the independent review team were then tied to milestones in the project to give the review team and the project team target items to focus on. These reviews became a mechanism by which the review process was streamlined. It cut the amount of reporting and the number of times they spent doing reviews. Many of the standard NASA reviews (i.e. test readiness review, pre-ship review) were incorporated into these annual reviews. A keynote to the formal reviews and this review committee was that they had no authority over the project, only the ability to recommend. The Lunar Prospector team did not consider most of the recommendations of the formal review because they did not have the time or money to implement them.

Because the amount of money spent on Lunar Prospector was minimal compared to other NASA missions, the amount of reviews was not considered an issue. Cox says, "By the time they considered it an issue frankly it was too late." Although all managers in Lunar Prospector attribute part of their success to the advice and guidance in the informal review from proven and successful project managers in the area of planetary exploration and project management. Specifically the advice of James Martin, Viking Project Manager, and Charlie Hall, Project Manager of the Pioneer exploration series. Both of these men provided thorough critique of Lunar Prospector and whether they were managing risk and budget properly. Martin held the position of chair of all of Lunar Prospectors external review boards, and was cited by all of the Lunar Prospector managers as a key component to providing the exact level of external guidance to allow Lunar Prospector to be successful without being held back by bureaucratic requirements.

***Organizational Problems***

It was clear with every team member that problems would only cause delays in the project, which would result in cancellation. Therefore, every issue was addressed right then and there with each person knowing their responsibility and only one person being responsible. If there was any significant conflict in Lunar Prospector, it was between Alan Binder and Scott Hubbard. Alan Binder truly believed that a PI, science led mission could be accomplished faster, better, cheaper. And Binder believed that the best way to accomplish this was to give him the money he need and let him foster his vision without any constraints (oversight). Hubbard's vision was similar to Binder's in that he wanted to prove that faster, better, cheaper could be successful, but Binder and Hubbard disagreed about the how. Alan believed very strongly in what his vision was whereas Hubbard believed very strongly that NASA had responsibility to have oversight and insight into what was going on with the mission. Cox described this as a conflict in vision. In many cases Binder and Hubbard agreed to disagree.

***Training***

As with most fast paced project, training on Lunar Prospector either received prior to the project start of on-the-job. Most of the managers did not have formal managerial training, but brought to the project a wealth of experience.

## Processes

### *Project Phases and Reviews*

NASA has a defined formal five-phase process for projects (A, B, C, D, and E). Each phase represent a progression in development and can be characterized as a stage-gate process. For Lunar Prospector Phase A (concept study) was already complete before the project got started. For Phase B (design study), Binder and a group of volunteer engineers from Hughes were able to complete with support funding from the Space Science Institute, so Phase B was completed before the project got started. For the first six months of the project, Lunar Prospector went through a Phase CB (technical design review). Management approached these reviews as scheduled checkpoints based on time and not completion of project phases. Therefore, if a subsystem was ahead of schedule, it did not slow down (as long as there was no impact on the system) to wait for approval from the formal review board.

### *Communications*

Lunar Prospector kept meetings to a minimum and worked to make sure that the time spent in meetings was effective and efficient. Every Monday morning they had a staff meeting to address objectives for the week, and every Wednesday they had a subsystem review so engineers could address the issues. Dougherty felt that if they found out a problem Monday, they had it finished by Friday. If they didn't find out about it until Wednesday it went into the next week. Binder said these pointed meetings were critical. These weekly meetings covered the current status of the project, key issues, and overall project process. They were team meetings and not solely controlled by management. Management was open with all team members at these meeting on issues of budget and schedule, and were always looking for input from the team on how to do things better. Communication was open and problem solving was real-time.

If someone had a problem with a subsystem that was not addressed in a meeting they went to Binder and/or Dougherty and it was dealt with immediately. As Binder stated, "We were always within five minutes of a problem." Communication was open door and co-location critical. As Binder stated, "having everybody within shouting distance" was critical, and made communication personal and instantaneous. Cox tells recollects, "The fact that I could get in my car and drive for ten minutes and be at Lockheed in the building, I was back and forth every day, just about. There were some days when I wasn't there or here actually. The same thing was true between Scott and myself. Scott was the Mission Manager. I had ready access to him if I felt like I needed it as his onsite Manager of Lockheed. So I felt like we had a very streamlined and efficient communication process and that co-location was a big piece of it. Binder prides himself on saying that he did not write any memos; it was done face-to-face. Binder's persistence in face-to-face communication is best described as,

> I want to talk to people because again when you write an email especially between scientists and engineers even though I'm well versed in engineering you don't speak the same language. You cannot communicate in the written word the way you can if you stand in front of a guy and you see the guy isn't comprehending what you say or vice a versa.

When Cox was asked what forms of communication were used, she simply answered, "It was almost all verbal communication." Hubbard stated that this open, frequent communications made all the difference in Lunar Prospector. They were able to work problems as they came up identifying them and not let them fester. They worked to be very proactive and try to figure out where the next problem might arise. Cox stated, "I was totally treated like I was a member of the team. There were no meetings that I couldn't go in there wasn't anything hidden from me. I saw all the reports they made to the management.  It was a very open process.  And I think that really contributed to people feeling like they were part of the team."

Lunar Prospector had a monthly reporting requirement to NASA management at ARC.  Cox states that this monthly reporting mechanism should be a confirmation of everything she already knew.  She believed that if she were really paying attention to the project, then she would not need a report to inform her of the projects progress.

***Resource Management***

"I had periods where the cost constraints and the inherent difficulties of space hardware development made me wonder if we were going to get this project off the ground."
- Sylvia Cox, ASK Magazine

Lunar Prospector believed resources was scarce and there was no room for error or contingency. They believed that the requirements were set early and you had to stick to them.  As Binder states, "This is why faster, better cheaper is tough to do."  Binder believes that in most aerospace projects engineers design for plenty of contingency, but contingency cost money.  The unforeseen events occur; the more requirements begin to grow over the life of the project.  Lunar Prospector would not tolerate a requirements growth.  They paid a great deal of attention after the initial distribution of costs to each subsystem and who was charging to the program and why. Cox says, "This is why most projects get in trouble with costs, because for the most part managers really don't pay attention until a project is in trouble and then it's too late."  Dougherty paid very close attention to resources, especially human resources.  They would look across Lockheed Martin and question anyone that they were unsure about that was charging time against Lunar Prospector.  If Dougherty or Binder questioned someone charging time to Lunar Prospector and no one could explain then that person was questioned or removed.

***Reducing Uncertainty***

"You fly what you test and test what you fly.
- Aerospace Proverb

The results of reduced technical uncertainty can sometimes mean increase spending.  Lunar Prospector's budget was based on a bare minimum.  Binder believed that the only way that Lunar Prospector was going to stay on budget and keep the costs down was to go "single string."  Lunar Prospector believed the answer to reducing technical uncertainty and budget was to minimize redundancy and test, test, test. They viewed testing as the way of being sure that a cost constrained approach was going to work.  Therefore, they spend a lot of discussion on how much testing was enough testing and which tests were critical.  There was not only no backups, but no test model.  The spacecraft that was tested was the one that flew.  Binder tells a story of when Lunar Prospector was tested in the thermal vacuum chamber that is the example of why testing was so important to Lunar Prospector's reduction in technical uncertainty.

> The people in NASA didn't think that you could build a spacecraft the way we were proposing to do for the costs.  So when we got ready for thermal vac test and I'm sure you know that that's the big test.  Lockheed's history and all the aerospace history is you go into thermal vac and find out what's wrong with the spacecraft, you take it out and fix it, and put it back into the thermal vac.  And you find if anything else is wrong and you might have to go in a third time.  We had a ten-day test cycle.  There were two hot and two cold cycles.  We reserved the chamber for two weeks.  And hoped that that would do.  We went and put it in there and got it all setup and closed the door pumped down for a day, and cooled

> down for a day and seven days later walked out with the perfect spacecraft. At that point I knew that everything that I had proposed in the whole concept worked, because we had just flown the mission in thermal vac. That had never happened in the history of Lockheed or probably in the history of aerospace.

The most perceived critical risk that received the most attention was the launch of Lunar Prospector on the unproven Athena II launch vehicle. During the first uses of a new commercial launch facility at Cape Canaveral, Florida there had been several commercial satellite and launch vehicle failures (e.g. Pegasus, Arianne V). Because of these recent failures, and it being the maiden launch for the Athena II, Lunar Prospector went through extensive reviews. They spent months and months with a Marshall/KSC review committee to convince top management that there was not a high risk in launching Lunar Prospector. It wasn't the dollars invested into Lunar Prospector that was of such concern, but how the people outside of NASA would perceive it if there was a launch failure.

***Systems Engineering***

All the managers for Lunar Prospector state that they did nothing unusual in the area of systems engineering. They used many of the standard techniques. What they will tell you was unique with Lunar Prospector was how the people dealt with and managed the subsystems. The exception was that people, who wrote the requirements, were the people who monitored the requirements, were the people who were involved in systems integration. The same core of subsystems engineers did all of the work that was done on the requirements and all of the work in terms of evaluating performance throughout the mission.

Lunar Prospector worked hard to cut costs and in order to accomplish this they streamlined processes that normally were performed by multiple groups and put the process into one team. An example of this was the wiring for the spacecraft was all performed in house. Normally time is spent developing wiring diagrams and these are then turned over to a wire shop who then turn the final product over to a spacecraft integration group. For Lunar Prospector, all three of these phases were consolidated into one, and the spacecraft was wired in real time. This meant that there was no room for error; one fault meant that the mission would be over. Although this method cut cost and time it increased risk. The true challenge to this as Binder stated was that when you do this with a tight schedule and tight budget, you have to have excellent engineers. When it came to design and requirements documentation, in many cases 'redlines' were accepted without being incorporated in to the final document. It was a work-it-out-as-you-go mentality.

***Risk Management***

Lunar Prospector believed that risk management could be handled with simplicity and looking at the spacecraft with a systems perspective. Cox said that when you consider the integration of the subsystems, you begin to see the risks. Lunar Prospector had a list of the top five risks and tracked what they believed the risks were in each subsystem. Dougherty monitored the whole project on the wall in his office by looking at the budget, the mass, and the power, and everyone in charge of each subsystem took accountability for their part. Binder firmly believed the first step in risk management was having someone that would be willing to take responsibility for the mission and the failures. It was a factor of personal responsibility with the project leaders and the team members. Also, Lunar Prospector believed that you fly what you test and test what you fly. They selected flight proven hardware whenever possible and tested everything in every possible scenario. Binder stated that Lunar Prospector's risk management was simplicity, straightforwardness, and minimal operational requirements.

### *Customer Involvement*

Lunar Prospector made it very clear and distinct that they had three customers: the Office of Space Science at NASA Headquarters and the Discovery Program, the sponsor; the scientific community, user of the data; and the general public.

### *Contractor Involvement*

"We got the subcontractors realizing that they were part of a real adventure."
- Scott Hubbard, personal interview

Lunar Prospector believed that vendor involvement was critical to mission success and getting the designs they needed and in a timely manor. Managers from Lunar Prospector would go to the individual vendors and tell them exactly what they wanted the equipment for, why they needed it early, and what it meant to the project. They made a personal visit to every major vendor and made sure he or she was part of the team from the beginning. At every visit they emphasized the spirit of Lunar Prospector and made sure that the vendor bought into this spirit. They contest that this was why they got the best hardware that they could build. Lunar Prospector may have used existing hardware, but they received it in half the normal development time and at significantly reduced costs.

## Tools

For Lunar Prospector there were no unique tools used to manage the project. The one tool that was used by Lunar Prospector, is used by many NASA space science projects, and unique to NASA is Earned Value Management (EVM). EVM is a standard NASA way of running planetary flight projects and performance metrics. EVM is based on a set of project tasks, and each task has a cost to complete and/or items to procure. Each task and procurement has a schedule for completion, and as each one is completed a monetary credit is assigned. These credits are then graphed against how much money has been spent thus far on the project to determine where project progress follows on the curve.

### *Knowledge Management*

"You don't have information being passed on by documents that no one reads and even if they did you know as well as I do that no two people understand the same thing the same way."
- Alan Binder, personal interview

Lunar Prospector kept documentation to a minimum, and did not spend time producing documentation that would not be used or read. Binder believes that there is a loss of information in excessive documentation. He says that there is a loss of information in the translation as the document is passed on. Binder says that the people are the key to passing information. This is why Lunar Prospector believed in keeping people on the project cradle to grave. Traditionally within NASA or most large aerospace companies somebody defines the Phase A, and then writes a report. This is then passed on to the people that will define the Phase B and they will write a report. This process is followed through all phases. In the end, a final report and specifications document is passed on to the team that will build the spacecraft. Lunar Prospector believed that this just generates a number of reports that no one reads and this information is passed on to people that will be building the spacecraft, and have not written a single requirement or specification. That is why they believed in the cradle to grave mechanism for retaining and passing knowledge.

Alan Binder tells the story of why Lunar Prospector believed knowledge was in the people and not the documentation:

> Because we had minimal documentation when we had our reviews we caught holy hell because there wasn't a stack of documents. And so Jim Martin said we want some documents the next time we come here. So Tom and I said ok guys every engineer write up some documents. Tom and I never looked at them; we signed them. We had a stack of documents nobody read, had them on the table when the review committee came back for the next review, and they said ok we see your documentation; fine.

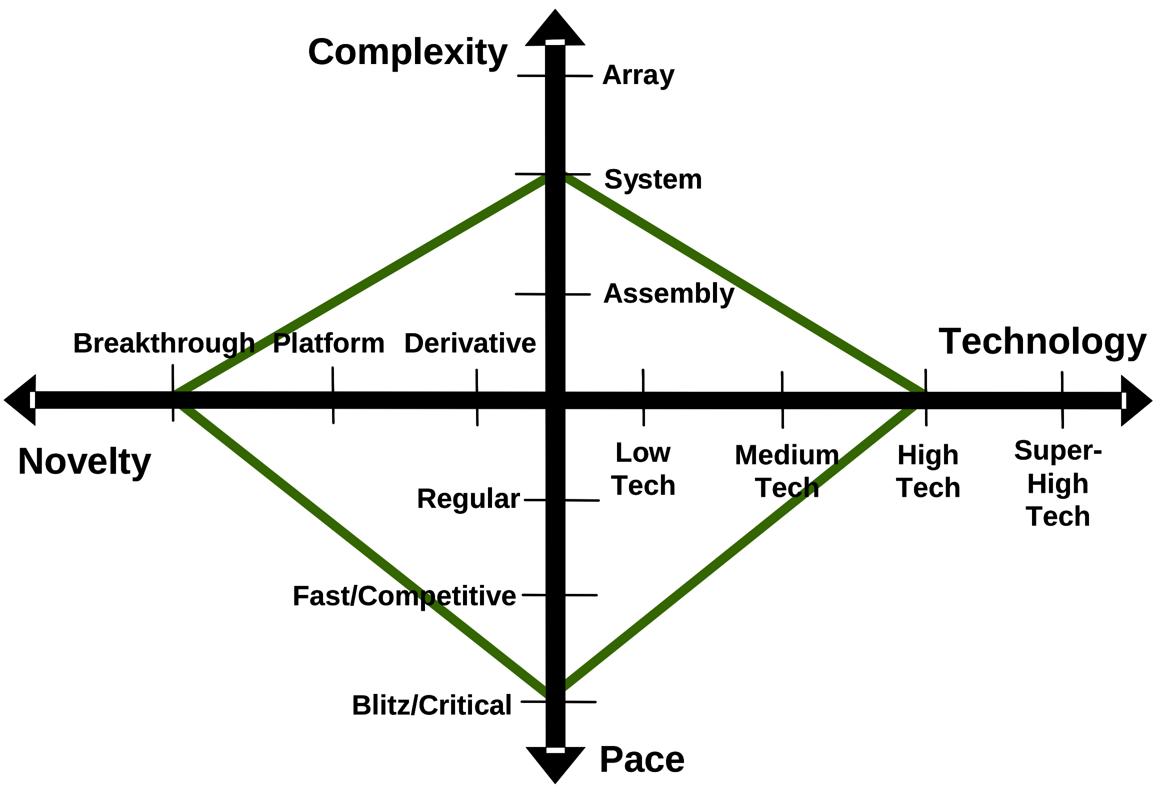
### *Learning Process*

It can be assumed that because Lunar Prospector did not believe in a lot of documentation, lessons learned were not a critical part of the post-project activity. Hubbard et.al. wrote several papers documenting some to the scientific and managerial lessons learned from Lunar Prospector. These papers were presented at several conferences and meetings. In addition Hubbard participated in NASA Shared Experiences APPL training program. But, for the most part little effort or emphasis was put on lessons learned. Most managers expressed that Lunar Prospector was very unique and the culture and environment that made Lunar Prospector successful may be difficult to repeat in the current NASA culture.

**Adapting Project Management to Project Type**

Lunar Prospector was a strategic project centered on a new research effort to explore the moon. Exploration of the moon of this magnitude had not occurred in more than 20 years (since Apollo). Lunar Prospector would sustain NASA's position in space exploration and significantly expand our knowledge of the moon. In addition, Lunar Prospector would represent the first competitively selected Discovery Program mission. The task outcome for Lunar Prospector was a tangible product of a spacecraft, orbiter, and scientific instruments. Lunar Prospector required a significant level of insight and creativity both technically and managerially built around a core of talented, experienced people to produce a valued product. The scientific community defined Lunar Prospector's scientific objectives; therefore, there was an obligation to satisfy their external customer with scientific data. While there was a project commitment to the scientific community, it was the financial commitment from the NASA Discovery Program that would define Lunar Prospector by their internal customer. When defining project success and making strategic decisions, Lunar Prospector was more concerned with their internal customer, NASA.

The NCTP Model below represents the analysis of Lunar Prospector in respects to its Novelty, Complexity, Technology, and Pace. Connecting the NCTP classification with a straight line to form a diamond, gives a representation of the level of risk associated with a project. The greater the area of the diamond, the greater the degree of risk. While there is not a linear relationship between the area of the diamond for correct and incorrect project risk, it can represent a difference in the degree of risk.



*Novelty*: Lunar Prospector was a breakthrough product. The technology used in Lunar Prospector was a new use for existing technology which aerospace had never seen before, and it pushed the boundaries of cost-effective space exploration. While there was much to be learned from Apollo, these early lunar missions only opened 20% of our understanding of the Moon, and little had been accomplished in lunar exploration since Apollo. Therefore, Lunar Prospector was based largely on scientific fundamentals, with limited experience in similar products and history of trial and error. This meant fast prototyping, keeping a close, honest relationship with its customer, and late design freezes.

*Complexity*: Lunar Prospector was a system project. As complex integration of scientific instruments and spacecraft subsystems, Lunar Prospector was lead by a main program office, NASA Ames Research Center, directing a prime contractor, Lockheed-Martin. There were several other subcontractors to produce the scientific instruments with a mix of in-house and external development. While Lockheed-Martin managed the project, it was NASA-Ames' ultimate responsibility to be accountable for the spacecraft. While the documentation was kept minimal, with any complex NASA project, the documentation is extensive compared to most projects. As an organization, Lunar Prospector was a pure project structure with tight control over the project and extensive reviews with the customer. Lunar Prospector had multiple key customers from industry, public, government, and the scientific community that were all vested in Lunar Prospector's development and success. As a systems project Lunar Prospector was a complex project that required extensive planning, computerized tools and software, hundreds or thousands of activities, tight and formal control, financial and schedule issues, and reviews with customers and management.

*Technology*: Lunar Prospector was a high-technology project. As a product, Lunar Prospector was not revolutionary but maintained a simple design using proven technology with only a few new iterations of those technologies. Although most of the technology was commercial-off-the-shelf or borrowed from other proven spacecraft, it was innovative in its application. With a simple design (by NASA standards), the project still involved long periods of design, development, testing, and redesign with multiple design cycles that had to start before the project started. With the extensive testing that was required for a high-tech project like Lunar Prospector, in depth, technical reviews were mandatory to make a project of this complexity successful. In conjunction with these reviews, communication had to be frequent and active. The complexity and communication demands required management to be of good technical skills and intimately involved in the project. They also had to recognize the unique challenges of CONTOUR and be flexible to extensive testing and design changes. Therefore, design freezes had to be scheduled and as late as possible. Lunar Prospector had a clear understanding of the complexity of the technology they were dealing with, and applied the right level of design constraints to the project to assure success.

*Pace*: Lunar Prospector was a blitz-critical project. All Discovery Program missions are under a contained development time, and any delays in that would mean cancellation of the mission. As a pure project, the team was specially assembled because of their unique and valued capabilities, and team members were only retained because they brought value to the project. When a crisis arose, it was dealt with in a quick and effective manor. People were open with in any crisis, realizing the end goal was more important. With a shortened development time, many bureaucratic policies were lifted and procedures were kept to the core minimum. Project managers were very involved in the project from beginning to end, and were never afraid to "pick up a wrench" to guarantee project success. In addition, management up the chain never questioned the status of the project. They were kept informed while allowing the project team the freedom to get the project done.

**Success Factors**

Lunar Prospector understood well before the project started that simplicity would be the key to project success. Lunar Prospector was well defined with a clear understanding of the scope, technical uncertainty, and pace. This guided management toward design constraints that kept Lunar Prospector on budge and on time. Key to Lunar Prospector's success were:

- Strategy
    - Strategy was determined before project started
    - Strategy was focused and clear
    - Continued articulation of the strategy
    - Objectives were simple, attainable, and valuable
    - Defined objectives based on customer needs
- Spirit
    - Focused, unspoken, common commitment to mission success
    - Willingness to do things differently
- Organization
    - Co-location
    - Limited involvement from top-management, but strong committment
    - Defined roles and responsibilities
    - People worked the project from beginning to end
    - Maintained only a core workforce
    - Mix of experience
- Processes
    - Stuck to the requirements
    - Test, test, test with quality, not quantity
    - Contractors were part of the project team
    - Informal (peer) reviews: quality, not quantity
    - Focused meetings

Lunar Prospector had an extensive pre-project definition period that was based on a long history of studies of lunar missions which gave a solid basis of the science and spacecraft requirements. Lunar Prospector realized that to be successful under the constraints of a Discovery Program project, objectives had to be clear, concise, and attainable. Objectives were designed to provide value, but attainable so as to increase the probability of success. The customer was a key contributor to defining these objectives, which fostered a strategic focus. Before Lunar Prospector started key leaders of the project got together to determine the project's strategy and how this strategy would be focused on the project objectives. Then management made sure that this strategy was understood by the project team by holding team meetings at the beginning of the project to articulate this strategy. Once the project started, they continued to articulate the strategic focus.

The spirit of Lunar Prospector was high, with focused and driven sprit. There were not a lot of spirited rituals and activities, but more unspoken, common commitment that was understood by all team members. People went the extra mile and had faith that their team members would do the same. People's commitment to the project was never questioned, and there was always a willingness to try a different way of doing business. Lunar Prospector was unique in how it was selected, managed, and developed, and this nutritioned a strong sense of what was mission success.

As an organization, Lunar Prospector was co-located. This meant that meetings could occur face-to-face with no part of the core team more than ten minutes away. This allowed Lunar Prospector to stay focused and directed while also having limited top management involvement, and being allowed to do things differently to get around certain bureaucratic obstacles. While top management allowed Lunar Prospector to be independent, it maintained a strong commitment to its success with a consistent funding stream from top management, which did not waiver throughout the project. Team members and management knew their roles and responsibilities from the beginning and no one ever questioned this. The team was maintained at a core minimum, if you were not needed, you did not work on the project. To accomplish this people worked the project from beginning to end. If their services were not needed at any point in time, they were not released but deferred to another project until they were needed. This allowed people to shepard systems through the project lifecycle. Having good shepards meant their were experienced people at the top combined with energetic young engineers. The focus of all of the managers was on making Lunar Prospector successful. When problems arose, the management set aside differences to keep the project directed with a common goal of doing it appropriately and timely.

Lunar Prospector had a good understanding of their technical capabilities, requirements, and constraints; therefore, they stuck to the requirements and knew when to freeze designs to maintain schedule. To support this, Lunar Prospector performed an extensive amount of testing. It was not how much Lunar Prospector tested, but the quality of their testing. This meant test every piece of equipment in every possible scenario. Lunar Prospector's understanding of the systems and instruments could only be accomplished with an intimate linkage to their contractors. Contractors were as much a part of Lunar Prospector as any person working on the project day-to-day. Lunar Prospector's relationship with its contractors was candid, informal, and frequent.

Lunar Prospector did not put a lot of weight in their formal reviews, but held their informal (peer) reviews as critical to achieving success. Great effort went into making sure the people on these committees were capable experienced individuals that would challenge Lunar Prospector while fully understanding their constraints.

### Recommendations

Lunar Prospector was unique in that it was one of the few NASA sponsored missions that was truly PI led. NASA has since moved away from allowing the PI to be the lead for all aspects of a project. This environment worked for Lunar Prospector because it was small and had an experienced and directed PI. Unfortunately this PI also brought an immense amount of tacit knowledge, thus it was difficult to document and transfer the project success to other projects.

**Recommendation 1 – Fully document the processes, even the process for success**: At the time of Lunar Prospector, the Discovery Program and Better, Faster, Cheaper were in their infancy. Documenting the how and why should have been more important to determining Lunar Prospector's success. Lunar Prospector was a focused project whose success, while measurable, was not captured. Lunar Prospector was the vision of one man, Alan Binder. Binder was focused, directed and driven to make Lunar Prospector successful. While these may be some of the traits of a good leader and what was needed to make Lunar Prospector successful, the style and processes that Binder used to help Lunar Prospector be successful were not well documented. Binder believed that to make Lunar Prospector successful, documentation had to be limited. While this streamlined processes, it left Lunar Prospector as a project that relied on the people as the keepers of the knowledge. This knowledge and lessons learned was never captured and documented during or post- project.

**Recommendation 2 – Resolve leadership conflicts quickly and have clear lines of leadership:** Lunar Prospector was not without conflict, and conflicts between managers were not uncommon. Another issue with the leadership was the lack of training. All of the managers were accomplished engineers/scientists, but almost all of them had little managerial training. This may have been the source of some of their conflicts (other than personality differences).

# APPENDIX C – COMET NUCLEUS TOUR (CONTOUR)

# Strategic Systems Innovation

# A Case Study of

# Comet Nucleus Tour (CONTOUR)

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## Executive Summary

As the sixth mission in NASA's successful Discovery Program, the Comet Nucleus Tour (CONTOUR) was a joint project between Cornell University and Johns Hopkins University Applied Physics Laboratory (APL), along with 14 other university, government, and industry co-investigators to study three major near-Earth comets. With a budget of $159 million and a development time of almost three years, it was scheduled to fly within 60 miles of each of three comets. From the time of 2003-2008, CONTOUR would take images, make spectral maps and analyze dust flowing from the comets to substantially improve the knowledge base and expand the understanding of comets.

As a breakthrough product, CONTOUR was a single spacecraft, and six scientific instruments designed to provide a detailed look at comets and answer questions about how comets act and evolve. While much of the technology was know, its application and what CONTOUR was planned to accomplish made it different than anything that had been done before. No one in the history of space exploration had ever brought a spacecraft as close to a comet as CONTOUR would. While they were using predominantly existing, off-the-shelf technology and technology from previous missions (NEAR and Stardust), CONTOUR was flying for the very first time a non-coherent DOPPLER navigation system and a Solid Rocket Motor (SRM) that had not been thoroughly tested with the spacecraft.

As a project, CONTOUR was to design, test, and develop an orbiter that would obtain scientific data on comets and demonstrate the philosophy of 'faster, better, cheaper.' CONTOUR could be described as a high-tech project. While much of the technology was proven from previous spacecraft, its application and what CONTOUR was planned to accomplish made it different than anything that had been done before. The complexity of the project could be described as a system with a collection of interactive elements and subsystems that has to perform a wide range of functions under extreme conditions. The pace of the project was a blitz-critical project. While many of the characteristics point to a fast-competitive project, it is the inflexible launch date of CONTOUR that moved it into a blitz-critical mode. Any error in time or budget meant cancellation for the project.

All of this would add up to what Cornell and APL believed would be a storied success, but what happened on August 15, 2002 when communications were lost was never to be expected. On August 15, CONTOUR was scheduled to accelerate the spacecraft and place it on a trajectory toward its first comet. While operations continued based on the assumption that the firing took place on schedule, no signal was received from the spacecraft. From August 16 through August 21, three objects were identified near the expected position of CONTOUR. Communications attempts continued with the spacecraft once a week through December 2002, and the mission was declared officially lost after the December communication attempts failed.

Wide spread faults were hard to find in CONTOUR, and it embodied many of the characteristics of successful Discovery Program missions. Management brought to the project years of success, and a firm belief that they knew what it would take to make CONTOUR successful. Without a good framework for determining the technological complexity and overconfidence from past success, CONTOUR was challenged with not having a clear understanding of the technological uncertainty. The challenges and pressures of BFC resulted in a need for clearer lines of leadership, co-locating key subsystems, having team members 100% on the project (cradle to grave), and independent in-depth, technical reviews with active communication with experts outside of the reviews.

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**<u>Participant Observation</u>**

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## Background

The concept of CONTOUR was conceived in 1972 at a space science conference where comet missions were one of the discussion topics. It was at this conference that Dr. Robert Farquhar, CONTOUR Mission Manager, and Dr. Joseph Veverka, CONTOUR Principle Investigator, first met and conceived of CONTOUR. From some of these early discussions, the idea of comet flyby missions had been debated and proposed many times, but it was not until the Discovery Management Workshop, held at San Juan Capistrano Research Institute in April 1993, that comet missions would eventually find a place that they could be openly discussed, researched, formulated and have an avenue for to be proposed for implementation. This would be through the birth of the Discovery Program. The Discovery Program was designed to competitively select and develop small, moderate risk spacecraft for a fraction of the cost of 'flagship' missions.

In late 1993, $100,000 was awarded to perform a paper study on a 'CONTOUR-type' concept of doing a comet flyby mission of multiple comets using Earth swing-bys (the steering wheel for going from comet to comet). Soon after that study, there was an Announcement of Opportunity (AO) going out from the Discovery Program. At this time, Farquhar and Veverka put together a CONTOUR proposal that looked very different from the CONTOUR that would eventually be selected. It looked like a more traditional spacecraft. This CONTOUR was cubed shape with articulated solar arrays, and would not fly as close to the comet nucleus as was planned in the design that flew. This original Discovery Program proposal was not selected, and did not even make it past the first round of selections. Between that AO and the next AO (AO-96-055-02), a complete revamp of how CONTOUR would work as a mission and how close it would fly by the nucleus was performed. The new CONTOUR got rid of the articulated arrays, went with body-mounted panels, and moved away from the cube shape to a spacecraft with eight sidewalls. One of the most significant changes, that later would became a critical design decision, was the use of Earth swing-bys which resulted in integrating the solid rocket motors (SRM) with the spacecraft.

With a new design, like many missions before it, CONTOUR was going to build on exploratory results from earlier missions, but do it in a unique and innovative way. Mars Pathfinder and Lunar Prospector opened new windows into the study of the Moon and Mars, but both had missions that went before them that laid the groundwork. Mars Pathfinder had Viking, Mariner, and Mars Global Surveyor, and Lunar Prospector had Gemini, Apollo, and Clementine, and CONTOUR had earlier flybys of Comet Halley, data from NASA's Stardust and the European Space Agency's Rosetta missions. But, like Mars Pathfinder and Lunar Prospector, CONTOUR was unique, innovative, and going to push the forefront of our understanding of the universe. Proposed by Cornell University as a principal investigator (PI)-led mission, CONTOUR was selected as the sixth Discovery Program mission in August 1997. As PI, Veverka quickly looked to the Johns Hopkins University Applied Physics Laboratory (APL) to lead the spacecraft development and act as the implementing organization. APL had a string of successes with the most recently noted being the Near Earth Asteroid Rendezvous (NEAR). The team was feeling confident with the simple complexity of CONTOUR that would make it another Discovery Program success and erase the negativity NASA was receiving from two Mars failures (Mars Polar Lander and Mars Climate Orbiter).

## Mission Description

As part of NASA's successful Discovery Program, CONTOUR was a joint project between Cornell University and APL, along with 14 other university, government, and industry co-investigators to study three major near-Earth comets. With a budget of $159 million, it was scheduled to fly within 60 miles of each of the three comets. From the time of 2003-2008 CONTOUR would take images, make spectral maps and analyze dust flowing from the comets to substantially improve the knowledge base and expand the understanding of comets. CONTOUR was scheduled to fly by Comet Encke, one of the most evolved comets that are still active, in November 2003, Comet Schwassmann-Wachmann-3 in 2006, and Comet d'Arrest in 2008.

CONTOUR was the second Discovery class mission for APL. Receiving many accolades from the success of the Near Earth Asteroid Rendezvous (NEAR) mission, APL believed they could replicate that success in CONTOUR. They believed that there were many similarities in CONTOUR and NEAR with respects to components, construction, and qualification techniques, but they differed in building and operating a spacecraft with much less money. With less money and a comfort for the technological challenge, CONTOUR sought some ambitious scientific objectives. CONTOUR mission objectives were:

1) Image the illuminated part of the fly-by hemisphere of each nucleus at resolutions of up to 4 meters/pixel (25 times better than GIOTTO) to reveal details of surface morphology and of the processes responsible for the evolution of comets;
2) For each nucleus, determine its size, shape, rotation state, albedo/color heterogeneity, and activity through global imaging (100-500 meters/pixel);
3) Obtain detailed compositional measurements of the gas in the near-nucleus environment of each comet in the mass range of 1-150 atomic mass number for neutral and low-energy ion species;
4) Obtain detailed compositional measurements of dust (volatile and refractory) in the near-nucleus environment of each comet for positive and negative ions in the mass range of 1 to 250 atomic mass number, and detect particles in the mass range of $10^{-15}$ to $10^{-9}$ grams;
5) Map the ice/rock surface composition of each nucleus surface through infrared spectroscopy;
6) Map the distribution of key radicals (OH, $C_2$, CN) and dust in the coma through filter imaging;
7) For each comet, assess the levels of outgassing (gas/dust production) through imaging and spectroscopy as well as through in situ measurements of gas and dust in the coma;
8) Assess the diversity of the target comets;
9) If feasible, investigate a "new" comet to assess the difference between Kuiper Belt and Oort Cloud comets.

As a six-year mission, CONTOUR was scheduled to fly by two comets (with an optional third flyby) while taking images, making spectral maps, and analyzing dust and gas. APL would use several innovative techniques for performing a low cost mission, such as indirect launch strategies, unattended hibernation and an innovative mission and spacecraft design. CONTOUR launched on a Boeing Delta 7425-9.5 Medium Expendable Launch Vehicle. The CONTOUR mission was to investigate comet nuclei and assess their similarity and diversity. During a four-year period, CONTOUR would fly within 100 kilometers of two comet nuclei: Encke in 2003 and Schwassmann-Wachmann-3 (SW3) in 2006 with the ability to fly by d'Arrest in 2008.

All of this would add up to what Cornell and APL believed would be a storied success, but CONTOUR never got that opportunity. What happened on August 15, 2002 at 4:49 a.m. EDT when communications were lost was never to be expected. On August 15, CONTOUR was scheduled to initiate a 50-second SRM burn to accelerate the spacecraft and place it on a heliocentric trajectory toward Encke. While operations continued based on the assumption that the firing took place on schedule, at 5:35 a.m. EDT no signal was received from the spacecraft. From August 16 through August 21, three objects were identified from the University of Arizona's Lunar and Planetary Laboratory Spacewatch Project near the expected position of CONTOUR. This led investigators to believe that the firing took place and that these objects were parts of the spacecraft and rocket engine. NASA's conclusions were confirmed by images taken by the Department of Defense. Communications attempts continued with the spacecraft once a week through December 2002, and the mission was declared officially lost after the December communications attempts failed.  Table 1 depicts the projects timeline from inception to completion.

**Table 1: Project Milestones (events in italics did not occur)**

| | |
|---|---|
| **1996** | |
| | NASA's Announcement of Opportunity for Discovery Program |
| **1997** | |
| **August** | CONTOUR Feasibility Study completed |
| **1999** | |
| **February** | Phase A/B started |
| **May** | System Requirements Review |
| **2000** | |
| **January** | Preliminary Design Review |
| **February** | Confirmation Review |
| **February** | Phase A/B completed and start of Phase C/D (Project Start) |
| **December** | Critical Design Review |
| **2001** | |
| **January** | Pre-Environmental Review |
| **2002** | |
| **May** | Pre-Ship Readiness Review |
| **May** | Mission Readiness Review |
| **June** | Flight Readiness Review |
| **July 1** | Schedule Launch at 2:56 EST |
| **July 3** | Launch at 2:47 EDT from Cape Canaveral, FL |
| **August 15** | Loss of signal from spacecraft |
| **August 28** | NASA Appoints CONTOUR Mishap Investigation Board |
| **December 13** | Team plans final attempt to contact spacecraft |
| **December 18** | No signal from spacecraft |
| **December 20** | CONTOUR team ends contact attempts |
| **December 21** | CONTOUR officially declared lost |
| **2003** | |
| ***Nov 12*** | *Comet encounter with Encke* |
| **2006** | |
| ***June*** | *Comet encounter with Schwassmann-Wachmann-3* |
| ***September*** | *End of baseline mission* |
| **2008** | |
| | *Comet encounter with d'Arrest* |

On August 22, 2002 NASA established a Type A Mishap Investigation Board (MIB) to review the circumstances and potential lessons learned from CONTOUR.  The Board was able to formulate a number of causes, but was unable to determine with certainty the proximate cause due to the lack of data during the SRM firing.  The Board categorized these causes into proximate causes, alternate proximate causes, possible causes, possible root cause, and significant observations.

These causes were[1]:

1) Probable Proximate Cause[2]:
    a) Overheating of the CONTOUR Spacecraft by the solid rocket motor exhaust plume
2) Alternate Proximate Causes
    a) Catastrophic failure of the solid rocket motor
    b) Collision with space debris or meteoroids
    c) Loss of dynamic control of the spacecraft
3) Root Causes[3]
    a) CONTOUR Project reliance on analysis by similarity
    b) Inadequate systems engineering process
    c) Inadequate review function
4) Significant Observations[4]
    a) Lack of telemetry during critical event
    b) Significant reliance on subcontractors without adequate oversight, insight, and review
    c) Inadequate communication between APL and Contractor
    d) Contractor analytic models were not specific to CONTOUR
    e) Limited understanding of solid rocket motor plume heating environments in space
    f) Lack of orbital debris conjunction plan
    g) Limited understanding of CONTOUR solid rocket motor operating conditions

**Technology Description**

CONTOUR was designed as a flexible, low-cost mission with four scientific instruments that would be used during each cometary nuclei encounter. At each encounter, CONTOUR would record images, spectral maps and measure dust and gas around the nucleus. The four-instrument payload consisted of the CONTOUR Neutral Gas and Ion Mass Spectrometer (NGIMS), Contour Remote Imager/Spectrograph (CRISP), CONTOUR Forward Imager (CFI), and CONTOUR Dust Analyzer (CIDA). The data that these instruments collected would allow for a significant assessment of the diversity of the nuclei of short-period comets.

The NGIMS was designed to measure the abundance and isotope ratios for many neutral and ion species in the coma of each comet during the flyby. These measurements together with data from the dust experiment would contribute to the understanding of the chemical composition of the nucleus itself and allow differences between the comets to be studied. The NGIMS instrument was developed by NASA/GSFC based on technology from the Cassini mission. The CRISP would actively track the comet's nucleus near CONTOUR's closest approach, taking high-resolution images, color images through 10 filters, and an infrared spectral map. The CFI was designed for high sensitivity and responsiveness to ultraviolet wavelengths. CFI would perform its measurements while CONTOUR was approaching the nucleus and at a range of >2000

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[1] CONTOUR Mishap Investigation Board Report. May 31, 2003. Page X.

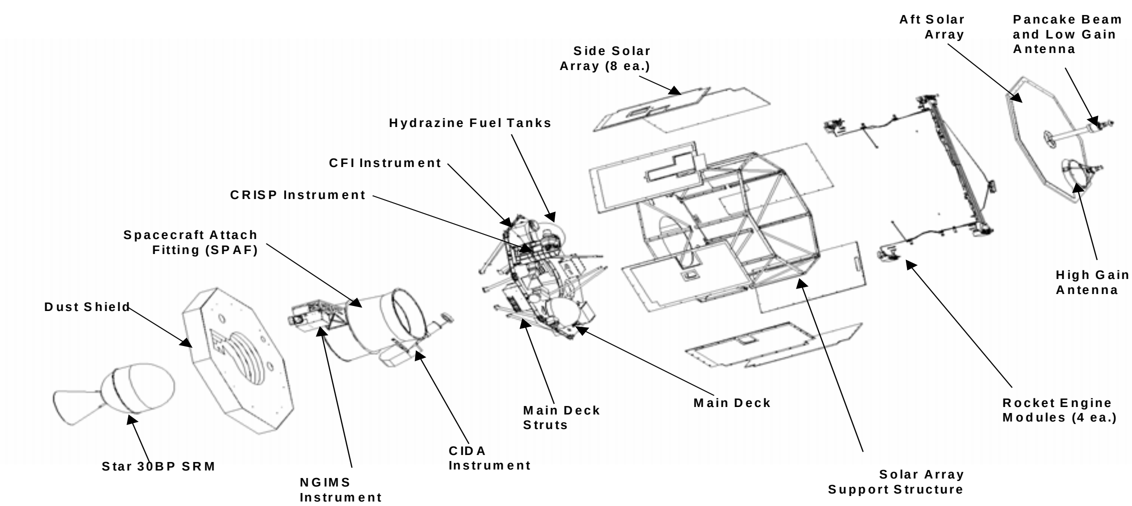
[2] The NPG 8621.1, *NASA Procedures and Guidelines for Mishap Reporting, Investigating, and Recordkeeping* defines proximate cause as: "The event(s) and condition(s) that occurred immediately before the undesired outcome, directly caused its occurrence and, if eliminated, or modified, would have prevented the undesirable outcome."

[3] The NPG 8621.1, *NASA Procedures and Guidelines for Mishap Reporting, Investigating, and Recordkeeping* defines root cause as: "One of multiple organizational factors that contributed to or created the proximate cause and subsequent undesirable outcome and, if eliminated or modified, would have prevented the undesirable outcome."

[4] The NPG 8621.1, *NASA Procedures and Guidelines for Mishap Reporting, Investigating, and Recordkeeping* defines significant observation as: "A factor, event, or circumstance identified during the investigation that did not contribute to the mishap or close call, but if left uncorrected has the potential to cause a mishap, injury, or increase the severity should a mishap occur."

kilometers. Its main functions were to locate the target comet against the star background days to weeks before an encounter, take color images of the nucleus, any gas or dust jets, and other features in the inner coma, and image the inner coma in wavelengths sensitive to major species of ionized gas. CRISP and CFI were developed by APL based on technology from the Near Earth Asteroid Rendezvous (NEAR) program. The CIDA instrument was fabricated by von Hoerner & Sulger and rebuilt based of the instrument developed and flown on the Stardust spacecraft. The CIDA instrument was to measure more than 1000 positive ion and 200 negative ion mass spectra from 1 to 250 atomic mass units, and detect particles from $10^{-15}$ to $10^{-9}$ grams. The CIDA instrument was fabricated by von Hoerner & Sulger and rebuilt based of the instrument developed and flown on the Stardust spacecraft.

The CONTOUR spacecraft was to provide the attitude control, propulsion, dust protection, thermal control, telecommunications, command and data handling and power. Figure 1 shows a drawing of the spacecraft. The design of CONTOUR was kept as simple as possible. The CONTOUR solar array was body mounted, and the mission geometry allowed CONTOUR to use fixed, passive, existing antenna designs. With the exception of the long-tracking mirror for CRISP, moving the spacecraft controlled all instrument and antenna pointing. A dust shield made of Nextel and Kevlar protected against impacts. The spacecraft had two main operating modes: hibernation and encounter. In hibernation mode, the spacecraft spun about its main axis at a rate of about 20 revolutions per minute. During encounter mode, the spacecraft was 3-axis stabilized, and was planned to be fixed with the dust shields and instruments aligned to the comet. Innovative to CONTOUR was the launch strategy, unattended hibernation capability, and an innovative mission design and spacecraft design.




Structure Exploded View
Figure 3.2.2-1

**Figure 1: Spacecraft Exploded View (taken from CONTOUR Project Plan, February 2001)**

## Strategic Project Leadership

### <u>Strategy</u>

#### *Objectives*

CONTOUR was submitted as a proposal in the first Discovery Program Announcement of Opportunity (AO), and was rejected because of its ambitious objectives and large budget. When the proposal team sat down to determine the winning strategy for the next Discovery Program AO, they specifically cut back the objects and minimized the budget. Objectives for CONTOUR were defined early in the proposal phase, written to address scientific inquiry, and then stuck to. In defining objectives for the CONTOUR mission Veverka viewed it as having two aspects to being successfully. The first part is to identify important scientific questions that remain to be addressed. For CONTOUR, this was the chemical diversity of comets, the actual detail isotopic chemical composition, and the actual working processes of comets. The second part is to identify ways of achieving those within the cost guidelines of a Discovery mission. For CONTOUR, with a budget of around $150 million, critics questioned if there was a way of answering or addressing these interesting questions within a tight budget. That meant both finding interesting scientific issues that could be addressed and the means of addressing them in an economical fashion.

#### *Competitive Advantage/Value*

"The overall value is that you are doing the mission that you sold."
- Ed Reynolds, personal interview

It is difficult for a government project to define a competitive advantage. Usually they are supported by a congressional or administrative push. In some cases they are developed from a scientific community pull. In either case there is usually little competition, but CONTOUR was subjected to stringent competition to be selected in the Discovery Program. The competition was in the initial proposal phase. As Ed Reynolds, Mission Systems Engineer, stated, "You sold it not really on one single competitive advantage, but you sold it on "Was it category one science?' In the end that is a hard question to answer." The number one competitive advantage in any Discovery Program project is the science. The selection panel is primarily scientist and they are asking the question, 'Is this mission answering one of the high priority fundamental questions that we have about science or the solar system.' Reynolds describes, "That if you are not what they term category one science, meaning that you are answering a very compelling question about what is out there. You do not get to go to step two." Once a project is selected for the second phase of proposal review, then the competitive advantage moves from the science to the mission design. For CONTOUR they believed this was being able to do three comet encounters with a single spacecraft and being able to launch on a small launch vehicle versus a big launch vehicle. Not only did CONTOUR feel competition from other proposals submitted under the same AO, but the previous AO saw a similar project called Stardust funded and the European Space Agency was developing their own comet flyby mission, Rosetta.

CONTOUR believed that their competitive advantage was that they had a unique mission design. Central to the success of the project and its design was the use of Earth swing-bys to gain delta velocity (and thus reducing mission costs) and propel the spacecraft to its next target. This was a theory that had only recently been tested but more missions were beginning to use the method. Farquhar was beginning to look at Earth swing-bys more as a "steering wheel" to go from place to place. It was a unique concept at the point CONTOUR was selected, but they believe it was one of the key factors that set CONTOUR apart from other missions, and more specifically multiple flyby missions. Farquhar believed that he could string out five or six comets encounters in the trajectories, and it was only a matter of timing and trajectory. There were many past proposals that designed for single flybys, but CONTOUR would put together multiple comets with a single spacecraft. A second competitive advantage was that CONTOUR was using a phasing orbit. This would mean that instead of having the launch vehicle launching at the comet-facing trajectory and having the launch vehicle doing all the work, it would be phased correctly in orbit. The spacecraft would launch, phase correctly and then fire the solid rocket motors at a precise time of perigee. This would avoid the use of a larger, more expensive launch vehicle. CONTOUR estimates they saved between $10 and 20 million using this method. APL believed another advantage was that they had had a history of successful projects with short periods of development, ideal for a Discovery Program mission.

Once the project started the competitive advantage transitioned into value. CONTOUR's crucial value would be to the scientific community. CONTOUR would ultimately deliver to the scientific community new and intriguing data on comets. CONTOUR would bring a new hope and enthusiasm to everyone that believed in space exploration. NASA was just coming off its investigations of the Mars 98 failures, which later resulted in CONTOUR becoming the last of the space science missions defined as 'better, faster, cheaper.' A successful mission would have shown Congress that BFC was still a viable management alternative to doing quality space science with reduced budgets, and build the Congressional support NASA needed for a struggling agency.

***Business Perspective (Success Dimensions)***

CONTOUR believed that their success should be judged based on what they specified in their project plan; therefore, they believed in staying strict to NASA's procedures and guidelines document on project management (NPG 7120.5B). They laid out the schedule, cost profile, risks, and risk management into the project plan; consistent with NPG 7120.5B. The schedule had enough detail in it that through the range of reviews, and status meetings, management could reconcile what they were doing as stated in that plan with what was happening in reality. Discrepancies could then be reported during a review, to the Space Department Management, and to the Discovery Program management office.

While focusing on the project plan, CONTOUR management also brought what they believed was a clear understanding of what would make CONTOUR successful. Veverka was known for his pictorial focus on the objectives and what it would mean to be successful with CONTOUR. Ed Reynolds tells the story of how Veverka would accomplish this:

> Joe would always put up a cover of a book about the Haley flyby, and he would say, 'This is the best picture that they got from Haley. There are lots of unknowns in this picture. This picture seems to ask more questions than it answers. The goal of CONTOUR is to get images that are at least 25 times better than this.' That kind of really made it clear as to why were doing it.

As with all Discovery Program missions, the primary success factor is the achievement of project objectives, and project objectives are built on science requirements. Because imaging of the comets was so important to CONTOUR, the most significant success criteria was to get images of the nucleus of at least one comet nucleus better than 50 meters per pixel. Second was to have a data set from either the gas analyzer or the dust analyzer. To guarantee success, CONTOUR built into the scientific instruments internal crossover functions, so they would have resiliency in the success criteria. They understood their capabilities and took advantage of that to give them enough elbowroom to achieve the mission success criteria.

### *Strategic Focus*

"There is first of all the plan and then what actually happened."

- Dr. Joseph Veverka, personal interview

CONTOUR believed in setting the strategic focus early, articulate it to the team and then consider it a 'done deal.' Reynolds believed that you have to have an awareness of what your customer wants or needs, and then enunciating those desires in the early phase of the project (proposal development phase). CONTOUR believed in the customer and what they wanted in a mission; therefore, the project was designed and focused to meet their needs based on their capabilities. For NASA this meant safety, cost, and implementation. For the science community, this meant quality data. Once the strategic focus was set, management laid it out as this is the mission design, this is the launch vehicle, and this is the approach that we think is going to win.

Mary Chiu, Project Manager, believed that to keep the team focused on the strategy she had to communicate it both orally and written, and reiterated it several times throughout the project. She felt as Project Manager it was her responsibility to make sure people stayed focus. Chiu stated:

> We wrote up several things about what we were going to do as far as the low cost nature, use technology that was existing, use good system engineering, incorporate things that were off-the-shelf if we could, and that was made very, very clear to the leads and all of the developers as we were proposing and developing.

More specifically, CONTOUR management identified specific events and actions that they believed allowed CONTOUR to maintain a strategic focus toward success:

- **Good Systems Engineering:** CONTOUR believed they had very good, experience leads in the various disciplines that were able to think out-side the box while grounded in the projects reality.
- **Frequent, Active Communication:** Frequent meetings with all of the key leads, and keeping everything balanced and making sure that people were held to that line.
- **Develop Requirements Up Front:** CONTOUR stressed to all of their leads that requirements should be developed early, froze early and followed.
- **Everyone was a Contributor:** CONTOUR believed everyone on the team was an engaged participant in the project success.

## Project Spirit and Leadership

### *Organizational Culture*

The one word used the most to described the culture of CONTOUR was “family.” As a family they experienced their shared differences and successes. As in the case of CONTOUR where there was a significant failure, it was described as loosing a member of the family. People were very close to each other and the project with a great sense of camaraderie. Veverka believed that at another level this meant that you could ask people to do tremendous things without feeling guilt because people were excited about the challenge. There was a very close kinship on CONTOUR.

Veverka stated, “I think the answer to having success with any kind of Discovery mission is that you need to have a partnership where the cultures are similar or the cultures are compatible.” He believed that this was the case with APL and Cornell with cultures that were very similar and compatible in that both places were involved in doing very complicated things with a small number of very talented, very dedicated people. He believed these smaller, directed organizations eliminated the negativities of large organization where “half the people only collect paychecks.” The people of CONTOUR were dedicated to a successful mission. With a small manageable organization, Veverka believed that “you can do very complicated things.” Part of this was having very few “really exceptional, absolutely unique” individuals that he believed were irreplaceable, and use of their talents to try and do something “really special.”

At APL, management saw a similar culture develop for CONTOUR as they did with NEAR. With a short schedule based on a planetary launch window, the culture was “exactly the same,” as Reynolds said. Reynolds stated that he has worked on missions that have taken five and six years to develop, and he believes the culture and spirit were a lot worse. He believes that for the missions with long development times, people are accused of having too much time, sitting around, ‘shooting the breeze.’ The culture that develops around a mission under a tight budget and schedule is more appealing to most people and keeps every team member engaged and excited.

### *Project Spirit*

“I got a lot of positive feedback that there was a lot of pride and enjoyment working on CONTOUR.”

- Mary Chiu, personal interview

Management believed that motivation and good spirit did not need to be fostered. They believed the people involved thought CONTOUR was a tremendous and challenging effort and this motivated the people. A lot of the elements that CONTOUR was trying to accomplish involved new, complicated tasks that people were genuinely interested in doing. Management stated that they were not aware of any time that they needed to motivate people or worry about project moral.

Although, many of the tensions and linkages associated with a ‘better, faster, cheaper’ project were present in CONTOUR, mainly budget and schedule. CONTOUR had enormous cost constraints, most notably after the Phase A/B study. This became a reality check for CONTOUR that it was going to cost quite a bit more than what was originally proposed. Budgetary issues in any NASA project can quickly lead to termination, so there was lot of pressure on everyone to get their costs down which did not have a positive impact on the team. Chiu described it as:

> One of the things that I insisted on, Ed was certainly part of this, was making sure that things were communicated. We were upfront with everyone as to what the facts were, what was going on with the NASA people, what was going on with our own management. Trying to keep people informed as to what was going on, rather than saying 'No, re-cost, re-cost… cut this, cut that.' There was lot of back and forth. A lot of sole searching as far as what was really needed in certain areas. What we could do with less money. What we couldn't do. Where was the line you were compromising the ability to get the job done if you went less than such, and such cost. I think during that time, people were not too happy. I know I wasn't. I think at that stage there were probably some low points.

Along with a tight budge, it was a tight schedule, and everyone knew it was a tight schedule. There was no relief of the schedule, and the launch window had to be met or the project would be canceled. The team worked very hard to prevent the project from turning over in its schedule to the point that it had to make up time. The immediate team at APL was a small team that worked single shifts with normal working hours. The pressures of meeting a strict schedule were kept to normal working hours, except prior to launch when some engineers worked four weeks day and night to get things done, but without question. Other than that, only once did the team have to work a Saturday to maintain the schedule. Management insisted on not asking team members to double up on hours, work weekends, or overtime. They held strong to that philosophy, even at the launch site, when time was the most critical.

Chiu believed in the team spirit and would even find fund sources outside of the project to try and foster the team spirit. She would go after money that was not tied to the project to get things like pens and decals. She would also find non-project fund sources for in-house and out-of-house picnics, and team building exercises. Another activity of Chiu was weekly write-up that would be posted on the external web site. It was about half a page of text with a photograph. She termed it 'Picture of the Week.' She made sure that this activity had a lot of involvement with the team members to express the type of work they were doing, why it was important to the program, and a picture of them doing it. She believed it was a way to make sure that people's work was recognized and highlighted. One manager gave an example of a classic 'Picture of the Week.' He describes:

> One time in one of our status meetings we were putting people together for the white room, so you need to know how to dress for the white room. The guy who was doing contamination control was showing us the outfits, but he really was not putting them on. People were saying, 'Oh, it is going to take us 10 minutes to put all of that on,' and he would say, 'No, you can get it on in 30 seconds.' So we said, 'Okay, go.' It caught him by surprise and he was scrambling to put all of this garb on, and I think he got it down to 50 seconds. Right there at the end we had a digital camera there, and we snapped it. That ended up on one of the pictures of the week. So there was a recognition point of view to it, and there was a kind of silliness point of view.

### *Policy to Support Strategy and Spirit*

"We basically tried to reach a balance between enough structure to do things well, also enough flexibility to allow individuals the opportunity to do the things they needed to do."

- Dr. Joseph Veverka, personal interview

As an organization, APL has a lot of guidelines that are used, but they are viewed in many cases as options. For CONTOUR, management tried to reach a balance with the level of procedures that were needed to make sure that things were done properly and without undue risk. This meant sometimes relaxing procedures to allow people the maximum flexibility to do things the way they really thought they needed to be done. CONTOUR management did not believe in micro-management of individuals. People had clearly assigned tasks, and there was great confidence in people that they could carry out those tasks. CONTOUR believed by lifting some of the procedural requirements, it gave people an empowered feeling and lifted the spirit.

***Leadership***

CONTOUR management worked to be fair and honest across the team while maintaining a professional but friendly relationship with team members. The management team was not hands-on managers, but rather worked for an informed, non-intrusive style. CONTOUR management believed that engineers should be allowed to perform their job without the restriction of managerial interference and believed their efforts should be focused toward maintaining the project strategy, structure, and lines of communication. As Project Manager, Mary Chiu was considered by most as the central leader for the project, with a "firm" management style. One manager described here as:

> We have projects here that people say, 'You know, instead of a linear polarized array, we can give you a circular polarized array that is only 10 million more dollars.' We have people that just say, 'Okay, do it.' Mary was firm in that people would come and say, 'Here is something that we can do that is different from the baseline,' and she would basically say, 'No!'

CONTOUR was basically the same spacecraft by design and budget at the time of launch as was proposed in 1997. From 1997 to the time of launch (July 2002) many factors weighed heavy on CONTOUR (e.g. the Mars 98 failures and 9/11), but many attribute Chiu's polite firmness and focused management approach to bringing this project in on time and on budget. This brought her respect from her team and set the tone for how CONTOUR would operate. Down through the organization, CONTOUR management relied heavily on their lead engineers to provide leadership. They were held accountable for keeping the communication lines open, and delegating decision making down through the organization.

***Team Empowerment***

"My concern as a PI wasn't to make sure that somebody was putting in the right number of screws."

- Dr. Joseph Veverka, personal interview

Management held a great deal of trust in team members to perform their job and believed trust to be an important element to how CONTOUR functioned. Management assumed that certain tasks were happening and believed in dealing with things at a higher level. CONTOUR tried to let the decisions be made at the engineering level. If decision that rippled back up to management conflicted, management was very quick to try and recognize this and call a meeting with the affected people to work out a compromise. The group decision was then rippled back down through the organization. Chiu stated, "I think that having people empowered to make those decisions and run with them until they ran up against someone else was a big factor in people's satisfaction and pride in the work." The way that CONTOUR was managed was not unique to CONTOUR but standard operating procedure at APL. For each project there is a Project Manager. Underneath the Project Manager are the Lead System Engineers, and then for all the different subsystems there is a Lead Subsystems Engineer. At the beginning of the project meetings are held to determine the budgets and schedules. Then there is an "unwritten contract" with the Project Manager and the Lead System and Subsystem Engineers for a commitment to this budget and schedule. The Lead Subsystem Engineer is then given the authority to work on the designs, the implementation, and how things get done within their subsystem as long as they are meeting the criteria establish at these initial meetings. CONTOUR believed they empowered at the lead level. For example, the lead mechanical engineer is empowered to procure, assemble, and test as long as they abide by their milestones and deliverables, and stay within the agreed upon budgets. CONTOUR believed this form of empowerment greatly contributed the team spirit.

## Organization

### *Project Organization*

The CONTOUR Principal Investigator was Dr. Joseph Veverka, Cornell University, who was responsible for the project and accountable to the Associate Administrator (AA) for Space Science for scientific success and the Discovery Program Manager (DPM) for programmatic success. Johns Hopkins University/Applied Physics Laboratory (APL) was responsible for implementing the project, and Mary C. Chiu was the project manager. The APL Space Department Management Advisory Committee (SDMAC) in addition to management personnel from Cornell University was the governing Program Management Council (PMC) for CONTOUR. The APL Space Department Head, Dr. Stamatios M. Krimigis, chaired this council. The DPM was an ad hoc member of these review boards. The APL Director was responsible for certifying the CONTOUR mission readiness to the AA for Space Science, through the Discovery Program Office. The PI directly managed the activities of the science team members, the Science Data Center (SDC) at Cornell and the Education and Public Outreach (E/PO) activities. The PI delegated the remaining project elements to the project manager at APL. The project manager was responsible for maintaining the project schedule, budget and mission capabilities across all team organizations in accordance with the project plan. The project manager also coordinated, via the Discovery Program Office (DPO) and with PI approval, the NASA facility support for CONTOUR.

The CONTOUR team included partners from three academic institutions, three NASA centers, one federal research laboratory and one company. The maximum number of people working on the mission was around 200. At APL, which was the bulk of the effort, ranged between 60 and 100 at the maximum and maintained a steady state between 20 and 40. The science team consisted of about 20 individuals at institutions around the country and one institution in Europe. Each of those institutions would on the average have four people working with them. This constituted about 100 people involved in the science; 20 of them directly as co-investigators, 60-70 as associates, and the rest as graduate students and technical associates. Table 2 indicates these partners and their role in CONTOUR.

**Table 2: CONTOUR Partners and the Responsibilities**

| Institution/Agency/Company | Responsibility |
|---|---|
| Cornell University | PI, Science Team and Science Data Center. |
| APL | Spacecraft, CONTOUR Remote Imager and Spectrograph (CRISP), CONTOUR Forward Imager (CFI), project management, and mission operations. |
| NASA Goddard Space Flight Center (GSFC) | Neutral Gas and Ion Mass Spectrometer instrument, and Science Co-Investigator (Co-I), Environmental Test Facilities |
| von Hoerner & Sulger | CONTOUR Interstellar Dust Analyzer (CIDA) instrument (under subcontract to APL). |
| Jet Propulsion Laboratory (JPL) | Navigation, Science Co-I, Deep Space Network (DSN) |
| NASA Kennedy Space Center (KSC) | Launch services |
| NASA Johnson Space Center (JSC) | White Sands Hypervelocity Test Facility (Dust Shield) |

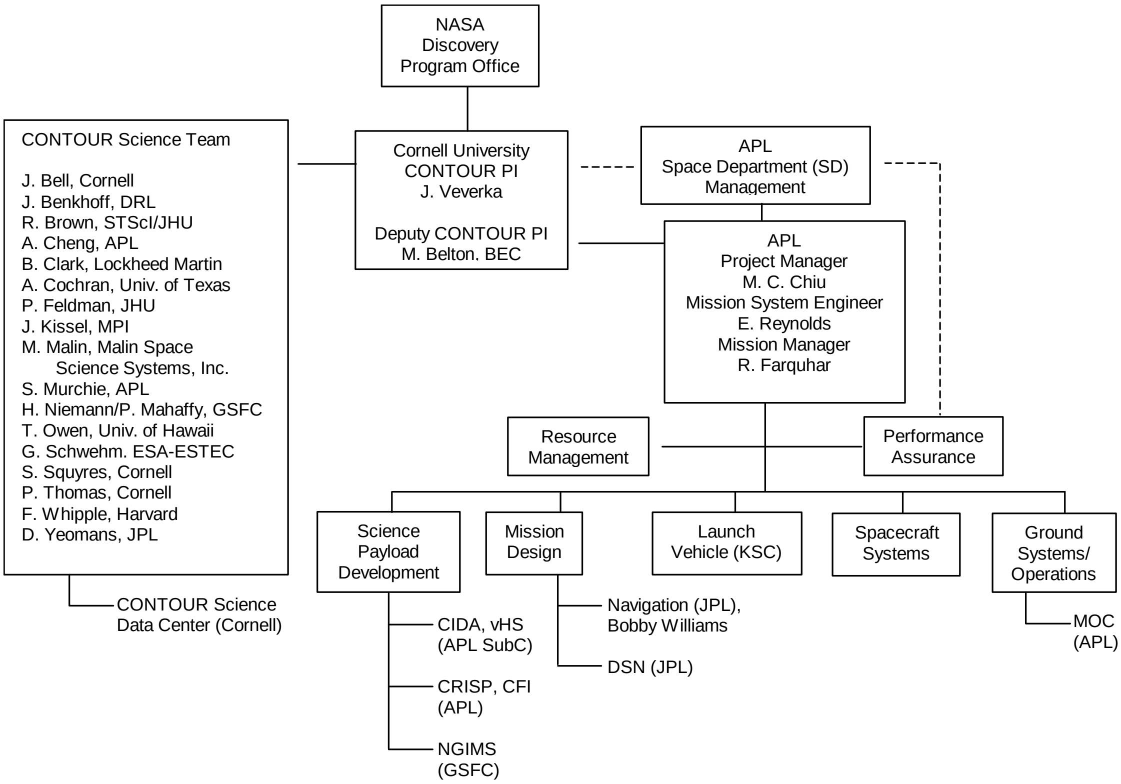



**Figure 2: Project Organization**

### *Structure*

The majority of the project team and effort was located at APL. At APL the project was kept small and co-located with most of the team located in two buildings. While the team at APL was predominantly co-located, many of the people came from matrix organizations and thus kept ties to their functional organization for the duration of the project. Because of co-location at APL, most communication was performed face-to-face, and the telephone was rarely picked up. Reynolds described it as:

> The answer you needed was right down the hall. You would go down and get it. A lot of times there are things that get resolved in hallways all the time. If you are all together, you are aware of other people's issues almost as fast as they are. So there was a lot of synergy by just pulling people together in one tight location.

While co-location was true for APL, it was not true for the entire project team. The Cornell team, which led one of the most significant developments of the project, the science experiments, was not co-located with the APL team. In addition, the contractor for the Solid Rocket Motor was not co-located with the spacecraft development at APL and the linkage between these two groups was later identified by the MIB as a factor in the mission failure. Ironically, co-location has not occurred at APL since CONTOUR.

### *Team Assembly*

"How people are selected is an art form rather than anything I can put into words."
- Mary Chiu, personal interview

In the early part of the proposal phase of the project, it started out with Farquar, Veverka, and Reynolds. When they decided to re-submit CONTOUR in response to the second AO, Mary Chiu was approached by the APL Space Science Department to be the proposal manager. With the core proposal team selected, leads for the subsystems were identified to work on their respective sections of the proposal. Despite their selection to the team, most of these leads during project development were not the same as during the project development.

Once CONTOUR was selected, Cornell and Veverka, as the responsible organization to NASA, were accountable for assembling a team for the project. This included building and launching the spacecraft and performing the mission operations once the spacecraft was launched. He had already chosen to work with APL because of his previous connection with them on the NEAR mission. Veverka believed you have to start at the top and find the best people to be project managers and mission directors, and then work your way to the best scientist. He stated:

> What you are really talking about is building four people. So once you have done that the process basically replicates itself. Then you let those people select whom they want to work with. I think by and large we really got the best people available at the time.

Once the process of team assemble was at APL, it relied primarily on the group supervisors to select team members. APL functions primarily as a matrix organization, and thus what typically happens is a request is made to a group supervisor for a lead engineer, and it is the responsibility of the matrix organization to provide the best person. Each matrix organization has degrees of flexibility on how they allow personnel to be selected from their group. Some are more ridge than others. Chiu said, "There is availability, then trying to piece together somewhat matching personalities. What you have available is kind of your field and sometimes at APL there was only two people in the availability groupings." Chiu also selected people from previous projects she had worked on, because she knew their personalities and talents well. In some instance she held out for these people until they were available. Chiu says it is a combination of who is available, past history, how they fit in with the rest of the team, and if the people had worked together before.

### *Responsibilities*

CONTOUR stayed strict to their Work Breakdown Structure (WBS) that was product oriented. The spacecraft functions and the design were set during the proposal phase; therefore, CONTOUR did not deviate from its original plan and thus the WBS.

### *Top Management Involvement*

As a project CONTOUR was responsible to the Space Department Advisory Committee, NASA, and administrators at Cornell and APl. The Space Department Committee was eight people consisting of the department head, the chief engineer, a representative from science, engineering, and software and marketing. This committee operates in the same role as the center counsel specified in NASA's NPG 7120.5B document. This group was given active updates on the status of the project every two months. The Project Manager performed this with a standard 30-minute oral presentation format. Standard topics would include cost reserves, schedule reserves, mass margins, power margin, action item close-out, and waiver status. In general, top management at APL stayed at arms length. Chiu recalls that most of the time they made a conscious effort not to be involved. Chiu said, “At APL it is sometimes best to be under the radar, and not to be noticeable to top management.” It was not until CONTOUR encountered serious money problems at the end of the Phase A/B that they became significantly involved.

Oversight from NASA headquarters and linkages to the project came in the form of people being specified as project scientist or engineers on the project. This opened them up to participating in regular meetings. But, one manager stated that this also caused some confusion. There did not seem to be direct lines of communication to the headquarters leads. Sometimes the project scientist, at NASA headquarters, would be in contradiction with the Discovery Program office manager. Reynolds said, “It is kind of hard being the guy underneath looking at this contradiction, and wondering who you are working for.”

In the planning stages of the project there were discussions and memorandums of understanding between administrators at APL and administrators at Cornell to outline their relationship and the project. But Veverka stated, “Nothing really happened with those things.” What happened is that Veverka and Chiu relied on active communication for the important decisions. At the administrative level there was very little involvement, accept when budgets were being discussed. Generally, Veverka and Chiu made 90% of the decisions. At the project management level Chiu was involved every day, and she had no other work responsibilities.

***Professional Advice and Reviews***

“We had more reviews than I think I had had on any other project.”
- Mary Chiu, personal interview

At the beginning of the project several boards were established, both external and internal. External reviews followed many of the standard NASA reviews. The APL Space Department (SD) Chief Engineer was responsible for assembling and chairing (or designate a chair) a committee of ten for this independent review board. They were responsible for the Preliminary Design Review (PDR), Critical Design Review (CDR), Pre-Environmental Review (PER), Pre-Ship Review (PSR), and Mission Readiness Review (MRR). Concerted effort was made to try and get members with diverse disciplines. The committee would be about 60% APL personnel not on the project, and 40% people from other organizations (not APL and not on the project). CONTOUR viewed reviewers as “little independent contractors.” Typical members came from other federal agencies, aerospace corporations, and NASA/aerospace retirees. CONTOUR would then subcontract them to be on review boards for their peer reviews. Once they got someone they felt was a good reviewer, did all they could to keep that person on subcontract. Chiu said, “When you got someone who was a good reviewer, and of course we took down names and numbers to know who to call back and who not to call back, they were worth their weight in gold.” Peer reviews were conducted at lower levels and assembled by the lead engineers and their technical organizations. Review board members were independent of the CONTOUR Project element under review.

***Organizational Problems***

“The reason why we got through them (our problems) was because we did have such a strong team; a lot of commitment within the team to each other.”
- Mary Chiu, personal interview

CONTOUR believed you address problems quickly and with the affected people. When a problem was identified, the people affected would get together and trying to come to some kind of resolution. Because CONTOUR was a small enough organization, Chiu and Reynolds would spend time each day outside of regular meetings walking around and making sure they understood what was going on; be able to address problems real-time. This strengthened their regular meetings by making sure that communication stayed fluid, so when there was something that did not sound right it could be addressed. Chiu said that as the project went on they had more and more people just showing up at management's doors saying 'Hey, something is not working out.' Problem resolution meetings were usually kept to four to five people involved and on rare occasion may have involved up to ten. Resolution meetings occurred in real-time and at most were delayed by only a day. CONTOUR tried to make things very responsive by getting the people involved and making decision quickly. If a decision from these meetings involved more people, an email was sent to a broader group of people to make sure that they were aware of what was going on and what was being decided and discussed.

The biggest organizational problem with CONTOUR was centered on an uncertainty in the technology. CONTOUR was flying for the very first time a non-coherent DOPPLER navigation system. Normally deep space mission fly coherent transponders, but CONTOUR figured out a way to use regular receivers and transmitters and apply counters to the receivers and transmitters embedding counts into the data stream. From the ground, the data would look just like a coherent transponder on the ground. The difficulty was that information had to be extracted out of the telemetry and applied to an algorithm before it could appear as a coherent transponder. The Deep Space Network team strongly disliked this method. The navigation team also did not like this method because it added a step to the process and they felt that it was very risky. This issue caused a lot of discomfort between the teams and an increase in testing. CONTOUR believed they overcame any uncertainty with a lot of testing. Even with all the testing there was still a lot of uneasiness between the teams.

***Training***

Since CONTOUR was primarily a matrix organization, it relied on the functional organizations to ensure the continuing education of their team members. As a project, CONTOUR viewed the attendance at conferences as their form of training.

## Processes

### *Project Phases and Reviews*

The APL Space Department Management Advisory Committee conducted programmatic reviews at APL of the implementation every six weeks. Despite the extensive reviews, the MIB concluded the "candid, critical, and constructive peer and independent reviews, as well as similar systems engineering work, were impeded by this approach (APL's processes and procedures), and that this situation enhanced the risk of potential design errors going undetected."[5] In addition to the APL designated review committee, the Discovery Program brought in an Independent Advisory Team (IAT). The IAT was comprised of non-NASA people with diverse backgrounds. At reviews, review team members would record actions or request for actions. These would then be consolidated into a written and oral report listing the action items, findings and recommendations. Internally, all of the subsystems and the instruments had their own PDR, CDR, fabrication feasibility review, mission operation review, and concept of operation review. In addition, all of the software had its own review process. The MIB stated that these relevant reviews did measure up to the rigors and completeness of similar NASA reviews. Table 2 shows the schedule project reviews.

| Review | Purpose | Content | Date |
|---|---|---|---|
| System Requirements Review (SRR) | Documents the requirements for the system needed to accomplish the science goals of the mission. | All project systems | May 1999 |
| Preliminary Design Review (PDR) | Confirms that the project systems, subsystems, and component preliminary designs meet project objectives and can proceed to detailed design with acceptable risk. | All project systems | Jan 2000 |
| Confirmation Review (CR) | Confirms that the project is accomplishing the work proposed in a timely and cost effective manner without compromising the original science requirements of the mission. | All project systems | Feb 2000 |
| Critical Design Review (CDR) | Confirms that project systems, subsystems, and component designs are of sufficient detail to continue with hardware/software fabrication, integration and test with acceptable risk. | All project systems | Dec 2000 |
| Pre-Environmental Review | Confirms that all project systems, subsystems and components have been integrated, tested and verified functionally to proceed with the spacecraft level environmental testing with acceptable risk. | All project systems | Jan 2001 |
| Pre-Ship Readiness Review (PSR) | Demonstrates that system elements constructed for use and support are ready for the start of launch operations. | All project systems | May 2002 |
| Mission Readiness Review (MRR) | Verifies that all system elements meet requirements of the mission and are ready to proceed into final launch preparation. | All project elements | May 2002 |
| Flight Readiness Review (FRR) | Determines that checkout has shown launch vehicle and spacecraft are ready for countdown and launch. | All project elements | June 2002 |

[5] Bradley, T. et.al. (2003, May 31). *Comet Nucleus Tour Mishap Investigation Board Report*. National Aeronautics and Space Administration, pg. 14

### *Communications*

Each month CONTOUR would perform standard project reviews, which involved all of the leads, the principle investigator, and usually a NASA person attended from Headquarters. In these meetings, which lasted about three-quarters of a day, the leads presented their month's progress, goals for next month and any problems. Chiu used these meeting to help her prepare for her monthly progress report to top management. CONTOUR also used these meetings as a time to get all of the leads in the same room and make sure they knew what was happening in other areas. Meetings were not just restricted to management and leads. These meetings were purposely held in a large room so anyone from the project could attend.

In addition, CONTOUR held mid-month meetings that were more of a technical meeting. The PI and a NASA representative did not attend these meetings. Chiu would also have a meeting once a month with the group supervisors and the lead engineers to discuss budgetary issues. Once the project moved into fabrication, CONTOUR had meetings with the fabrication group on a regular basis, but not on regular intervals. In communication with top management, Chiu would hold monthly project status meetings with reports from all implementation elements and weekly, monthly and quarterly status reports to the Discovery Program Management Office for implementation activities.

While CONTOUR believed in face-to-face communication and co-location, this was the case at APL, and not the case between APL and the other organizations. This was relevant in the communication linkages between APL and the Cornell led science team that did not sit at APL, and thus did not participate in regular weekly meetings or have the ability to have real-time face-to-face communication with the implementing organization, APL. To formulate the linkage between APL and Cornell, Veverka would hold weekly and as needed telecons with Chiu, travel to APL once a month, and every two months, other key individuals would make the trip to APL. The lack of communication was most prevalent in APL and the SRM contractor. The Contractor stated that they had historically dealt with customers that had more experience with SRM application and thus usually did not play an active role in spacecraft design. While the MIB stated that the linkages and oversight of APL with the SRM subcontractor was not adequate.

### *Resource Management*

"CONTOUR was a really great project, and if it hadn't been for the budgetary restrictions, it would have been a dream project."

- Mary Chiu, personal interview

CONTOUR decentralized the management of resources by distributing money and responsibility for that money to each organization. While Veverka, as PI, was in charge of approving the overall budgets, he let Chiu manage APL's part and concerned himself only with the science team at Cornell. Once the money was distributed, CONTOUR believed in staying strict to the WBS. At the beginning of the project templates would be distributed within the groups to lay out schedules, milestones, and resources (e.g. people, material, equipment, and subcontractor estimates). These templates would then evolve into contracts. It was the responsibility of every team member to live by these contracts. If they were having ten people working on the contract in March and eleven in April, they knew that the program manager saw that through the chart sheets. As long as a manager or lead was within their profile, management left them alone. Chiu then relied on the weekly status meetings with the lead engineers and the group supervisors to comment of any abuse of resources.

The schedule and budget responsibility was ultimately the responsibility of the lead engineer. Chiu said that it depended on the lead engineer how active they were in those two areas.

Schedule tracking and budgetary tracking, especially in the “bureaucratic manor that a lot of the NASA people like is a lot of effort and can suck up a lot of time if done in certain ways,” Chiu said. Chiu balanced this by giving responsibility to those that wanted it and managing the responsibility of those that did not. Chiu believed the leads most significant responsibility was for their technical expertise, not their budgetary and scheduling skills.

As for the scheduling, Chiu believed that the lead engineer had to be cognizant of the schedule and needed to know all the different elements that go into the schedule. She stated that this was most important when coordinating with the fabrication facility. She held the lead engineers accountable for knowing their schedule, but not for tracking their schedule on Microsoft Project©. Despite her persistence and some of the leads starting off with great enthusiasm for tracking their schedule, many tapered off after a while because they felt it was time consuming. Chiu compensated for this with her own efforts by picking up where they were delinquent.

In retrospect, Chiu says if she had to do it again, she would have had a much bigger staff at the project management office to do budget and scheduling. She said there were other projects that had Schedulers, but because of the low cost nature and the budget restrictions of CONTOUR, they had to rely more on their lead engineers.

### *Reducing Uncertainty*

“We were doing a big rocket mission on a little rocket. In the end, that turned out to burn us, because we had the mishap right at the very end of the solid rocket motor burn.”

> - Ed Reynolds, personal interview

In many NASA projects, great emphasis is placed on budgetary reserves to address any unforeseen issues. Chiu said that reserves were something that NASA wanted CONTOUR to do in the AO but when the budget ran thin, reserves were the first thing to go. What reserves remained, were at the project level. Therefore, at the engineering level, reserves were replaced with an emphasis on off-the-shelf technology, testing, and internal system redundancy. CONTOUR believed they could dramatically reduce technical uncertainty by flying almost all of their spacecraft from commercial-off-the-shelf technology and a rigorous testing program. They did not believe CONTOUR was a new technology development program in any sense. Mary Chiu stated:

> We were trying to do it with state of the art technology, but not out-there technology. It was with known techniques. There was not a lot of ‘We have to do research and develop new technologies type of thing.’ It was ‘What can we pull from off-the-shelf to meet the objectives.’

They would breadboard certain parts and put those parts through a testing program to resolve the uncertainty as early as possible. They tried to understand what uncertainties they could tolerate without a bad outcome. They were applying sensitivity analysis to determine which things they should focus the highest priority, and put a lot of resources there. This was a standard approach for APL and routinely used as a method of reducing engineering documentation compensated by a “robust test program.”

Additionally, to overcome any technological uncertainty, they used built-in redundancy. An example of this was in the design of the power switching; the designer always slipped in a few more relays through the design review requirements for any unanticipated problems. As Chiu stated, “Then when someone would say, ‘Oh my God, I need a relay,’ he would come in as the savior.” An engineer on CONTOUR also believed it was their responsibility to try and break their own systems. Chiu said:

> In many cases I became very frustrated and irritated by these three plus sigma things that people envisioned and why they were taking all the time to test all of this, but I think that is what made the designs so good. Unfortunately, we did not get to prove our designs. I think in the past we have had a fairly high success rate in the things that were developed at APL.

While these processes had shown success on previous Discovery missions and past APL missions, the inability to test the assembly of the SRM with the spacecraft did not allow for the implementation of rigorous testing and the SRM ultimately became the primary failure point. Farquhar, Mission Manager and Designer, came up with the scenario of using the gravitational pull of the Earth to achieve a very low energy way of reaching three comets, but to accomplish this the SRM had to be added to the main spacecraft, complicating the simplicity of the spacecraft.

***Systems Engineering***

CONTOUR believed that because they were using predominantly off-the-shelf or re-use technology (e.g. the gyros, the star trackers, the avionics were all based on designs that had flown previously), that systems integration and engineer were very straight forward. CONTOUR used what they termed as 'traditional margins.' APL, at the beginning of a project, requires a project to start with at least 15% margins. CONTOUR met this requirement even with actual mass measurements on 90% of the hardware. CONTOUR bragged that they kept to their numbers and had very high confidence in these numbers. Because a lot of technology was re-use, CONTOUR relied heavily on standard interfaces for systems integration. They believed they were not doing anything unique. As an example, CONTOUR relied on plume heating analysis by non-APL personnel for a commercial spacecraft, later revealing that there were distinct difference between CONTOUR and the commercial spacecraft CONTOUR was using for its design analysis. While designers attempted to overcome these differences by applying a 2x factor of safety, proper analysis was not performed on the design changes to reveal the discrepancies.

The confidence in the inherited technology also resulted in CONTOUR waiting until late in the projects development phase to have a focused effort on systems integration. The MIB referred to this as "inheritance reviews," and specified that these did not occur early enough in the project life cycle. The efforts on integration did not become concentrated until each of the subsystems was almost finished.

***Risk Management***

When the Discovery Program was first envisioned as a program, the term 'acceptable risk' was used to describe projects with significant return for a minimal cost. The Discovery Program placed a tolerance on 'acceptable risk' as a project of $125 million (1992 dollars), and could tolerate a failure from time to time. As time passed, and Dan Goldin was appointed NASA Administer, 'acceptable risk' and the Discovery Program became defined by 'better, faster, cheaper.' After the Mars '98 failures, the term 'acceptable risk' disappeared from presentations and documents. There was a tightening of what the Discovery Program was and how much risk could be tolerated. Also during this time the NASA Investigative Action Team (NIAT) was formed to review the Mars '98 failures and NASA project management. Before the NIAT had completed their investigation, CONTOUR was selected. Therefore, CONTOUR was late in incorporating recommendations from the NIAT report to lower the overall risk of CONTOUR. While the original vision for the Discovery Program was to perfect 'faster, better, cheaper', to have focused, dedicated project teams, and no formal reviews, after the NIAT things got tighter and tighter. It became a situation that Discovery Program projects did everything the large projects did without exception, including full documentation, concepts, and parts. From what it was conceived and born as, it very quickly became a standard NASA program, from approach to oversight. CONTOUR fell right in the middle of this identity crisis.

CONTOUR did do a standard preliminary risk analysis (PRA), and did perform other standard risk analysis before the project started (e.g. fault tree and event tree). What CONTOUR did not do was combine all of the analysis into a formalized PRA. They believed that the risk analysis that was preformed gave them insight into where to focus and where risk was acceptable. One area that CONTOUR always felt was a high-risk, single point failure from multiple angles was the solid rocket motor. What if the motor did not light? What if it lit and it went, and they were five minutes off, fifteen minutes off? What if the motor blew up? All of these were single point failures. CONTOUR just did not role it up together into a PRA, but believed they had enough insight into all of their analyses to figure out where the sensitive points were.

***Customer Involvement***

CONTOUR had three customers: congress, the public/science community, and their sponsor (NASA Discovery Program). Congress is a harder customer to please, but plays an important role in determining future funding. CONTOUR believed that the best way to satisfy their congressional customer was to do quality science and have a successful project. All Discovery Program missions are based on a scientific inquiry, which is usually defined by the scientific community. For CONTOUR mission objectives addressed the area of greatest importance identified by the Committee on Planetary and Lunar Exploration (COMPLEX) in its recommendations on the exploration of primitive bodies (e.g. comets). As a mission selected via the NASA Discovery Program AO process, the science community played a key role in the approval of CONTOUR and its science goals. The involvement of the science community was further enhanced by CONTOUR presentations in conferences and scientific meetings, as well as early release of all data to the Planetary Data System (PDS). For the general public, CONTOUR had an Education and Public Outreach effort planned to include the general public and educational institutions in the mission. This was to be done primarily via a public website and materials generated by the CONTOUR team. The Discovery Program Office was an integral part of the project, and CONTOUR actively kept them involved and informed through regular briefings and their involvement in reviews.

***Contractor Involvement***

CONTOUR strived to make contractors an integral part of the team. CONTOUR management described the relationship with their contractors as active, with regular meetings via teleconference. As the instruments were being built, lead engineers would visit contract vendors for face-to-face meetings. Most of the APL involvement with the contractors was left to the lead engineers. Chiu did not participate in most of these communications. The MIB later reported that the linkages with contractors was weak, which was evident in the projects understanding of the subsystems during integration.

## Tools

For CONTOUR, there were no unique tools used to manage the project. The one tool that was used by CONTOUR, is used by many NASA space science projects, and unique to NASA is Earned Value Management (EVM). EVM is a standard NASA way of running planetary flight projects and performance metrics. EVM is based on a set of project tasks, and each task has a cost to complete and/or items to procure. Each task and procurement has a schedule for completion, and as each one is completed, a monetary credit is assigned. These credits are then graphed against how much money has been spent thus far on the project to determine where project progress follows on the curve.

### *Knowledge Management*

CONTOUR believed that they had basic full documentation needed to be a "full blown NASA mission:" project plan, system requirements document, test plans, formal test procedures, MSPSP, safety plan EMC plans, component specifications, performance assurance implementation plan, procurement plan. From these they had flow-down documents where the subsystem team members developed flow-down requirements documents. All of these were documents that went through a review and approval process with signatures. Like many Discovery Program missions, attempts were made to keep the documentation to a minimum. CONTOUR believed that a vigorous testing program in addition to necessary redesign and retest compensated for a less than formal documentation process.

A fundamental issue associated with capturing and documenting project knowledge Chiu said was that engineers are notorious for not liking to write memos. She found that they were pretty good at writing responses on email in memo form, so she substituted formal reporting and documentation with email communication where necessary. What documentation did exist, was kept in hard copy in Chiu's office, and in electronic copy on a shared server. In additon to required project documentation, CONTOUR maintained a record of engineering data, project review notes, and questions/answers from the reviews. All documentation was categorized and organized by the CONTOUR administrative assistant, Mary Stevens. The shared server was maintained as an online library. In the online library, aside from engineering documentation, items such as policy statements, level of reviews, what reviews were required, what constituted approvals, approval signatures were kept.

### *Learning Process*

CONTOUR did not perform any lessons learned mining from previous projects before starting CONTOUR. Lessons learned from pervious projects were captured by CONTOUR through people's institutional knowledge. One of the events that were unique to CONTOUR was that the Mars 98 mishaps occurred during the developments of CONTOUR. This prompted NASA and CONTOUR to react quickly to the Mars 98 mishap investigation and the MIB's recommendations. Reynolds stated:

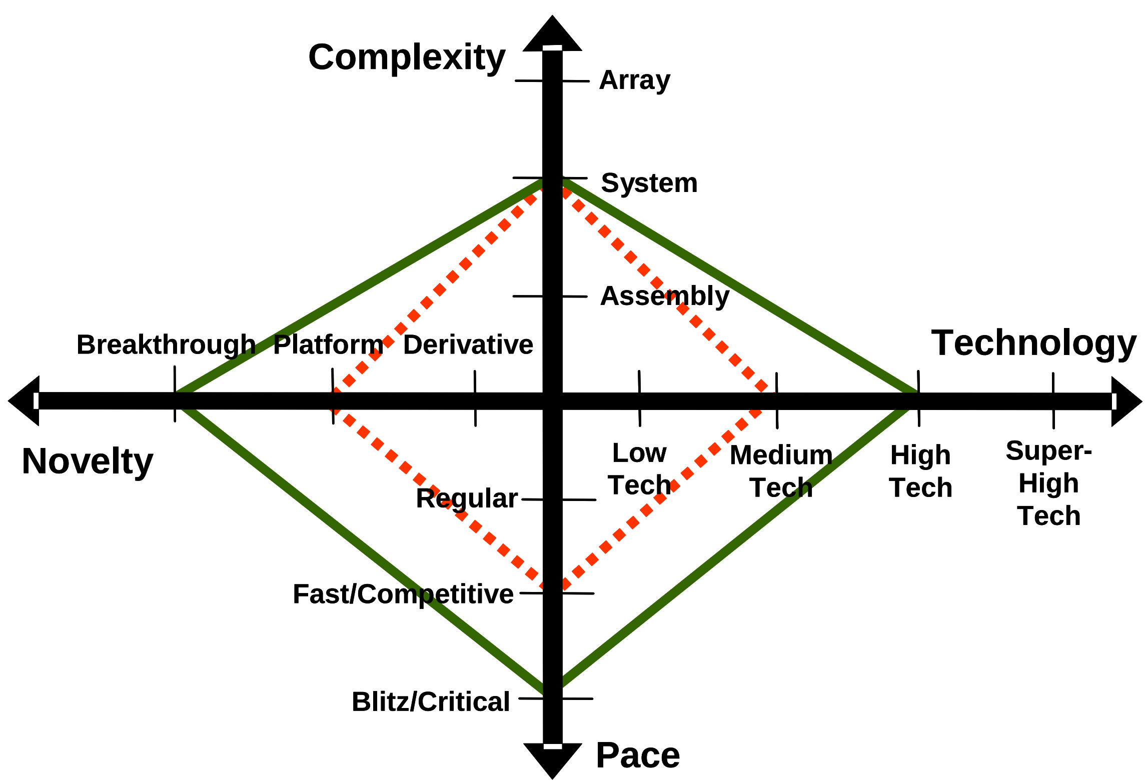
> We were extremely mindful of the issues that happened on the spacecraft right before us, and with the Mars failures and the Mars Observer failure, we were making damn sure that we were not going to repeat the same problems that they had. But something else got us.

CONTOUR placed extra emphasis on testing and reviewing many of the same systems that caused the Mars 98 failures while paying less attention to other subsystems that had greater technological uncertainty. Post-project, other than the CONTOUR Mishap Investigation Board's work, there was no extensive amount of effort placed on documenting and reporting lessons learned from CONTOUR.

### Adapting Project Management to Project Type

CONTOUR was a strategic project that would help APL maintain and build upon their growing competitive edge in deep space missions. In addition, Cornell would begin to build a strategic position as an academic leader in space exploration. Without a framework to truly understand the fit that is needed between the project management style and the risk of the project, CONTOUR was approached more as an operational project. They believed that they were improving on existing products using technology and concepts from previous missions (NEAR and Stardust). While the technology may have been proven, the concepts and challenges of rendezvousing with a comet were not. Without a good framework to identify this, it created fuzziness between being an operational or strategic project. They did understand who was their customer. There is a fine line between a NASA project's internal or external customer, but CONTOUR understood their ultimate customer was the Discovery Program (NASA). The outcome for CONTOUR was a tangible product of a spacecraft, orbiter, and scientific instruments with an intellectual activity. CONTOUR required a significant level of insight and creativity both technically and managerially built around a core of talented, experienced people to produce a valued product.

The NCTP Model below represents the analysis of CONTOUR in respects to its Novelty, Complexity, Technology, and Pace. Connecting the NCTP classification with a straight line to form a diamond, gives a representation of the level of risk associated with a project. The greater the area of the diamond, the greater the degree of risk. Also presented in the model, is how CONTOUR differed in its level of risk and how the project assumed a lower level of risk. While there is not a linear relationship between the area of the diamond for correct and incorrect project risk, it does represent a difference in the degree of risk.



*Novelty*: CONTOUR was a breakthrough project. No one in the history of space exploration had brought a spacecraft as close to a comet as CONTOUR would. Almost all of the technology they were using existed or was previously tested or being tested on NEAR and Stardust. Although APL had been successful with recent missions, not one successful mission had been repeated. Each mission, even if using similar, proven technology from past missions, had some degree of unproven technology and was a new venture. CONTOUR was no exception. There was still a lot to be learned about how to perform an Earth swing-by and rendezvous with a comet. Traveling to a comet incorporated a lot of calculated risks, intuition, and trial and error. CONTOUR would require fast prototyping, late design freezes, and constant interactions with their customers.

In many respects, CONTOUR was very new, as this technology was being packaging into a new product with a new, first-time-used, non-coherent DOPPLER navigation system and the SRM had to be integrated into the spacecraft to perform the scheduled Earth swing-by maneuvers. This novelty in technology alone defines CONTOUR as a breakthrough project, but it was managed as a platform project. Without a framework to understand the right management style, management believed that they were building upon the success and technology of past missions (NEAR and Stardust) and approached this project as a derivative project. This gave the perception that CONTOUR would be a next generation in existing technology. Few projects in space exploration can be defined as platform projects (e.g. Expendable Launch Vehicles – Delta II, Atlas).

*Complexity*: As a very complex interaction of subsystems and elements performing multiple functions, CONTOUR was a system project. CONTOUR was a system project that understood the integration and complexity of that integration to develop a spacecraft. CONTOUR was truly a collection of interactive elements working together for a common goal, exploring a comet. Spacecraft development was lead by APL, Cornell lead the science, and other institutions subcontracted to develop the scientific instruments. CONTOUR had multiple key customers from industry, public, government, and the scientific community that were all vested in CONTOUR's development and success. As a systems project CONTOUR was a complex project that required extensive planning, computerized tools and software, hundreds or thousands of activities, tight and formal control, financial and schedule issues, reviews with customers and management, and extensive documentation.

While much of the development occurred in-house at APL, a significant portion of the scientific development occurred externally to APL. This geographic separation between major systems and management (Principle Investigator and Project Manager) restricted real-time, face-to-face communication. While CONTOUR understood the subsystems of the spacecraft very well, a lack of framework to define unique project characteristics resulted in performing integration testing late in the development, thus not giving them a full understanding of the uncertainty of the system. In addition, being a heavily matrixed organization, team members were not privileged with the ability of cutting ties to their parent organizations to fully commit to the project.

*Technology*: CONTOUR was a high-tech project. The technology was mostly proven technology but being applied in a new way. There were significant improvements made to the technology to develop CONTOUR from its original design, with minor modification to bring it together to function as a complete system. CONTOUR required long periods of design, development, testing, and redesign with multiple design cycles that had to start before the project started. With the extensive testing that was required for a high-tech project like CONTOUR, in depth, technical reviews were mandatory to make a project of this complexity successful. In conjunction with these reviews, communication had to be frequent and active. The complexity and communication demands required management to be of good technical skills and intimately involved in the project. They also had to recognize the unique challenges of CONTOUR and be flexible to extensive testing and design changes. Therefore, design freezes had to be scheduled and as late as possible.

Without a NASA-specific framework for distinguishing CONTOUR's unique technology characteristics, CONTOUR assumed a lower level of uncertainty in the technology that they were using for the mission, and managed the project more like a medium-tech project. This resulted in an approached to the technology as a non-revolutionary improvement to past missions when the application of the technology was very much the first of its kind. Development and testing of the integration of the SRM was limited and did not receive extensive review. Communication was not as frequent with subcontractors and key contributors as needed for a high-tech project.

*Pace*: CONTOUR was a blitz-critical project. From the time the project got the green light, they were under the pressure to meet a specified launch opportunity with a strict schedule. Time was critical for project success, and delays meant project failure. The project team had to be specifically picked for CONTOUR and they were considered a special group trying to achieve a rapid solution to a vital project. Procedures had to be shortened, made simple, and non-bureaucratic, while top management had to remain highly involved and constantly supportive.

The huge success of BFC at the time of CONTOUR built a confidence in Discover Class Missions and gave the appearance that they may be managed like a fast-competitive project. While management understood they were under a constrained time factor, they believed that the project could be accomplished with matrixed team members maintaining a 40-hour workweek. In addition, not having access to a framework to determine the project risk led management to believe that events such as integrations and testing could occur late and less frequently in the project. The consequence was that there was not the sense of urgency as seen in successful BFC projects.

**Success Factors**

Wide spread faults were hard to find in CONTOUR, and it embodied many of the characteristics of successful Discovery Program missions. Management brought to the project years of success, and a firm belief that they knew what it would take to make CONTOUR successful. Factors that may have contributed to CONTOUR's prospective success were:

- Strategy
    - Strategy was determined early and articulated often
    - Objectives were simple, attainable, measurable, and valuable
    - Defined objectives based on customer needs
    - Competitively selected
- Spirit
    - Focused, unspoken, common commitment
    - Team empowerment
- Organization
    - Limited involvement from top-management
    - People worked the project from beginning to end
    - Maintained only a core workforce
- Processes
    - Stuck to the requirements
    - Informal (peer) reviews
    - Active communication

A concerted amount of effort went into the preparation of the proposal and early developments of CONTOUR, and thus significant thought went into determining CONTOUR's strategy for success. The key visionaries and a handpicked project manager dedicated themselves to defining and later articulating the strategy. Mary Chiu believed as Project Manager, it was her sole responsibilities to communicate frequently and clearly CONTOUR's strategy to the project team. She believed she had to keep the team focused and she should use all powers necessary to make that happen. The strategy for CONTOUR could not have been successful without attainable and measurable objectives defined by the customer. CONTOUR believed that their objectives had to be simple, attainable based on the resources, measurable by their customers, and valuable to the scientific community. While these objectives never had the opportunity to be met, each day the project team worked with a clear understand and commitment to those objectives. The proposal team that put the competitively selected CONTOUR proposal together clearly understood their competitive advantage and who were their competitors. The proposal team looked outside the normal proposal process and was able to identify and define their competition and what set them apart from everyone else. With a clear understanding of there competitive advantage, they were able to articulate this advantage through the proposal selection process.

In many Discovery Program missions, there is a camaraderie and common commitment that can only be understood by those that have worked on a Discovery project. With a short development time and a challenge usually unparalleled in space exploration, team members develop a focused, unspoken commitment to the project and its success. For CONTOUR this was described as 'family.' People believed that that they were contributing to something special, and the success or failure of any one system, subsystem, or component, was a lose to the team. They truly believed that they were successful as one unit and thus would fail as one unit. Management points to the empowerment of the team as part of the reason for a dedicated team. Management believed that decisions had to come from the people making the project happen on the day-to-day. They made sure that team members were empowered to make decisions, and speak up when they were not comfortable with a decision. Team members were given the tools or access to the tools they needed to do their job.

Limited top-management involvement is a common trend in Discovery Program projects, and CONTOUR was no exception. Top-management played a limited role in the direction of CONTOUR. While kept informed, they let CONTOUR management perform the job they were hired to do. While not all of the people that worked on the project during the proposal phase were part of the development phase, those that started with the project at the beginning of the development phase saw the project through to the end. Partly because of budgetary constraints, the workforce was kept to a core minimum, but once a good engineer, scientist, or reviewer was part of the project they were retained. People that started with the project at the development phase carried through to the assembly and then operation phases. It was a cradle-to-grave, keep-it-in-the-family mentality.

CONTOUR set requirements early and stuck to them. Management had a firm understanding of the schedule constraints that CONTOUR was under. This meant there was very little room for changing direction, thus once the requirements were set, they were able to freeze the design early and focus on assembly in time to make their deadlines. Mary Chiu was praised for her firmness on the requirements, being able to tell an engineer "no," and knowing when to freeze the design. CONTOUR understood the value and importance of reviews, and more importantly who were the reviewers. CONTOUR sought experienced and knowledgeable review team members, and when they found a good reviewer, they did everything in their power to retain them throughout the project. While the reviews may not have been as encompassing of the entire system as they should have been (including certain subcontracted subsystems), they were many. Management stressed active, frequent communication between team members. If a team member was not co-located they made sure they could contribute via phone. If problems arose, management made sure the resolution was achieved with good, immediate communication.

## Recommendations

The CONTOUR MIB specified that there were two major managerial errors, and inadequate systems engineering process and review function. These two principles were fundamental to CONTOUR's success and failure.

**Recommendation 1 – Understand the technological uncertainty to apply the right management approach:** The fundamental factor in CONTOUR's failure can be related to a reliance on past success and inherited systems that lead to a false sense of confidence. No one in the history of space exploration had ever brought a spacecraft as close to a comet as CONTOUR would. While they were using predominantly existing, off-the-shelf technology and technology from previous missions (NEAR and Stardust), CONTOUR was flying for the very first time a non-coherent DOPPLER navigation system and a SRM that was not thoroughly tested with the spacecraft. Fundamental to general systems theory are four basic assumption: (1) the sum is greater than the parts and there are consequences for not understanding the dynamics of each part, (2) there is multi-lateral causality between subsystems, systems, and the environment they function in; (3) one set of initial conditions can give rise to different final states; and (4) there is concern with the flow of information between subsystems (components).[6] The lack of a framework that could help understand the fit that is needed between the project management style and the risk resulted in CONTOUR not being able to identify key areas of risk in the integration of subsystems. The Deep Space Network team and the navigation team recognized some of these uncertainties, which caused a high level of discomfort between teams and in the processes. While CONTOUR attempted to overcome this with extensive testing, the extensive testing did not extend throughout the integration phase.

**Recommendation 3 – Avoid overconfidence from past success:** BFC was pushing the enveloped of doing high-tech projects cheaper. Meet the cost challenges of BFC, CONTOUR management believed that they were building upon the success and technology of NEAR and Stardust. This may have led to a false sense of confidence by CONTOUR management based on the successes of NEAR and Stardust, thus management approached CONTOUR as a next generation in existing technology (platform). Few projects in space exploration can be defined as platform projects (e.g. Expendable Launch Vehicles – Delta II, Atlas). By approaching this project as a derivative of other projects, there were unable to compensate for the risk and uncertainty in what they were trying to accomplish. To compound this, the implementation of the NASA Integrated Action Team's (NIAT) recommendation from their investigation of the Mars 98 failures were coming out almost three quarters of the way through CONTOUR's project life cycle. This resulted in CONTOUR management directing a significant amount of attention to similar issues on CONTOUR, and may have drawn attention away from other subsystems that needed attention.

**Recommendation 4 – Resolve leadership conflicts quickly and have clear lines of leadership:** A project team relies on their leadership to guide them and provide them with their strategic focus and vision. Some managers commented that conflicting direction came from top management, and it was not always clear who within top management was in charge. Conflict and undefined leaders only lead to confusion down through the organization.

[6] Ruben, B.D. and J.Y. Kim. (1975). *General Systems Theory and Human Communication*. Rochelle Park, NJ: Hayden Book Company.

**Recommendation 5 – Key subsystems should be co-located:** BFC missions have been successful because of co-location, and CONTOUR had significant portions of the project in significantly separate locations, the spacecraft at APL (Maryland), the science at Cornell (Ithaca, New York), and the SRMs at a Contractor. While CONTOUR worked very hard to achieve active communication through telephone, email, and scheduled site visits, an engineer or scientist could not always walk down the hall to get the answer to their question.

**Recommendation 5 – Team members should be 100% on the project (cradle to grave):** Because of a limited budget, CONTOUR was forced to rely on the matrix organization. In a project that has a strict schedule such as a Discovery Program mission, team members should cut ties with their home organization and become 100% part of the project they are supporting. This may have been the case for the management, but it was not the case with all of the team members. While the spirit and commitment by team members was high, many team membes were still anchored to their matrixed organization. This resulted in a lack of a sense of urgency. Team members through almost the entire project worked 40-hour weeks and rarely weekends. In projects with limited schedules and fixed launch dates, team members routinely work extra hours to guarantee project success.

**Recommendation 6 – Independent reviews should be in depth, technical reviews with active communication with experts outside of the review:** CONTOUR had a good frequency of independent and peer reviews in the project, but there were no consistent linkages to those review members outside of the actual reviews and they addressed only top-level issues. There should have been more linkages to review members and independent experts while addressing in-depth technical issues.

## APPENDIX D – MARS CLIMATE ORBITER

# Strategic Systems Innovation

# A Case Study of

# Mars Climate Orbiter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**Executive Summary**

In 1993, NASA started the Mars Surveyor Program to develop a series of missions to study Mars. A Mars Program Office was established and given the responsibility of defining the objectives of these Mars exploration missions. Chartered under this office would be two missions with biennial launching opportunities (Mars Climate Orbiter and Mars Polar Lander). The Jet Propulsion Laboratory (JPL) created the Mars Surveyor Project ’98 (Mars ‘98), which would be responsible for these missions. One of these missions, the Mars Climate Orbiter (MCO), was a strategic project that would help build a sustained position in space exploration with recent successes in Mars exploration (Mars Pathfinder and Mars Global Surveyor). MCO would build upon those successes, and lay the groundwork for several planned Mars exploration missions over the next 15 years. MCO was a tangible product of a spacecraft, orbiter, and scientific instruments which required a significant level of insight and creativity both technically and managerially built around a core of talented, experienced people to produce a valued product.

As a project MCO was to design, test, develop, launch and operate an orbiter that would collect weather data from Mars and act as a relay station for five years, assisting in data transmission to and from the Mars Polar Lander (MPL). Jointly developed with the MPL and 300 people from JPL and Lockheed Martin, they had a 37-month development schedule with spacecraft launch masses of a medium-light class launch vehicle, and a financial cap of about $184 million (covering development of the spacecraft, scientific payloads, and the ground operations system). As a project MCO was a high-tech project with development of one-of-a-kind single flight systems. While some of the technology was new, much of it existed at the time the project was initiated. What was unique was how the technology was brought together in a single spacecraft. The complexity of the project could be described as a system. As is the case with all deep space missions, they are a collection of interactive elements and subsystems that must perform a wide range of functions under extreme conditions. The pace of the project was a blitz-critical project. Time and budgets became fixed and any error in either of these areas meant cancellation for the project.

On September 23, 1999, MCO would begin its orbiter insertion maneuver, but shortly after beginning orbit insertion, the signal was lost from MCO, and on September 24 search for the orbiter was abandoned. On September 30, a JPL peer review committee reported that small forces of velocity changes reported by the spacecraft engineers for use in orbit insertion were low and the likely causes of the MCO lose. On October 6, a MCO Mission Failure Investigation Board was appointed by NASA to independently look into all aspects of the failure of the mission. On November 10, the Board released their report that idenified the root cause for the loss of the MCO spacecraft as the failure to use metric units in the coding of a ground software file.

While the root technical cause was a coding of metric units in the software, the over arching cause of the MCO failure was a stategy designed to cost and not capability. This can be attribued to the pressures and challenges of BFC which resulted in cuts in areas that later proved to be key in contributing to MCO’s failure. Because of cost constrains, peer reviews were de-emphasized, there was not an active involvement from experts, dual development was used on subsystems for multiple missions, the number of people on the project was kept below minimum, expertise for key subsystems was unavailable to the project, testing was streamlined in key areas, and key policy was reduced. Designing to capabilities may have revealed that this project could not have been done under the specified budget. With all of its constraints, the MCO team maintained a high spirit with an unmatched drive to be successful. Unfortunately, not managing the spirit resulted in team members overworking themselves and maintaining a consistent energy level from beginning to end.

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## Participant Observation

Academy of Program and Project Leadership Advanced Project Management training course. June 11-22, 2000.

## Background

NASA was beaming with a string of storied successes from the Discovery Program and showing all of its critics that ‘better, faster, cheaper’ (BFC) could be successful. The agency had been so successful with its previous ten BFC missions that they never saw what was coming September 23 and December 4, 1999. It was what did not happen on September 23 with Mars Climate Orbiter and later on December 4 with Mars Polar Lander that forced NASA and the space science community to take a long hard look at how it managed its projects and wondering if BFC could be successful.

In 1993, the National Aeronautics and Space Administration (NASA) started the Mars Surveyor Program with the intent of performing a series of missions to explore Mars. The Jet Propulsion Laboratory was commissioned as the lead center for this program, and Mars Global Surveyor (MGS) was identified as the charter mission. To follow MGS would be Mars Climate Orbiter (MCO) and Mars Polar Lander (MPL). To champion MCO and MPL missions, JPL established the Mars Surveyor Project ’98 (Mars 98) office with the responsibility of defining and developing the spacecraft and all payload elements, and integrating, testing, and launching both flight systems. Additionally, the Mars Surveyor Operation Project (MSOP) would be responsible for conducting flight operations for MGS, MCO, and MPL. JPL selected an industry partner with Lockheed Martin Astronautics for the Mars Surveyor Program to develop the spacecraft. This intensely competitive contract would give Lockheed Martin the opportunity for eight spacecraft for Mars opportunities, the first of which was MGS. JPL envisioned duplicating the spacecraft for every opportunity, so the spacecraft development would become “carbon copies” for subsequent opportunities. JPL believed that this could result in immense cost savings in the long-term. While the Mars Surveyor Program mission was not part of the Discovery Program, the hallmark of BFC, they were charted to follow the principles of BFC and manage them accordingly. But, after the MCO’s orbit insertion failed on September 23 and MPL crashed into the surface of Mars on December 4, wide-ranging and critical managerial and technical actions were taken by NASA, Congress, the scientific community, and the media to determine what went wrong, what was wrong at NASA, and could BFC work.

## Mission Description

MCO was to have mission duration of two years where it would accomplish its entire science objectives (See Figure 1 for project timeline). It was then planned to operate an additional three years as a relay station for the Mars Polar Lander and the 2001 Lander mission. The orbiter would carry two instruments: the Pressure Modular Infrared Radiometer (PMIRR) and the Mars Color Imager (MARCI). These two instruments would work to accomplish the following science objectives:

1. Monitor the daily weather and atmospheric conditions.
2. Record changes on the Martian surface due to wind and other atmospheric effects.
3. Determine temperature profiles of the atmosphere.
4. Monitor the water vapor and dust content of the atmosphere.
5. Look for evidence of past climate change.

The PMIRR would provide the detailed information about the atmospheric temperature, dust, water vapor, clouds, and carbon dioxide that is added and removed from the poles. The MARCI consisted of two cameras that would observe the behavior of the Martian atmosphere and interaction between the atmosphere and the planet surface. A successful mission would have yielded the atmospheric conditions on Mars through each of its seasons and give a glimpse of Mars past and future weather conditions.

MCO was launched on a Delta II Lite launch vehicle December 11, 1998 from Launch Complex 17 at Cape Canaveral Air Force Station, Florida. After launch, MCO would spend the next nine and a half month traversing through space toward Mars. On September 23, 1999, MCO would begin its orbiter insertion maneuver before start of the aerobraking process. At 09:00:46 (UTC) MCO began orbit insertion, but a short four minutes later and 49 seconds ahead of the schedule Mars' occultation, the signal was lost from MCO. After a 21 minute predicted occultation interval, signal was not reacquired, and engineers spend the next two days unsuccessfully attempting to communicate with MCO. On September 24, search for the orbiter was abandoned, and on September 27, the operations navigation team and the spacecraft engineers debated discrepancies regarding velocity change, only to discover on September 29 that the small forces of velocity change's reported by the spacecraft engineers for use in orbit insertion were low by a factor of 4.45. On September 30, a JPL peer review committee confirmed these as the likely cause of the Orbiter lose. October 6, Dan Goldin, NASA Administrator, appointed Arthur G. Stephenson, Director of NASA's Marshall Space Flight Center, to be the head of the Mars Climate Orbiter Mission Failure Investigation Board (MIB). The MIB would look independently into all aspects of the failure of the mission, and report its initial findings to NASA Headquarters by November 3, 1999. On November 10, the MIB released the report, *Mars Climate Orbiter Mishap Investigation Board Phase I Report.* In this report they idenify the root cause for the loss of the MCO spacecraft as the failure to use metric units in the coding of a ground software file.

| | |
|---|---|
| **1995** | |
| | Mars Climate Orbiter is identified as a mission. |
| **1998** | |
| **December 11** | Launch at 11:45 EST from Cape Canaveral, Florida |
| **December 11** | Start of Cruise Phase |
| **1999** | |
| **September 23** | End of Cruise Phase |
| **September 23** | Mars Orbiter Insertion; 09:00:46 (UTC) |
| **September 23** | Loss of Signal; 09:04:52 (UTC) |
| **September 25** | End of Attempts to Reacquire Signal |
| ***September 27*** | *Mars Aerobraking Begins* |
| **September 29** | Spacecraft engineers discover conversion error |
| ***November 10*** | *Mars Aerobraking Ends* |
| ***December 1*** | *Transfer to Mapping Orbit* |
| ***December 3*** | *Start of Mars Polar Lander Support* |
| **December 4** | Mars Polar Lander is Lost |
| ***2000*** | |
| ***March 3*** | *Mars Mapping Begins* |
| ***2002*** | |
| ***January 15*** | *Mars Relay Mission Begins* |
| ***2004*** | |
| ***December 1*** | *End of Primary Mission* |

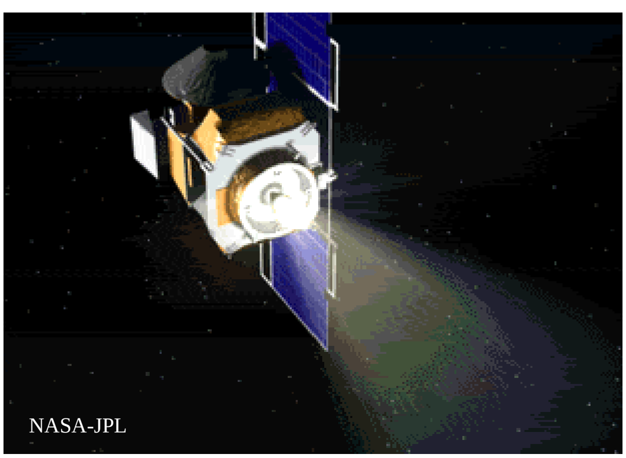
**Figure 1: Project Timeline (Events in italics did not occur because of orbiter failure.)**

**Technology Description**

Once in orbit around Mars, MCO's science mission was to last two Earth years collecting data. But of most significance was that the Orbiter would act as a relay station for three additional years, assisting the MPL and a 2001 Lander mission.

Aboard the Orbiter were two instruments: the Pressure Modulator Infrared Radiometer (PMIRR), and the Mars Color Imager (MARCI). PMIRR was to provide detailed information about the atmospheric temperature on Mars, dust, water vapor, and clouds. Most significantly it would provide valuable information about the fluctuations in carbon dioxide, Mars most abundant atmospheric gas, at the poles during a Martian Year. PMIRR was a nine-channel limb and nadir scanning atmospheric sounder designed to vertically profile atmospheric temperature, dust, water vapor and condensate clouds and to quantify surface radiative balance. PMIRR observed in a broadband visible channel, calibrated by observations of a solar target mounted on the instrument, and in eight spectral intervals between 6 and 50 µm in the thermal infrared. PMIRR science observations were to start only after the PMIRR radiator door was fully opened. Once PMIRR was deployed in the mapping orbit, vertical profiles of atmospheric properties were to be constructed. MARCI was comprised of two cameras that would observe the behavior of the Martian atmosphere and interaction between the atmosphere and the surface of the planet. MARCI combined Wide Angle (WA) and Medium Angle (MA) cameras with individual optics but identical focal plane assemblies, data acquisition system electronics, and power supplies. Each camera was small in size (6 x 6 x 12 cm, including baffle) and mass (combined mass 2 kg). The cameras were electronically shuttered at intervals timed so that the spacecraft motion spatially overlaps each filter strip view, thereby providing a "color" composite. Near the end of the Orbiter's cruise phase, MARCI was to acquire approach images of Mars. Once in the mapping orbit, MARCI would provide daily global images of the Mars atmosphere (and surface) with the WA camera and monitor surface changes with the MA camera during mission periods with high data rates.


NASA-JPL


NASA-JPL

If MCO were successful, scientist would have been able to witness the atmospheric conditions on Mars through each of its seasons. This kind of information is key to understanding Mars' past and even the evolution of Earth. Once MCO arrived at Mars it was scheduled to perform a burnout of the 3rd stage, followed by a yo-yo de-spin of the entire stack, and then spacecraft separation. From this point both the spacecraft and upper stage have been injected onto a Type 2 trajectory to assure that the upper stage has less probability of impacting Mars, as required by Planetary Protection regulations. Although this is where MCO was lost, if it had continued on its scheduled deployment, the solar panels would have been deployed and pointed to the sun, and initial acquisition achieved by the Deep Space

Network (DSN). Approximately 15 days after launch, the largest Trajectory Correction Maneuver was executed, which was supposed to remove launch vehicle injection errors. Provisions had been made to execute up to 3 additional small Trajectory Correction Maneuvers during the remainder of the cruise, as needed, to shape the orbit and direct the spacecraft to the proper Mars Orbit Insertion. Although, navigation anomalies (units error) observed during the cruise from Earth to Mars were not appropriately addressed. With insufficient preparation, the chance for final trajectory correction maneuvers was not employed. The Orbiter engines were to be used to insert the spacecraft into an elliptical capture orbit. Over the next two months, the energy of the orbit is reduced via successive passes through the atmosphere of Mars, controlled by small Orbit Trim Maneuvers. Once aero-braking was complete, two maneuvers were to transfer the Orbiter to its final, frozen, near sun- synchronous mapping orbit. This was to occur long before the MPL’s arrival in December 1999. During the Mars Polar Lander's surface operations, the Orbiter was to provide command and data relay support for three years, and maintain a limited level of orbital science.

## Strategic Project Leadership

**Strategy**

***Objectives***

As a Mars Exploration Program project with a programmatic mission, MCO's objectives were defined by scientific community needs. The Mars Exploration Program is interested in investigating the existence of water on Mars and if it exists, what happened to it. Water is a fundamental building block of life and the existence of water (past or present) would lead to proving once and for all if life exists or existed on Mars. The theme for the program has been 'Follow the Water.' Using information from the MGS, MCO would have follow-up scientific objectives defined by some of the most distinguished scientist (some of the National Academy of Science).

***Competitive Advantage/Value***

"We pushed the boundaries like never before…And had not yet reached what we thought was the limit."

- Daniel S. Goldin, remarks at JPL March 29, 2000

NASA had selected JPL to lead the Mars Surveyor Program because of their lengthy history of Mars exploration. But, for JPL to select Lockheed Martin Astronautics as the prime contractor to develop the spacecraft for Mars 98 was a very competitive selection process. The contractor selected to lead the Mars 98 spacecraft development would be winning a contract to develop eight Mars exploration spacecraft. Lockheed Martin had originally bid quiet aggressively since they had already had MGS in progress at the time. Lockheed Martin believed they had a very rich history in Mars exploration (i.e. Viking), and they were very motivated to win this program. Later Lockheed Martin management would be told that their proposal stood far above all the rest. The project manager that preceded Ed Euler, Lockheed Martin Project Manager, was a very experienced vice president within Lockheed Martin and to win the contract really cut everything down to the minimum. In the end, Lockheed Martin won the Mars 98 contract because of two factors, experience and cost. Unfortunately, cost would become MCO's biggest challenge and a catalyst to its failure.

Once the project started the competitive advantage transitioned into value. Part of MCO's value was to make up for the science that was lost on the Mars Observer. While MGS had repeated most of what was lost on Mars Observer, MCO would fill in the additional gaps in scientific inquiry. MCO would ultimately deliver to the scientific community new and intriguing data on our closest planet. Mars is attractive to the scientific community and the general public, because it has an atmosphere and the potential of past or present water. To the scientific and general imagination, an atmosphere fosters a belief in past life and a future human presence on a habitable place in the near neighborhood of Earth. The successful Mars Pathfinder and MGS had broadened and deepened that imagination. MCO was to bring a new hope and enthusiasm to everyone that believed in space exploration. MCO would lay the groundwork for a continued U.S. exploration of Mars. A successful mission would show to Congress that quality space science could occur with reduced budgets, and build the Congressional support NASA needed for a struggling agency.

***Business Perspective (Success Dimensions)***

"To put it your way, 'What they did to guarantee success.' I would address that question from a different view. Which is what did they do to try to guarantee that it did not fail?"
- Peter Rutledge, personal interview

As with any planetary mission, there is very little leeway for failure. Planetary missions are restricted based on a window of opportunity due to celestial alignment (launch windows). MCO was no exception. While MCO worked towards a self-measurement of success that appeared to be straight forward, it was what MCO benchmarked itself against that was harder to define. As with many NASA projects post-Apollo, it is really hard for project teams to benchmark themselves against something. Rarely is there anyone to beat or is anyone doing anything even remotely similar. As with MCO, they ultimately benchmarked themselves against what they promised.

The Mars Exploration Program had a vision to go to Mars every three years (every time there was a launch opportunity), and learn as much as they could about Mars, it's history, and it's future. The Mars Exploration Program was very confidant they could deliver, and building on the past successful missions to Mars. These and previous Mars missions that had been successful leant to a frame of mind that 'We had done this before, successfully orbited Mars, and other planetary bodies, so we can do it again, and it is not so hard.' The MIB viewed this attitude as over confidence.

Even though, MCO was viewed as the next step in a line of investigative missions to explore the Red Planet. MCO's success would be measured on its ability to stay within budget and on schedule while maintaining the science objectives (one of the most critical factors in determining MCO's success). Noel Hinners, Lockheed Martin Program Manager, said that the potential success of MCO could have been judged falsely had it worked on Mars and got tremendous science results. If MPL had failed and MCO been successful, "You would say 50/50, we got one out of two. Faster, better, cheaper approach can work and you would cruise on." Hinners says that a bright spot in the two failures was that JPL and Lockheed Martin were on a path to do a Mars sample return in the '03 and '05 timeframe. These missions would be based on the same faster, better, cheaper approach and projected price. Hinners stated,

> There is no way, NO WAY, that mission could have been done for anywhere near what people were talking about at the time and think that they would get success out of it. So the failures said to people, Whoa, this faster, better, cheaper, is not all that it is cranked up to be, at least not the way we are trying to implement it. So that resulted in the end of the '03, '05 sample return study, and the activity that was going on that would lead to a mission. And I say, 'Thank God.' In my view there is no way it could have ever worked. It would have been an unbelievable, and much more costly embarrassment. When you look for the bright points, the Mars 98 said, 'God, I hope we have learned that lesson, that you cannot do these complex missions on the cheap. You have got to have the right investments in them.'

***Strategic Focus***

"Came close but didn't make it, and close doesn't count."
- Noel Hinners, personal interview

For MCO there was a drive to do good science, but the drive to develop MCO at a bare minimum cost is what fostered the strategy. JPL made several strategic decisions, which ultimately became key for MCO, that were driven by cost. One of those decisions was to use much of the science from the failed Mars Observer. The second was to award a contract for spacecraft development that would result in an opportunity for up to eight almost identical spacecraft.

The culture of the scientist is always to want to do more science, and the engineer that responds to ever scientists request will find themselves consumed by ever changing requirements, resulting in a scope and strategy change. Changes in scope drive cost. Many projects have resulted in cost overruns because people responded to requirements changes without changing the scope or strategy (i.e. Mars Observer and the Space Shuttle). Ken Atkins, Project Leadership Processor, stated that management has to say, “What you are asking for here is not the job we originally bid. We cannot win the gold star with the money we got adding these additional requirements.” The ‘better faster, cheaper’ missions were supposed to move away from that paradigm built on cost constrained missions and into a paradigm of a capability driven strategy. The idea of a capability drive strategy is to take an inherited, given, or well, understood capability that one knows can be built and see if it captures enough science to satisfy the scientists and principle investigator. For MCO, management were cost driven. To accomplish the most science for the least dollar, the project was designed around cost and not the science. Cost became the performance floor that the project had to guard. The strategy for MCO should have been built around the project scientific objectives and the follow-on of the successful Mars Global Surveyor, but as requirements crept, no one stood up and said, “No, or that it was not in line with the original scope and strategy of the project.”

In addition to the science strategy being driven by cost, so was the spacecraft development. Everyone was bidding on the Mars Surveyor Program, because they realized that this was more than just bidding on a spacecraft, but a unique opportunity for multiple spacecraft. As a strategy, those bidding on the contract knew that they may not profit on the development of the first spacecraft but each subsequent mission will have increasing dividends. This set a mood in the program, and as Hinners stated, “Your competitive environment tends to push you to bidding lower cost to try and squeeze all of the cost out the first time. To try to win.” The strategy of building around a minimal and potentially inadequate budget, fostered for MCO a strategy that later was defined as not what was done to guarantee success but what was not done. Hinners stated, “We did not do some of those essential things that improve greatly your probability of success.”

## Project Spirit and Leadership

### *Organizational Culture*

"It was very difficult for people to understand the environment that the NASA administrator had established. The axe he was holding over everybody. It was a challenge we accepted, and we paid the consequences."

Ed Euler, personal interview

The culture in MCO was described as can-do, driven, independent, self-reliant, we know how to do it, we'll get there, and a high degree of confidence. The people leading it were defined as good leaders and very capable. With a low cost and schedule driven mission, there was a sense of urgency and desire to succeed. It also resulted in not being able to afford oversight or extensive testing, either with JPL or Lockheed Martin. Therefore, the project developed a 'protective shield' toward outside opinion.

Atkins stated, "I think in most cases a unique sort of characteristic or culture evolves for each project, and it is largely a function of the management and the kind of relationships that are built." Atkins believed that the relationships management builds are influenced and characterized by the type of contract the project functions under. The contract type places restriction on how management can foster relationships. MCO was a cost-plus contract with a certain amount of the fee paid to the contractor for its success. "This builds a prime and sponsor relationship and not a team or collaborative culture," says Atkins.

### *Project Spirit*

"The team spirit was so good that it probably blinded us to the amount of work and stress that was existing on the project."

- Noel Hinners, personal interview

For MCO, project spirit was described as the least of their concerns. Euler described it as, "phenomenal." The team was always highly motivated from project start through launch and into the cruise phase. Euler said there was nothing he needed to do to worry about motivation, that was the easiest part of his job. The people were highly motivated. Team members knew they were doing something challenging. Hinners said, "There was not anybody who had any doubt that we were going to succeed." People put their hearts and souls into the project with a lot of time and even overtime, while maintaining an incredible enthusiasm. Hinners described them as, "Just a bunch of space nuts." From management on down, they wanted to show everyone that this could be done. People devoted their lives, weekends, and time as Euler stated. While the team spirit was described as excellent, Hinners stated that this may have been deceptively so. MCO worked on the minimums in almost every area, and one of those was people. Not having enough people, but dedicated, committed people, meant people worked extra hard to get the job done and do it right. This may have taxed the time and capabilities of the team.

### *Policy to Support Strategy and Spirit*

"Sometimes the pendulum swings a little too far."

- Ken Atkins, personal interview

JPL and Lockheed Martin's culture and history are mainly on large flagship missions such as Galileo, Cassini, and Viking, which are billion dollar projects with 10 to 14 different instruments and a number of principle investigators. With a budget and scientific objectives this significant it requires a large set of people. Under Dan Goldin, former NASA Administrator, he wanted to do more for less money and thus the birth of ‘faster, better, cheaper’ and a new culture.  As one of the inaugural missions of ‘faster, better, cheaper,’ Mars Pathfinder, had a spirit that said, ‘get good people, get out of their way, and they will do a great job.’  While Mars Pathfinder may have been successful, not everyone attributes its success solely to hard work, good management, and an effective strategy.  While changing JPL policy to allow co-location and breaking some of the barriers to communication may have fostered the Pathfinder team spirit, some believe Mars Pathfinder was part of “providential experience.” Others at JPL and the NASA community sometime say that JPL means “Just Plain Lucky.” When MCO started they attempted to embrace this reduction in policy to support the strategy and spirit of the project, but MCO shifted the pendulum too far as one manager stated.  Giving MCO the liberty to restrict or change policy, gave them the ability to do this to fit cost.  Therefore, policy for certain requirements was viewed as non-applicable to meet cost constraints.

### *Leadership*

Many team members on MCO specified that leadership problems on MCO were centered on accountability and authority.  Team members at times were not sure who was in charge or who was the mission manager.  Lines of leadership were not clearly defined and some managers stepped outside their responsibilities.  Many project team members did not identify project managers as leaders.  The MIB specified that project managers were competent but inexperienced, with minimal senior level management involvement to balance the lack of experience.  While the leadership appeared positive, enthusiastic, and convinced that they could and would be successful, some identified this as an over-confidence.  One manager identified the leadership style as autocratic with tendencies to breed conflict.  A characteristic that was missing from the leadership was a collegial or trusting relationship with team members.  Atkins stated, “The word trust is a very, very big element of achieving the kind of spirit that you really need.” Leadership for MCO lacked a balance between confidence and arrogance.  Some team members felt it was difficult to achieve a team spirit because they were pressured to perform as management wanted or they were not valued on the project.

### *Team Empowerment*

MCO worked to empower team members and more specifically subsystem leads with the information and tools they needed to perform their job.  For Lockheed Martin, they emphasized empowerment more so than most missions.  The team had a lot of autonomy, and team members were given in a very large part the autonomy to make their decisions.  While the project manager was ultimately accountable, they gave subsystem leads a lot authority and accountability.  Euler stated that subsystem leads had full responsibility for their hardware, whether they were designing and building it themselves or contracting it out.  He did not believe in micromanaging, but in giving the responsibility to the leads.  Euler said, “We were ‘lean and mean’ at the time.  We essentially had no checks and balances on the program as we do today.  I could not possibly execute that program under the environment that we live in today.”  While management worked to empower the team with relinquishing control over budgets and requirements, they were empowering a team of limited experience or depth.  Atkins states that the openness (managing at an arms length) to the navigation processes while empowering junior engineers with limited depth was too much for those engineers to handle.

## Organization

### *Project Organization*

What made MCO unique was that it was one of two projects called Mars 98. As part of Mars 98, MCO and MPL could have individually been classified as projects. Each carried a complexity and uncertainty that could warrant a project organization all their own. While they were two slightly different flight systems, they were not two unique budgets. While the two projects organizationally functioned semi-independent, they shared a funding level of one project. A consequence of this was that MCO was organized too broadly. Atkins stated, “They had to organize in a way that tried to get as much quality and depth in both of these in an equal balance approach.” This thinness in the organization resulted in lack of oversight and balance in quality. People held dual responsibility on both spacecraft. The computer systems were the most noted area where people had dual responsibility. In a Discovery mission which is deemed less complex by NASA standards, that only has one spacecraft to build, it is ideal that the organization be as lean as possible with clear lines of authority, and making sure the decisions get made appropriately. While MCO was not a Discovery Program Mission, it was under the pressures of ‘better, faster, cheaper,’ and thus worked towards what many considered a ‘better, faster, cheaper’ standard organization structure. Atkins defined this as having four hubs: (1) the project management and the principle investigator, (2) the science payload which is the responsibility of the principle investigator or the project scientist, (3) the flight systems which are usually managed by a contractor, and (4) the mission engineering and operations which deals with the early design, trajectory, navigation planning, ground systems, communications link from Earth to the spacecraft.

### *Structure*

While MCO followed mostly classical development lines, there were some areas that were a little different. Because the MCO spacecraft was viewed as the first in a line of identical spacecraft some of the subsystem development was being performed for multiple missions. For example, certain subsystems being developed for MCO were also being developed in parallel with the Stardust mission. Therefore, certain parts of the MCO development were reliant a product development organization, and that organization had the responsibility for producing the subsystems that were common to three missions: Stardust, MPL, and MCO. Hinners said, “Project Managers tend not to like that. They want to have total control over everything they can; that is the ideal for them. Having two project managers having to work with a PDO, product development organization, frustrated the project managers a little bit but they worked it.”

For the spacecraft development Lockheed Martin worked very hard to locate almost all of it in one building, and went out of their way to co-locate as many people as possible. For example, the product development organization was on the first floor (one floor down from where the project was located), software development was the next floor, the mission support area was on the third floor, the developers were on the fourth floor, and test facilities were right across the street. JPL made sure that they had a number of team members there on site at Lockheed Martin. MCO believed that by co-locating a significant portion of the team you have the operating team in close proximity to the developers so when an issue arises with the performance of a subsystem or the software, the people who developed it are right there. Trying to have a good flow from the development team into operations was a key piece of the strategy.

***Team Assembly***

"If you don't spend the money on the people, you do not have enough of them to go and ask others as much as you should."
- Ken Atkins, personal interview

In the formulation stage, the leaders of the team, the project manager and the main subsystem leads, would competitively select team members with a selection board. They would review candidate's qualifications, judge them, and then have a selection. Working with the central engineering organization they would try and identify people with the right skills and availability. As Hinners stated,

> Sometimes you say I want X, but X is committed to another program and you cannot get X. There is a lot of tussling that goes on so you can get the best people you can for your program. That is normal. That is up to the subsystem leads with a lot of help from central engineering to try and assemble as strong a technical team as you can.

MCO relied heavily on matrix organizations with teams assembled from functional organizations. When the team for MCO was being assembled many team members were still involved in other projects and continued to play advisory roles to those projects while attempting to work MCO full-time. The MIB stated that key team members were added to the project too late in the process. Some of these key team members were not brought to the project until just before launch; long after requirements had been established and hardware had been assembled. Not only were key personnel added late but also, the MIB stated that MCO was understaffed throughout the project and key people did not transition between subsystem phases. Science teams were not prepared for mission operations supporting science data collection. Some even believed that if MCO had entered into Martian orbit, the lack of involvement of scientists from the beginning of the project would have resulted in insufficient data return. Particularly, scientists were not intimately involved in the project from its inception and were not made full partners in the project development and operations.

The project had a limited number of members with experience that could act as mentors for the inexperienced team members. In addition, this experience could have identified issues associated with many of the technical problems with MCO. The MIB identified the team's inexperience as a key factor in the root cause of the MCO failure. MCO was criticized for missing things because they did not have enough people to do peer reviews or take a second look at things. With few people, team members never had time to think about anything but the task in front of them. Hinners stated,

> You will not find this in the review board notes, the Lander Lead said to me when I was talking to him about the mission and how he felt, he said, 'When looking back on it, our biggest problem was no A'Ha time. We were so busy doing the work that had to get done, we did not have the luxury of just sitting back on a weekend or on when you got home at night and just conjugating about what went on.' When you get that time that things come together in your mind and something bothers you, and you say, 'Boy, did we do that. I better go back and re-look that or there is something we need to work a little harder or take another look at.' When you squeeze people so hard and it is all essential work, you loose that capability to exercise your mind and give it a little relax-time when things pop into your head.

### *Responsibilities*

"You have formal organization arrangements and responsibilities and then there are the way things really work."

- Noel Hinners, personal interview

The MIB believed that roles and responsibilities were not clearly defined by project management with any mechanism for accountability. In addition, management did not infuse a sense of responsibility in team members and make them feel responsible for the mission's success. Most notably, the lines of accountability were faint. With the lack of responsibility and accountability, came differences in opinion and project direction. After the failure of MCO, one of the MIBs most difficult tasks was to determine accountability. It was determined that the employees did not fully understand nor were trained properly on aspects of subsystem/line organization interactions. This was distinctly clear in how major project responsibilities were delineated. MCO project managers were responsible for development only, and a separate organization and project managers were responsible for operations after launch.

### *Top Management Involvement*

Like most BFC projects, MCO had limited top management involvement. The key difference was that the lines of communication between project management and top management were not clearly defined nor did either party aggressively pursue interactions. There was no single point of contact between levels of management; resulting in multiple channels for information exchange. In addition, top management was not kept well informed as to the project risks. John Mcnamee, JPL Project Manager, was described as buying the JPL support 'by the drink.' Because of a reduced budget, his linkage to top management was on a needed basis. John was very cautious about signing up any external help because it cost his budget. So he tended to fend off the JPL engineering support. This inadequacy in MCO resulted in the establishment of a new position at JPL to specifically monitor projects.

Standard, were monthly reviews with the Lockheed Martin management, monthly financial meetings, and extra reviews if the project was running into cost problems. For the Mars Surveyor Program this became all too common because of the cost pressures.

### *Professional Advise and Reviews*

"JPL/NASA center policy and guidelines should be modified as necessary to emphasize the need to conduct, the value of, and the implementation of peer reviews."

- NASA Lesson Learned Database Entry: 0929

Traditionally at JPL, peer reviews and professional advice play a key role in project integration and success. Peers are used to discuss the threats and progress of the project with an unbiased perspective. People are selected that have 'guru status' of a long history of expertise in a specific area. These people are brought together with the team and they work in an informal environment looking at the detail of the subsystem and the issues. The results of these reviews are then rolled up into a presentation package for one of the major phase reviews. Peer reviews are also used to evaluate the inheritance of a piece of equipment from another spacecraft. This allows for an understanding of the capabilities of that design or piece of equipment to capture the requirement that it will face in the new environment. In MCO, peer reviews looked at the experience and inheritance from the Mars Global Surveyor, and how that applied to MCO. JPL believes that these help reduce the risk and get more expertise on the issues at hand.

Yet, one of the key factors identified by many of MCO's team members was the lack of involvement of project scientist in critical decisions throughout the project life cycle. MCO reduced significant monetary and personnel resources from the project that was allocated to support science objectives (key to measuring project success). This reduction in resources had a direct result on the interaction of key scientist with critical decisions during the mission design and operation. The MIB believed that proper representation by key personnel was not present at reviews. Without these key personnel, MCO felt that there was a lack of formality at many of the reviews and almost all of them lacked a deep penetration of technical issues. Most noticeable was the absence of discipline experts like software navigation experts. Even with the absence of key personnel at reviews, there was still lack of cross observation by subsystems. For example, members of the navigation team did not always attend the systems design reviews and vice versa.

***Organizational Problems***

"The experience on any of these projects depends on the level of team building and trust that can exist."

- Ken Atkins, personal interview

A MCO manager stated that an overestimate of the magnitude of the project brought conflict and tension throughout the project. The MIB stated that a deficiency in the MCO project management was in their lack of reporting problems and insufficient follow-up. Atkins stated that someone could be working on a piece of equipment, and say to themselves, 'Oh my goodness, I didn't get enough money into this but it has a conflict going on. I hate to put myself into a position that I did this wrong in terms of bidding the right size of this activity versus I should be open about this and go ahead and do this and let other people help me.' This resulted in team members feeling they were not on top of their job in estimating the project from the beginning, and ultimately leading to a position of denial. Management did not give team members a sense of importance in reporting problems, and there was no means to allow team members to report or resolve problems.

Discussions and conversation did not occur that allowed for a consensus to declare that the organizational structure needed to change and that help was needed to carry a task out. This apprehension was magnified by the fear of a specific position change, additional peer reviews, or support groups to guide the cognizant person to a successful conclusion. In MCO there was a lack of openness and willingness of the personalities to accept outside help and organizational, structural change. The failure of MCO resulted in problems in other projects, most notably the Mars Polar Lander. At the time of MCO's failure, MPL was already on its way to Mars. The failure of MCO caused a crisis mode activity in MPL. Management was constantly asking, "Have we done everything that we should have done." Ultimately this project failed when there was a premature shutdown of the descent engines and it crashed into the Martian surface. Because MPL and MCO were integrated managerially, many of the implementation errors identified by the accident review boards were the same for MPL as they were for MCO.

***Training***

The MIB identified training as a key to the failure of MCO. They felt that the navigation team was not familiar enough with the operations of the spacecraft, and this lack of knowledge limited their ability to make informed decisions. As inexperienced team members were added to the project, they were not trained nor received any mentoring in what they were tasked. This was most prevalent with the attitude control system. Euler said additional training was necessary for MCO to meet cost constraints and relied on "one deep" personnel.

## Processes

In pre-project planning and determining requirements for the Mars' 98 missions, the Mars Program Independent Assessment Team (MPIAT) stated that there were inadequate resources to accomplish the requirements, and NASA Headquarters had applied pressure on JPL and LMA to be successful with the concern for loss of business. During the pre-project development process and during the project the pressure of meeting the cost and schedule goals resulted in increasing risk and knowingly cutting proven engineering practices to meet the cost and schedule demands. Project planning and engineering development cost for Mars' 98, two missions, was half of that of Mars Pathfinder. The planning process for MCO was adequate, because it showed that there were not enough resources or contingency to be successful. Although the pressure to be successful was significant enough to proceed in conditions that were later termed "inadequate."

### *Project Phases and Reviews*

MCO followed the standard NASA technical review and approval process (i.e. PDR, CDR, SDR), but there were not adequate resources to support the review processes. Euler stated, "It was mandatory that we cut corners, primarily in the review process and the quality engineering process. It was mandatory that we didn't get a second set of eyes on everything we needed to. Otherwise we could have never met the cost goals." As a result, these review processes were not rigorous and key experts in the field were not sought to fill some of these positions on the reviews. Some of the most recognized experts in deep space exploration are employed by JPL. The use of subject matter experts can validate requirements to which a design is built. This was not evident in the review of the small forces data, which later became mission critical. The MIB contends that this internal expertise and capability was not effectively utilized. Additionally, the MIB stated that project phases did not have clear transitions and team members were not sure when one phase had ended and another began. Also contributing to this dysfunctional transition was an inadequate transfer of information between phases. Atkins stated,

> In the case of Mars 98 in trying to do two major and different flight systems with a very limited amount of money that made the depth that you could go with peer reviews not as deep as you would like to have done. So that brings a little more risk into the issue. For example, the navigation. If we might have had a little bit more of a peer review focus on the issue of small forces and how they applied in the navigation file transfer and so on, we probably would have been able to avoid the crash of MCO.'

### *Communications*

Communication for MCO between project elements was considered by most to be inadequate. There was a lack of early and constant involvement of team members and the communication lines, as identified by the MIB, were not active or open for real-time decision-making. The contractor was remote from JPL (Lockheed Martin in Denver, CO), and a significant amount of communication was through email. In some cases critical decisions were made based on an assumption that the other person got the email, read it, and acted on it.

### *Resource Management*

MCO fell into a transitional period of NASA's definition of 'better, faster, cheaper.' NASA had a few recent successes and was beginning to define what they believed was 'better, faster, cheaper' in their guidelines for project management. Up until this point, through most of NASA history the culture was, if you run into a problem, you can always go back to NASA and say, "I have a lot of problems" and more money would be provided. Over time and some visible failures, these became viewed as overruns and people's credibility on cost estimations was in question. The glory of NASA's prestigious past could not carry the institution of NASA any longer. Therefore, MCO was under extreme pressure to keep within budget, and thus performed extreme cost cutting in the projects development. Euler stated that when he entered the project around Critical Design Review (CDR) they had excessive hardware development problems and extreme weight challenges, which meant a lot of new development. This became very difficult on an already bare bones budget. Euler described,

> John (Mcnamee) and I sort of mapped out a strategy to keep the costs down, and that was the challenge at that time during the better, faster, cheaper days. Don't you dare go back to headquarters and ask for more money because you are not going to get it. We worked out a strategy that really was to make sure that we very carefully managed our resources. He was willing to spend all of his reserve to get us off. Everything was out in the open on what we had left to spend, and we managed very carefully along those lines. We had absolutely no profit to be gained on the program for the company, but I had strong company backing because this was important in getting us back into the Mars business.

Because of challenges like this, the idea of cost capped activities with the 'better, faster, cheaper' program required some additional help with regards to processes to make sure that these projects could be successful. By the time MCO was started one of those processes began to move towards mandatory, and that was the earned value management system. Earned value is based on a cost per task performance standard. While MCO made a concerted effort to implement the earned value system, the system had to be tailored from the cumbersome and detailed earned value system adopted from the defense department to something that could be done on a 'better, faster, cheaper' project. MCO was able to implement that system using the experience Lockheed Martin had building defense projects and modifying it into something that could be used on 'better, faster, cheaper' activities. This was fine for managing standard, planned resources, but MCO had difficulty with managing reserve, unplanned resources.

For MCO reserves were held and managed at as a distribution through the depth of the management structure. Each subset of work that was managed by a subsystem manager was performed based on agreements that were rolled up into a project agreement. Once these agreements were established at the beginning of the project, the reserves were established throughout the project. A subsystem manager had no flexibility because they had already established their reserves. MCO did not hold a set of uncommitted reserves at the project level, in addition to the initial set of reserves inside the work agreement for use at the subsystem level. There was very little room for error at the subsystem levels, and no room for unforeseen occurrences.

***Reducing Uncertainty***

"Mistakes are prevented by oversight, test, and independent analysis, which were deficient for MCO."

- Mars Program Independent Assessment Team Summary Report

MCO had a combination of cost, schedule, and technical requirements that were unheard of in a new interplanetary mission. To lower the technological uncertainty for MCO, there was a heavy reliance on the inheritance of technology from the Mars Global Surveyor spacecraft design. MCO used many subsystems, computers, attitude control, and propulsion technology from Mars Global Surveyor, but Euler stated that the dependence on these systems eventually became a contributing factor in the loss of the MCO. Inheritance allows for a reduction in much of the time, cost, and uncertainty in development of technology, but it does not reduce the uncertainty associated with the integration of inheritance. MCO did not perform adequate testing with all of the technology that was inherited from MGS. In addition, MCO shared development and operations with MPL. The MPIAT stated, “If efficiencies from shared development and operations are factored in, it appears that the Mars’ 98 project was under funded by at least 30 percent.” Where there was very little inheritance from any previous missions was in the navigational software, and the spacecraft configuration. Euler stated that technical management accepted a “just like MGS” argument and did not focus on the details of the software. The MPIAT stated that the navigation team was inadequately trained, did not understand the spacecraft, and did not pursue known anomalies. One of the root causes of the MCO's failure as stated by the MIB was related to the modeling of spacecraft velocity changes. Inadequate verification and validation of the software contributed to an increase in uncertainty and loss in performance. Few actions were taken to understand the uncertainty of the software. After MCO’s failure, various analysis were run that showed the high level of uncertainty related to the technology, specially with the navigation software. This analysis indicates that an extensive testing program should have been implemented to integrate the navigation software. Unfortunately, budget constraints forced a reduction to the testing program.

Without an understanding of the uncertainty, limited action was taken to reduce or address the uncertainty. Testing was limited and end-to-end validation and verification was not conducted through simulations or testing. The pressures of schedule and cost also led to some decisions not to retest critical systems or inadequate testing. Hinners said, “If you are trying to do your best to ‘guarantee success,’ at least get as high as you can, you don’t squeeze test time. Testing is critical to system integration, and finding the inevitable problems and errors that are a part of the system.” Euler stated that the full up tests that were run focused on crew certification and data path determination, and not flight product/process validation and data correctness.

***Systems Engineering***

“A very important lesson learned is to follow your standard practices rigorously and think carefully about every decision and its potential impact on mission success throughout the life cycle of the project.”

- Ed Euler, et.al. (2001), pg. 655

System engineering at the project level for a deep space mission occurs between the hardware systems (launch vehicle, payload, navigation, flight), the mission operation systems (tools, processes fly the spacecraft, return data back to Earth), and the product systems (attitude control, propulsion). Once these are designed and tested, there is extensive integration testing and software developed to support the integration. From the integrating and testing at the subsystem level, the development moves up to the integration and testing at the system level. Then once this is complete, the end product has to be tested in an operational phase. The ultimate technical failure of MCO was attributed to the integration of the navigation system. Some of the people working on the navigation system were working half time on MCO and half time on another project. These people would be working the same type of subsystem for each project while the process that each project was using was different. This was identified as causing confusion in the engineers, and resulted in engineers applying the wrong process to MCO. For MCO this was very evident in the failure relative to the navigation process that was applied based on the Mars Global Surveyor system, which was a symmetrical spacecraft, and applying that process without making adjustments or variation that are required to do the asymmetrical spacecraft of the MCO. The MIB believed that there was strong evidence that systems engineering and the systems processes were inadequate on MCO. The MIB felt that there was a lack of communication and transition between phases and subsystem operations with no one responsible for making sure these transitions occurred. In addition, it was identified that following basic standard company procedures, this error would not have been made.

### *Risk Management*

"I was looking for fault tree analysis, and I guess I was looking for risk management tools, but I do not recall seeing any evidence of them."

- Peter Rutledge, personal interview

In any project there are significant risks associated with schedule, cost, and technology. Each of these risks has a margin of error associated with it and for most projects, all or any one of these factors will slip and the project still be considered successful. For a deep space mission like MCO, the margin of error for any one of these factors is almost zero. With a fixed launch date due to celestial mechanics, the project schedule was fixed. With a fixed cost contract, the cost was fixed and any overruns meant cancellation. With a given launch vehicle and competitively selected payloads, the technical requirements were fixed and even slight changes would result in significant costs overruns. With a budget for MCO and Mars Polar Lander equal to that of Mars Pathfinder, MCO's margins were very small. The MIB later stated that MCO was under-funded by 30 percent. Ed Euler, et.al. (2001) stated,

> Many of the decisions made early in the project were later criticized by the various failure review teams as too risky, but at the time, they were consistent with 'FBC' philosophy and reviewed and accepted by NASA review boards external to the project.

The MIB stated that there was no identification of what was acceptable risk, nor was there a process for determining mission-critical elements throughout the mission. The MIB identified that not only did MCO not perform adequate risk analysis before the project started, but also there was not a continual systems analysis throughout the project to identify new or changing risks. One MIB member stated, "I was a little disappointed in what I observed that they did or did not do to try and anticipate what might go wrong." Standard methodologies for determining or questioning what might go wrong in a mission were not used (e.g. fault tree analysis, integration of the risk management with the earned value system). When threatened with risk, actions such as support groups, addition or change of personnel to be more efficient, changing the scope, or pushing back the requirements were not aggressively pursued. Traditionally at JPL, there would be a Mission Assurance Manager, who would be responsible for identifying risk and inadequacies in systems integration. They are responsible for ensuring project success or failure avoidance. This person was clearly identified as being involved during the development phase, but was not evidently involved in the operational phase of the project. This inadequacy prompted NASA to require more involvement on the part of the mission assurance people during the operational phase.

A key tool for identifying and avoiding risk is testing. The MCO spacecraft was launched without an end-to-end testing to validate critical systems of the navigation system. Some managers of MCO identified inadequate advanced planning, testing, and verification of mission maneuvers and sequences. Peter Rutledge, Investigation Lead from the Office of Safety and Mission Assurance, stated, "I guess it really was not up to the usual standards of what we would expect as far as documenting what the risks are and prioritizing them and estimating their probability and consequences. I do not think that I saw that kind of formal approach to any great extent on the project."

### *Customer Involvement*

MCO had three customers: NASA, the Science Community, and the Public. Any NASA funded project has itself as a customer. This usually is NASA Headquarters or the Program Office for which the project is being funded. For MCO it was the Mars Exploration Office at the Jet Propulsion Laboratory and the Space Science Enterprise within NASA. Other than John Mcnamee, JPL involvement was significantly less than on previous programs. In addition, one of the items that came out in the review process was that the NASA Headquarters was much less knowledgeable and involved in the program than was either desirable or historical. This was a prime factor in leading NASA to establish a separate program office for the Mars program. The review process found a lack of adequate participation by NASA in the whole process.

The second customer was the scientific community that the project supported. As a scientific mission, MCO believed that its main customer was the scientific community. While MCO believed in listening to the scientific community to determine its mission objectives, MCO involved this customer very little once the project started.

With the storied success of Mars Pathfinder, the public was very aware of the Mars 98 missions and MCO. Therefore, its failure was that much more apparent to one of MCO's customers, the public. With the public, it is the scientific knowledge, the excitement and that sense of participation that can make a space mission a success.

***Contractor Involvement***

Linkages between the project and contractors were limited and faint. This was most noticeable in the acquisition and oversight of contracted software development. MCO identified a lack of control and effective processes for acquisition of contractor-developed, mission critical software. The main technical failure of MCO, metric to English units, was a failure in the communication between the government and the contractor.

## Tools

For MCO there were no unique tools used to manage the project. The one tool that was used by MCO, is used by many NASA space science projects, and unique to NASA is Earned Value Management (EVM). EVM is a standard NASA way of running planetary flight projects and performance metrics. EVM is based on a set of project tasks, and each task has a cost to complete and/or items to procure. Each task and procurement has a schedule for completion, and as each one is completed a monetary credit is assigned. These credits are then graphed against how much money has been spent thus far on the project to determine where project progress follows on the curve.

### *Knowledge Management*

Decisions were made at very high level in the organization and information did not readily flow down through the organization. The MIB believed that systems engineers did no possess the skills to fully employ the subsystem engineers and thus the communication lines were weak and thin.

### *Lessons Learned*

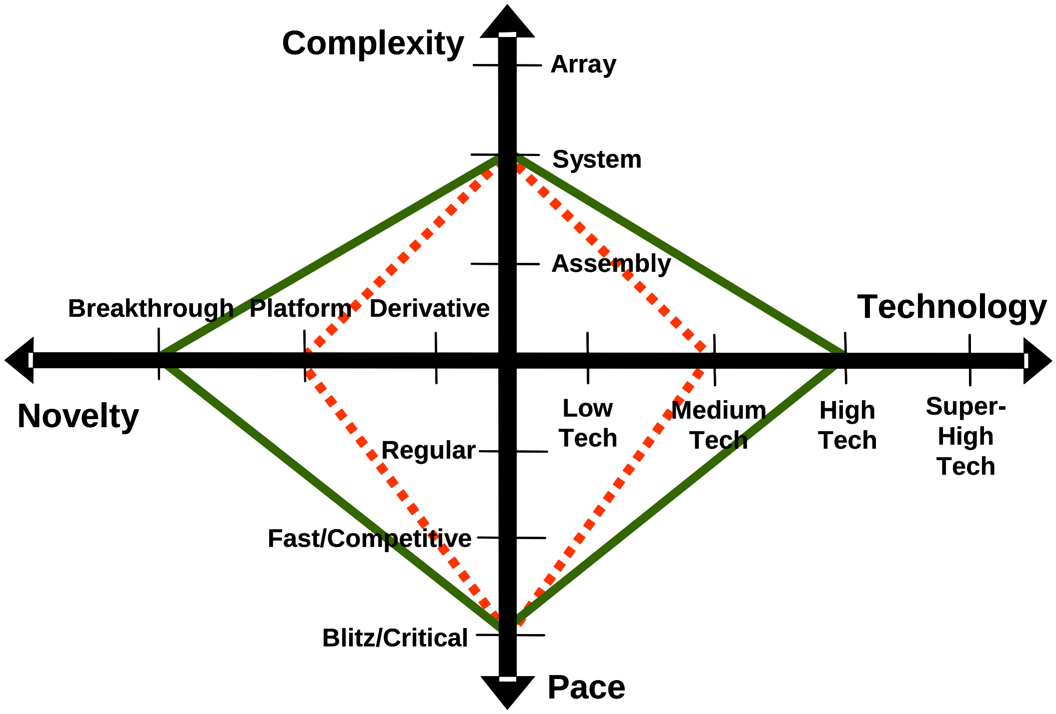
Traditionally JPL is known for there commitment to lessons learned. JPL has always been good at documenting and using lessons learned for its projects, and JPL uses lessons learned more than any NASA center. As a result of the failure, there are more documented lessons learned from MCO than most other projects within NASA. But this was only the result of a failure that resources were allocated after the fact to document lessons learned. One manager described the documenting of lessons learned as “very poorly done across the board.” If not for the failure, many of the lessons learned would have gone undocumented. Even with all of the lessons learned documented from MCO, Hinners describes some as “dead on arrival,” because are so specific that circumstance would never repeat again. The challenge as Hinners described, was that, “An engineer would not sit down and go through a thousand lessons learned on a database, particularly in the heat of a project. Second, there is no funding to do the job right.” Hinners stated that on MCO and other projects there is never funding to support capturing and utilizing lessons learned. Lockheed Martin did not have funding that they put a priority lessons learned. Hinners said that a lot of the lessons learned do not come during the development, but during operating a mission and the lessons learned process ends before operations, which is when MCO failed.

### Adapting Project Management to Project Type

"There is a fine line between success and failure in these one-of-kind missions."
- Ed Euler, et.al. (2001), pg. 655

Mars Climate Orbiter (MCO) was a strategic project as NASA and JPL were beginning to build a sustained position in Mars exploration with recent successes of Mars Pathfinder and Mars Global Surveyor. MCO would build upon those successes, and lay the groundwork for several planned Mars exploration missions over the next 15 years. MCO fully understood the project's implications and the impact of a successful project. The task outcome for MCO was a tangible product of a spacecraft, orbiter, and scientific instruments centered around an intellectual activity. MCO required a significant level of insight and creativity both technically and managerially, built around a core of talented, experienced people to produce a valued product, but cost constraints forced these requirements to be compromised. MCO was two projects on a single project budget with extreme pressures from their internal customer. The pressures of being successful in the new era of BFC directed MCO in making sure that there internal customer would be pleased, which resulted in compromising key issues and losing sight of the needs and communications with their external customer. MCO lacked framework that could help understand the fit that is needed between the project management style and the project risks. It was forced to work under constraints that were impossible to achieve under the combined requirements of 'better, faster, cheaper' and high project risk.

The NCTP Model below represents the analysis of MCO in respects to its Novelty, Complexity, Technology, and Pace. Connecting the NCTP classification with a straight line to form a diamond, gives a representation of the level of risk associated with a project. The greater the area of the diamond, the greater the degree of risk. Also presented in the model, is how MCO differed in its level of risk and how the project assumed a lower level of risk. While there is not a linear relationship between the area of the diamond for correct and incorrect project risk, it does represent a difference in the degree of risk.




*Novelty*: MCO was a new-to-the-world product that developed a new use for a product that NASA had not seen before. This defines MCO as a breakthrough project. As the first in a series of Mars missions, MCO was to integrate some mature technology into a new and untested spacecraft. Although NASA had been successful with recent missions to Mars, not one successful mission had been repeated. Each mission to Mars, even if using similar, proven technology from past missions, had some degree of unproven technology and was a new venture to the Red Planet. MCO was no exception. With only a few successful missions to Mars (Mariner, Viking I and II, Mars Global Surveyor, and Mars Pathfinder), there was still a lot to be learned about how to enter into Martian orbit. Traveling to Mars still incorporated a lot of calculated risks, intuition, and trial and error. MCO would require fast prototyping, late design freezes, and constant interactions with their customers.

Unfortunately, the cost constraints of MCO forced MCO to be managed and designed as a platform project. Using some proven technology and the history of NASA and JPL's successfully missions to Mars, the strategy on MCO was that of a new generation in an existing product family. MCO had minimal technological success to build on. While MCO used some of the proven technology from the Mars Observer and Mars Global Surveyor, only the Mars Global Surveyor had been successful. Fast prototyping was compromised by inadequate testing and streamlined reviews. For example, the navigation software system was the most novel and uncertain of all the systems on MCO, but received no more testing or review than any other system. In addition, the interaction with customers was less than optimal and sometimes defined as "confusing."

*Complexity*: As a very complex interaction of subsystems and elements performing multiple functions, MCO was a system project. In addition to its own complexity, MCO was designed to work with the Mars Polar Lander when it arrived at Mars. MCO had multiple key customers from industry, public, government, and the scientific community that were all vested in MCO's development and success. As a systems project MCO was a complex project that required extensive planning, computerized tools and software, hundreds or thousands of activities, tight and formal control, financial and schedule issues, reviews with customers and management, and extensive documentation.

MCO was managed with its main contract under JPL and the Mars Surveyor '98 office, and several smaller subcontracts to complete the development. The control on MCO was formal with standard reviews, but not tight. Management worked to empower the subsystem engineers so they did not play an integral role in overseeing the project integration. This was reflected in reviews, and control of technical, financial, and schedule issues. A reduction in these areas as a result of cost constraints resulted in limited control of the subsystem integration and the absence of adequate end-to-end verification and validation through reviews. While much of the project was treated as a system, certain subsystems with high levels of uncertainty were managed as assembly projects (i.e. navigation). Key people were balancing time with multiple projects, and working the same type of subsystem for each project while the process that each project was using was different. This was compounded by a lack of communication and transition between phases and subsystem operations. Inheritance from past systems was assumed to reduce the uncertainty, but it did not reduce the uncertainty of integration. Key to any system is an understanding of the impact change and risk has on any subsystem. To treat any part of a system as an assembly is to treat the entire system as an assembly.

*Technology*: MCO was a high-tech project that used a mixture of existing and new technology. Much of the technology on MCO had been developed prior to the project's inception and building an orbiter spacecraft was not new, but MCO was the first of its kind. MCO required long periods of design, development, testing, and redesign with multiple design cycles that had to start before the project started. With the extensive testing that was required for a high-tech project like MCO, in depth, technical reviews were mandatory to make a project of this complexity successful. In conjunction with these reviews, communication had to be frequent and active. The complexity and communication demands required management to be of good technical skills and intimately involved in the project. They also had to recognize the unique challenges of MCO and be flexible to extensive testing and design changes. Therefore, design freezes had to be scheduled and as late as possible.

MCO more than any other project was under extreme pressure to push the boundaries of BFC. These pressures, constraints, and challenges limited MCO ability to fully recognize it technological challenges, thus MCO was managed more as a medium-tech project. There was not enough testing, reviews, communication, or technical skills to manage a high-tech project. Because of budgetary constraints, many of these key elements to managing a high-tech project were reduced to meet cost and schedule, while some were just overlooked. The dependence on inheritance systems (i.e. navigation) eventually became a contributing factor in the MCO failure. While inheritance allowed for the reduction in time, cost, and uncertainty in development, it did not reduce the need for extensive testing and review of the systems integration. MCO was treated as a "just like MGS" spacecraft, and with a good framework to understanding of the uncertainty, limited action was take to reduce the risk. Testing, verification, and validation were reduced, and sliding design freezes. Because of budgetary constraints, management left no room for error or the ability to be flexible to design changes. In depth, technical reviews were streamlined and nominal. Peer reviews had insufficient resources, could not aggressively seek experts in the field, and did not have peers as an integral part of the project.

*Pace*: MCO was a blitz-critical project. Time was critical for project success, and delays meant project failure. The project team had to be specifically picked for MCO and they were considered a special group trying to achieve a rapid solution to a vital project. The MCO team truly felt the pressure of MCO's project schedule, sometimes working 100-hour weeks to stay on schedule. Procedures had to be shortened, made simple, and non-bureaucratic, while top management had to remain highly involved and constantly supportive.

### Success Factors

MCO understood the impact of a successful mission, and approached the project with a drive and commitment to be successful. Management brought to the project what they believed were the keys to being successful in a cost constrained environment. Factors that may have contributed to MCO's prospective success were:

- Strategy
  - Customer defined objectives
  - Modest and attainable objectives
  - Clearly defined success dimensions
  - Competitive selection and understanding of competitive advantage
- Spirit
  - Focused, unspoken, common commitment to mission success
  - Team empowerment
- Organization
  - Co-location
  - Limited involvement from top-management, but strong commitment

Most space science missions are based on a customer-defined need. MCO was no exception. The scientific community is always requesting more data and they clearly articulate what they need. MCO listened to this customer to define their project objectives, and like other successful BFC missions, kept the objectives modest and attainable. Defining project success on clearly defined objectives made sure that MCO understood what would classify it as successful, and there was no question by anyone on the project what constituted success. By selecting Lockheed Martin as the lead contractor through a very competitive review process, JPL was able to team with a proven company that clearly understood their competitive advantage.

MCO's spirit was described as unmatched by any other project. Team members were deeply rooted and devoted to MCO and its success. There was a strong sense of ownership from every team member, and this made team empowerment a natural and easy process for management. As an organization all key subsystems were co-located for MCO. Even some JPL management relocated to Lockheed Martin for the project. Decisions could be made real-time. In conjunction with co-location, not having an aggressive involvement from top management allowed MCO to move quickly on making key decisions and overcoming some obstacles in the decision process.

### Recommendations

The MIB identified eight contributing factors for the cause of the MCO failure. Of these eight contributing factors, three dealt with the technical and five dealt with project management issues. Based on these eight contributing factors, the MIB provided ten recommendations and observations, eight were management related and two were technical. Even with the MIB's extensive review, Ed Euler, Steve Jolly, and Lad Curtis stated, "The causes and corrective actions were well documented, however, these reports did not capture inner workings of the projects and the subtle things that happened that eventually led to the failures."

**Recommendation 1 – Design to capabilities, not cost:** MCO as a standalone mission was a complex project. Combined with MPL as one project (Mars 98), MCO could not be considered a small mission by anyone's standards. Unfortunately, NASA held Mars 98 to the same expectations as other successful, much smaller BFC missions. With a budget that did not match the project's complexity or size, MCO was designed to cost. Management approached the project and all components with a cost constrained strategy. Cuts were made in areas that later proved to be key and contributed to MCO's failure. Because of cost constraints, peer reviews were de-emphasized, there was not an active involvement from experts, dual development was used on subsystems for multiple missions, the number of people on the project was kept below minimum, and testing was streamlined in key areas. Designing to capabilities may have revealed that this project could not have been done under the specified budget.

**Recommendation 2 – Understand the technical uncertainty to apply the right management approach:** With cost constraints creating more of a reliance on past missions, a reliance on past systems created a false sense of confidence in the team's ability to understand and integrate the subsystems. Assumptions were made about how systems from previous missions would integrate into MCO. Some even defined this as arrogance, which created blindness to the technical uncertainty of the systems and the level of testing.

**Recommendation 3 – Know the critical link in the subsystem integration:** There was not enough resources, contingency funds, expertise, testing, or technical peer review with relation to the integration of subsystems and how the system will function from end to end. Fundamental to general systems theory are four basic assumption: (1) the sum is greater than the parts and there are consequences for not understanding the dynamics of each part, (2) there is multi-lateral causality between subsystems, systems, and the environment they function in; (3) one set of initial conditions can give rise to different final states; and (4) there is concern with the flow of information between subsystems (components).[1] The fact that a significant subsystem (navigation) and the integration of the subsystem carried a high level of uncertainty should have raised the level of awareness and concern of the technological uncertain and risk associated with the project.

**Recommendation 4 – Avoid overconfidence from past success:** NASA and JPL really believed they were hitting their stride with Mars exploration and BFC at the time of MCO. They had a number of BFC successes and MCO was supposed to be the beginning of a series of Mars exploration missions. NASA was confident that they could push BFC even father, but had not yet developed a clear understanding or framework of how and why those other projects were successful. For example, the success of Mars Pathfinder was well documented, but how these success principles applied to other projects was not yet been well understood or studied.

**Recommendation 5 – Build a policy that supports the strategy and know its impact:** One of the characteristics of BFC was the ability to tailor, reduce, or create policy to help manage a project. In order to alter policy, management has to clearly understand how that policy impacts the project. Because of extreme pressures to be successful under BFC, MCO reduced key policy directives that later had a key impact on the project.

**Recommendation 6 – Build a team with a mix of experience:** MCO was charted with accomplishing two projects with the budget of one and an organization the size of two. This limited MCO's ability to attract and secure a good mix of experience and expertise across the project. Repercussions of this were inexperienced team members leading key subsystems, limited oversight from experienced team members, and not enough advice from experts on some of the subsystems.

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[1] Ruben, B.D. and J.Y. Kim. (1975). *General Systems Theory and Human Communication*. Rochelle Park, NJ: Hayden Book Company.

**Recommendation 7 – Build the project spirit, starting with a vision that will be exciting and inspiring, and build the project culture to support the vision:** No matter how high the spirit, it still needs to be managed. MCO was described as very high spirited and committed to success. Management stated that motivating the team was the least of their concerns. By not managing the spirit and drive of the team, they ended up with too much of a good thing. Team members worked themselves too hard, resulting in lack of concentration at times, not enough time to think about the decisions they had made, and an extreme level of confidence.

## APPENDIX E - CURRICULUM VITAE

**BRIAN J. SAUSER**

Place of Birth: Texas City, TX
Date of Birth: November 8, 1970
Marital Status: Married

## EDUCATION AND TRAINING

Ph.D., Technology Management, 2005
Stevens Institute of Technology – Hoboken, NJ
Dissertation: *Assessing NASA Strategic Project Leadership in an Era of "Better, Faster, Cheaper"*
Advisors: Dr. Aaron Shenhar and Dr. George Korfiatis
M.S., Bioresource Engineering, 1998
Rutgers, The State University of New Jersey – New Brunswick, NJ
Thesis: *Modeling the Effects of Air Temperature Perturbations for Control of Tomato Plant Development*
Advisor: Dr. Gene Giacomelli
B.S., Agricultural Development with an emphasis in Horticulture Technology, 1993
Texas A&M University (TAMU) – College Station, TX

Technology Assessment, 2002
Robert C. Byrd National Technology Transfer Center – Kennedy Space Center, FL
Commercialization and Marketing Technologies, 2002
Robert C. Byrd National Technology Transfer Center – Kennedy Space Center, FL
NASA Advanced Project Management Training Program (APM-43), 2000
NASA Academy of Program and Project Learning – Wallops Island, VA

## PUBLICATIONS

Sauser, B.J., A.J. Shenhar, and E.J. Hoffman. (2005). "Identifying Differences in Space Programs." Accepted to PICMET 2005. Portland, OR.

Sauser, B.J. (2005) "Using Self-Assessment to Evaluate the Effectiveness of an Engineering Management Course with Cross-Functional Teams." Accepted to the 2005 American Society for Engineering Education Annual Conference and Exposition. Portland, OR. Paper No. 2005-197.

Sauser, B.J., J.W. Quinn, and A. Helminger. (2004). "Environmental Remediation Technologies Derived from Space Industry Research." 34th International Conference on Environmental System. SAE Paper No. 04ICES-066.

Rodriguez, L., B.J. Sauser and K.C. Ting. (1999). "Information Flow Analysis of the Lunar Mars Life Support Test Project." 29th International Conference on Environmental Systems, Denver, CO. SAE Paper No. 1999-01-2046.

Sauser, B.J., G.A. Giacomelli, P.P. Ling. (1998). "Development of the Basis for an Automated Plant-based Environmental Control System." 28th International Conference on Environme Systems. SAE Paper No. 981551.

Sauser, B.J., GA. Giacomelli, and H.W. Janes. (1998). "Modeling the Effects of Air Temperature Perturbations for Control of Tomato Plant Development." Second International Symposium on Models for Plant Growth, Environmental Control and Farm Management in Protected Cultivation. *Acta Horticulturae.* 456:87-92.

Giacomelli, G.A., B.J. Sauser, P.P Ling, D. Li. (1997). "Automated Machine Vision Monitoring and Feedback Control of Plant Growth." American Society of Plasticulture.

Sauser, B.J. (1997). "Investigation of the Effects of Temperature Perturbations on Tomato Plant Development." Proceeding of the Northeast Agriculture and Biological Engineering Conference (NABEC) of the American Society of Agriculture Engineers. Paper No.: 9712.

Sauser, B.J. (1991). *Assessment of the Production Efficiency of the Hydroponics Garden at Fiesta Mart*. NASA Document: JSC-25349. National Aeronautic and Space Administration, Johnson Space Center: Houston, TX

**PRESENTATIONS**

"Environmental Remediation Technologies Derived from Space Industry Research." July 2004. Sauser, B.J., J.W. Quinn, and A. Helminger. 34th International Conference on Environmental System. Colorado Springs, CO.

"Strategic Systems Innovation: A Case Study of Mars Pathfinder." February 2003. Seminar for the Stevens Project Management Research Forum. Hoboken, NJ.

"The NSCORT Experience: Bringing Tomorrow's Frontiers into Today." July 1999. Invited Lecturer for the Space Life Sciences Training Program, Kennedy Space Center, FL.

"Information Flow Analysis of the Lunar Mars Life Support Test Project." July 1999. Rodriguez, L. and B.J. Sauser. 29th International Conference on Environmental Systems, Denver, CO.

"Bringing Tomorrow's Frontiers into Today: from Exploring to Terraforming Mars," February 1999. Invited Lecturer at Workshop '99: Attitudes for the New Millennium, Texas A&M University, College Station, TX.

"Development of the Basis for an Automated Plant-based Environmental Control System." July 1998. 28th International Conference on Environmental Systems. Boston, MA.

"Mission to Mars." May 1998. Keynote speaker: Eco-Living Festival- Mission Possible. Westampton, NJ

"Modeling the Effects of Air Temperature Perturbations for Control of Tomato Plant Development." August 1997. Second International Symposium on Models for Plant Growth. Environmental Control and Farm Management in Protected Cultivation. Wageningen, The Netherlands.

"What Temperature Do You Really Want? Getting the Most out of a Growth Chamber." July 1997. Association of Education and Research Greenhouse Curators Annual Meeting. New Brunswick, NJ.

"The Use of a Logistic Plant Growth Model for Prediction of Tomato Plant Development Based on Air Temperature." October 1996. Department of Bioresource Engineering. New Brunswick, NJ.

"Modeling the Effects of Temperature Perturbations on Tomato Plant Development." July 1996. Annual Meeting of the Center for Controlled Environment Agriculture. New Brunswick, NJ.

"An Approach to the Investigation of Temperature Perturbations on Tomato Plant Development." July 1996. Seminar given to the Advanced Life Support Program at NASA-JSC. Houston, TX,

"Investigation of Temperature Perturbations on Tomato Plant Development in Support of the NJ-NSCORT Program." June 1996. NE-164 working group of the American Society of Agriculture Engineers. Atlantic City, NJ.

**TEACHING AND CURRICULUM DEVELOPMENT**

*Advanced Life Support Systems – Undergraduate Capstone Course (11:015:418)*
*Developer and Instructor, 1998-2001*
Rutgers, The State University of New Jersey

*Environmental Systems Analysis for Engineers (11:127:495)*
*Guest Lecturer, 1999-2001*
Rutgers, The State University of New Jersey

*Eco-Lab Space Program*
*Program Director, 1996-2001*
Science and Math Curriculum for Grades 5-8

**APPOINTMENTS**

NASA Advanced Life Support Education and Outreach Working Group, Secretary, 2001-2002
NASA Spaceflight and Life Sciences Training Program, National Recruitment Coordinator, 2000-2002
4th International Life Support and Biosphere Science Conference, Program Coordinator, 2000
NASA Advanced Life Support Education and Outreach Working Group, Chair, 2000

**GRANTS AND AWARDS**

*Building a Strategic Systems Approach to NASA's Project and Program Management, 2004*
NASA USRA CPMR Phase 1; A.J. Shenhar, et.al.; $75,000
Investigator
*Faster, Better, Cheaper Management: A Case Study of NASA's Strategy- Concepts, Lessons, and Future Recommendations, 2000-01*
Center for Technology Management Research; A.J. Shenhar and B.J. Sauser; $8,000
*Spaceflight and Life Sciences Training Program, 2000-02*
National Aeronautics and Space Administration; $51,400
*Academic Professional Excellence in Academic Innovation and Creativity, 2000*
Cook College, Rutgers, The State University of NJ; $1,000
*Graduate Assistantship, 1996-97*
New Jersey-NASA Specialized Center of Research and Training; Rutgers, The State University of NJ
*Graduate Assistantship, 1995-96*
Center for Controlled Environment Agriculture; Rutgers, The State University of NJ

John F. Kenney Space Center Certificate of Appreciation, 2004
*In recognition of key contributions to the establishment of the Spaceport Research and Technology Institute.*
John F. Kenney Space Center Certificate of Appreciation, 2003
*For exceptional support of the 2002 Environmental Cleanup Technology Industry Briefing*
KSC Center Director's Gold Dollar Award, 2003
*In honor of commitment to safety, teamwork, innovation, and willingness to go above and beyond normal job requirements*
American Institute of Aeronautics and Astronautics Space Coast Chapter Medal of Appreciation, 2002
Dynacs Exploration in Excellence Team Award, 2002
Rutgers University Award for Academic Innovation and Creativity, 2000

**PROFESSIONAL ORGANIZATIONS**

Academy of Management
IEEE Engineering Management Society
IEEE Communications Society
Society of Automotive/Aerospace Engineers

## PROFESSIONAL EXPERIENCE

*Research Assistant Professor*
Stevens Institute of Technology, Hoboken, NJ, 1/05-present

*Account Manager/Technology Transfer Agent*
ASRC Aerospace, Kennedy Space Center, FL, 3/03-12/04

- Negotiate and assist in the development of industry partnerships, licenses and Space Act Agreements (cooperative agreements) for Kennedy Space Center
- Cultivate invention disclosures in environmental science, biological science, data acquisition, instrumentation, and wireless systems at various stages through the commercialization process.
- Provide strategic management support to the university-affiliated Spaceport Research and Technology Institute.
- Provide assistance in the development of the University Spaceport and Technology Development Contract metrics and refinement of processes.

*Project Administrator/Technology Commercialization Agent*
Dynacs Corporation, Kennedy Space Center, FL, 3/02-2/03

- Negotiated and fostered over 15 partnerships, licenses and Space Act Agreements for Kennedy Space Center.
- Cultivated over 100 invention disclosures at various stages through the commercialization process.
- Developed and implemented industry focused marketing strategies for Kennedy Space Center developed technologies in environmental science, biological science, data acquisition, instrumentation, and sensors.

*Senior Program Administrator*
*New Jersey – NASA Specialized Center of Research and Training (NJ-NSCORT)*
Rutgers, The State University of New Jersey, New Brunswick, NJ, 9/97-3/02

- Managed the operations of a $5.2 million, multi-institutional research center (New Mexico State University, Ohio State University, Rutgers University, Stevens Institute of Technology, Tuskegee University, Utah State University).
- Developed and implemented multi-institutional, collaborative research and technology programs aligned with NASA strategic plans.
- Fostered a synergistic relationship between NASA engineers and scientists and university researchers.
- Directed the integration and application of 20 different projects in 5 multi-institutional research and technology programs.

*Scientist, Associate*
G.B. Tech Science and Engineering, Houston, TX, 12/93-8/95

- Managed laboratory budgets and personnel for the NASA-JSC Advanced Life Support Laboratory.
- Directed over 15 applied research and technology development projects.
- Responsible for the investigation, study, analysis and reporting of all laboratory operations.