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Toward Mission Assurance: A Framework for Systems Engineering Management

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ABSTRACT

From its inception, NASA has pushed the boundaries of science and engineering and prided itself on knowing how to manage these engineering innovations. 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. Too often attempts to resolve errors in these areas are through technical solutions when the root cause is managerial failure. The purpose of this paper is to illustrate the value of using a systems engineering management framework based on a contingency approach for associating a correct management style to a project classification, thus reducing the ultimate failure point (i.e. managerial error). Shenhar and Dvir's Novelty-Complexity-Technology-Pace (NCTP) framework was used as a representative framework to provide an empirical analysis of four noted NASA projects. The NCTP framework uses a contingency approach to provide a multidimensional categorization of projects based on their novelty, complexity, technology, and pace with a correlation to an appropriate management style. The paper will conclude with a discussion of how a contingency framework can have implications on NASA and systems engineering. © 2006 Wiley Periodicals, Inc. Syst Eng 9: 213–227, 2006

Key words: case study; contingency theory; systems engineering management

1. INTRODUCTION

Historically, NASA projects have been difficult, large ventures that inevitably carried high costs. What re-

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sulted 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. Large systems projects 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]. The knowledge base of large systems projects is limited in the area of project management and systems engineering. There is limited theory on how these projects develop and are managed. This need for management theory has become even more important as there has been increasing attention on large systems projects in the economic activities of firms, industries, and nations [Hansen and Rush, 1998]. 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.

In NASA's long history, it has conducted numerous projects of various kinds, but its most noted has been in the development of large systems (e.g., Apollo, Space Shuttle, Mars Pathfinder). However, with the recent loss of the Space Shuttle Columbia, NASA has had to take a concerted look at how it manages these types of projects. The *Columbia Accident Investigation Board Report, Volume 1* (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 [CAIB, 2003]. The CAIB would later state that one of the root causes in the Space Shuttle Program failures was a "mischaracterization of the Shuttle as operational rather than developmental" [CAIB, 2003: 9]. The NASA guidelines and requirements on project management (NPR 7120.5C) do not address characterization differences among projects and the ways they should be managed. These challenges are not unique to NASA as other government agencies documentation and guidelines have endeavored to address the developments of management frameworks for characterizing and managing projects. For example, the U.S. Federal Aviation Administration (FAA) in cooperation with the U.S. Department of Defense has developed an integrated model as an "effective and efficient framework to guide process improvement efforts" [Ibrahim et al., 2004]. Key to the FAA model is the construct of application areas. An application area classifies related application practices that are deemed necessary for accomplishing the essential outcomes distinct to the application or discipline. These application areas provide a guide for distinguishing which identified process areas and practices in a reference model need to be put into practice to concentrate on the purpose of the application area. Within NASA, in spite of several attempts and suggestions, there is still no agency-wide framework for distinction among projects, and differentiating the systems engineering management principles in these projects. Additional investigations have also suggested that the two Space Shuttle accidents or other project failures were the result of incorrect management style used in these projects [Dimitroff, Schmidt, and Bond, 2005; Guthrie and Shayo, 2005; Griner and Keegan, 2000; Shenhar, 1992].

The purpose of this paper is to illustrate how a systems engineering management framework can use a contingency approach to identify the appropriate management style for a project and thus reduce the potential risk of managerial error in a project. A contingency approach analyzes an appropriate fit between project characteristics and project type to define a managerial approach or style. To show the potential impact of this contingency approach, Shenhar and Dvir's [2004] NCTP (Novelty-Complexity-Technology-Pace) framework was used as a representation of a systems engineering management framework that uses a contingency approach. The NCTP framework provides a multidimensional categorization of projects based on their novelty, complexity, technology, and pace with a correlation to an appropriate management style. A case study methodology was used with the NCTP framework to analyze four NASA projects. This paper will use this analysis to describe the managerial error of one of the projects in detail (i.e., Comet Nucleus Tour), and show how it defined the managerial approach to the other three projects (i.e., Mars Pathfinder, Lunar Prospector, and Mars Climate Orbiter). I will conclude with an explanation of how a systems engineering management framework, using a contingency approach, can have implications on NASA and the discipline of systems engineering.

2. CASE OVERVIEWS

Comet Nucleus Tour (CONTOUR) was proposed during the original Announcement of Opportunity (AO) from the Discovery Program, but this proposal was not selected, and did not even make it past the first round of selections. Between that AO and the next AO, a complete revamp of how CONTOUR would work as a mission and how close it would fly by the nucleus was performed. One of the most significant changes, that later would became the focus of its technical failure, was the use of Earth swing-bys which resulted in integrating the solid rocket motors (SRM) with the spacecraft. Proposed by Cornell University as a principal investigator (PI)-led mission, CONTOUR would be a joint project between Cornell University and Johns Hopkins Applied Physics Laboratory (APL), along with 14 other university, government, and industry co-investigators. Cornell led the science and APL led the spacecraft development. APL had a string of successes with the most recently noted being the Near Earth Asteroid Rendezvous (NEAR). With a budget of $159 million, CONTOUR was scheduled to fly within 60 miles of three comets. The team was feeling confident with the complexity of CONTOUR that would make it another Discovery Program success and erase the negativity NASA was receiving from two Mars failures (Mars Climate Orbiter and Mars Polar Lander).

CONTOUR was scheduled to initiate a SRM burn to accelerate the spacecraft and place it on a heliocentric trajectory toward Encke (its first comet encounter). While operations continued based on the assumption that the firing took place on schedule, shortly after initiation of the burn, no signal was received from the spacecraft. A few days later, 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 the next few months, and the mission was declared officially lost after these attempts showed no signs of success. NASA established a Mishap Investigation Board (MIB) to review the circumstances and potential lessons learned from CONTOUR. The Board concluded that the probable cause was a failure in the integration of the SRM, but was unable to determine with certainty the root cause due to the lack of data during the SRM firing.

The additional three cases are summarized in Table I. Combined, these four case were chartered under NASA's "faster, better, cheaper" (FBC) mantra and represented the maturation of this initiative. These cases represented a challenging time in the development of a new management initiative in NASA and some failures and successes of these types of projects.

3. THEORY FOR A SYSTEMS ENGINEERING MANAGEMENT FRAMEWORK

Although there are texts and guidebooks written on project management and systems engineering 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, 2001]. What is traditionally not well defined is the complex activity of a project and how this activity is managed. In spite of a growing use of project management and systems engineering as a practice, most of the classical studies have often advanced knowledge in a single focused area. In the most recognized project management professional society, Project Management Institute (PMI), they have fostered and developed a classical project management process for all projects [PMI, 2004]. For systems engineering, the International Council for Systems Engineering (IN-

Table I. Case Overviews

Mission	Description	Outcome
Mars Pathfinder	A single vehicle (lander), with microrover and several instruments designed to demonstrate a low-cost system for cruise, entry, descent, and landing on Mars.	Success – Was marked as one of NASA's most historic and accomplish successes since the first Space Shuttle launch.
Mars Climate Orbiter (MCO)	A single spacecraft that would operate in Mars' orbit collecting weather data from Mars and act as a relay station for Mars Polar Lander.	Failure – A failed coding of metric units in the ground software file resulted in the spacecraft buring up during Martian orbit insertion.
Lunar Prospector	A spin-stabilized spacecraft designed to map the surface composition and magnetic field of the Moon.	Success – 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.
CONTOUR	A single spacecraft and six scientific instruments designed to provide a detailed look at comets, and answer questions about how comets act and evolve.	Failure – The solid rocket motor failed when it was scheduled to accelerate the spacecraft out of Earth orbit and place it on a trajectory toward its first comet.

COSE) has likewise produced a fundamental body of knowledge on systems engineering [INCOSE, 2004]. Fundamental bodies of knowledge are essential to building project success, as is the tailoring of these practices to fit project diversity, which both of these documents uphold. However, the scope of engineering systems has changed dramatically and become a significant challenge in our ability to achieve project success [Calvano and John, 2004]. Therefore, no one approach can solve these emerging problems, and thus no one strategy is best for any one project [Drejer, 1996]. It becomes challenging to know what practices to effectively apply to these increasingly complex projects within varying domains. For instance, the management strategies for building the Space Station or designing a MP3 player can be effective and efficient, but both are very different.

PMI has recently begun to recognize the need for unique management principles for different project types with the development of government, U.S. Department of Defense, and construction extensions to the *Guide to the Project Management Body of Knowledge (PMBOK®)* [PMI, 2003a, 2002, 2003b]. These advancing concepts in management were fostered by several studies that have expressed that not only are all projects not the same but a categorization, classification, or typology system is needed with corresponding management practices and styles. Most noted in these studies are Lewis et al. [2002], who proposed a framework that showed that management styles fluctuate over time and blending of styles enhances performance; Archibald and Voropaev [2003; Archibald, 2003], who proposed project categorizes and subcategorizes as essential steps in the project portfolio management process; Crawford, Hobbs, and Turner [2004], with support from PMI, who studied project categorizations and their purposes and attributes, as used by companies around the world; and Shenhar and Dvir [2001; Shenhar, 2004], who developed a typological theory of project management and a four dimensional framework for project analysis. These studies are referenced because they approach project management with a systematic interpretation, allow for managerial decision-making in their application, take a universal, multiproject approach to project categorization, and address issues related to project complexity. However, there are few grounded research studies that use a typology matched to a project classification and management style.

The linkage of a project classification to a management style becomes decisive, as organizational errors have been shown to often be the root of failures in engineering systems [Paté-Cornell, 1990]. In Reason's [1997] *Managing the Risks of Organizational Accidents*, he contends that the engineering and management processes are the primary areas for failure factors in projects. In a study of space systems, Newman [2001] analyzed 50 space system failures from 1960 to 2000 and concluded that failure in these projects was caused by the need for "across the board systems engineering rigor." In spite of this recognized gap, projects are still failing, and routinely the failure is caused by an inability to perform rigorous project management and systems engineering practices. Furthermore, there is still confusion on the effects of these practices to organizational outcomes [Gatignon et al., 2002].

4. NCTP FRAMEWORK

Based on classical contingency theory, Shenhar and Dvir [Shenhar, 2001; Shenhar and Dvir, 1996, 2004] have proposed a typology based on an elemental foundation in contingency theory for managing different types of projects (e.g., systems projects). This typology theorizes a framework for project managers and systems engineers for the planning and execution phases of a project with a correlation to a management style that includes systems engineering principles for a systems engineering management framework. Assessing the environment and the task, a project is classified on four dimensions, and the right management style to fit to the project type. Shenhar and Dvir state that projects carry contingencies based on the four dimensions of novelty, complexity, technology, and pace, the NCTP framework. These four dimensions and the subfactors for these dimensions are defined in Table II.

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 how the four dimensions are reflected on a graph, and that connecting the NCTP classification with a straight line to form a diamond gives a qualitative representation of the level of risk associated with a project.

5. METHODOLOGY

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, 1994]. Eisenhardt [1989] states that case study research provides a conduit to go from theory to data and back to theory.. Eisenhardt describes a fundamental difference in case study research is that cases are

Table II. Definitions of NCTP Framework Dimensions

The NCTP Framework	
Novelty: How new is the product to the market: ▪ *Derivative*: Extensions and improvements of existing products (e.g. a new color option in a MP3 player; the addition of a search feature in a software program) ▪ *Platform*: New generations in existing product families (e.g. new automobile model; new commercial airplane). ▪ *Breakthrough*: Introduce a new concept or a new idea, or a new use of a product, which customers have never seen before (e.g. the first Post-it Note; the first microwave).	**Complexity:** How complex is the product: ▪ *Assembly*: A collection of components and modules in one unit, performing a single function (e.g. CD player; cordless phone). ▪ *System*: Involve a complex collection of interactive elements and subsystems, jointly dedicated to a wide range of functions to meet a specific operational need (e.g. spacecraft; cars). ▪ *Array*: Deal with large, widely dispersed collections of systems (sometimes called system-of-system or super systems) that function together to achieve a common purpose (e.g. New York transit system; air traffic control).
Technology: Extent of new technology used on the project: ▪ *Low-tech*: Rely on existing and well-established technologies (house; city street). ▪ *Medium-tech*: Use mainly existing or base technology, yet incorporate some new technology or new feature that did no t exist in previous products (automobile; appliances). ▪ *High-tech*: Represent situation in which most of the technology employed are new but nevertheless exist when the project is initiated (satellite; fighter jet). ▪ *Super high-tech*: Based on new technologies that do not exist at project initiation (stealth bomber; Apollo moon landing).	**Pace:** Project urgency and available timeframe: ▪ *Regular*: Efforts where time is not critical to immediate organizational success (e.g. community center; wetlands development). ▪ *Fast-competitive*: Time-to-market is directly associated with competitiveness, and although missing the deadline may be not fatal, it could hurt profits and competitive positioning (e.g. satellite radio; plasma television). ▪ *Time-critical*: Project completion is time critical with a window of opportunity (e.g. mission to Mars; Y2K). ▪ *Blitz*: Crisis project- Emergency or crisis project (e.g. Apollo 13; September 11, 2001).

chosen for theoretical reasons, not statistical reasons. This research used the following steps.

5.1. Case Selection and Definition

This step involved 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 a project that represented a maturation of FBC with the following attributes:

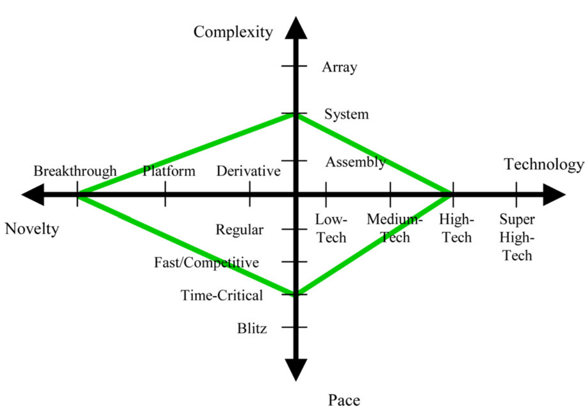

Figure 1. NCTP framework.

- Tasked to be completed under a FBC management style.
- Defined as a large systems project.
- Classified as a government or industry aerospace development project.
- U.S.-based prime contractor.
- Completed project in the last 12 years.
- Project life cycle was completed at least through launch.

5.2. Data Collection Techniques

A descriptive case study methodology was used where cases were defined by a descriptive theory (i.e., NTCP framework) [Yin, 1994]. To address any threats to validity as defined by Yin [1994], multiple sources of evidence supported by data source triangulation [Denzin, 1984; Stake, 1995; Yin, 1994] and a study protocol were established for future replication and to reduce any bias in the collection of data [Shenhar, 1999]. Data collection was performed using the following sources of evidence:

- Interviews: 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 was conducted by the prime researcher of this investigation while performing field research as an aerospace contractor at a NASA center. Six key personnel related to the project were interviewed. These people represented program management, project management, systems engineering, team members, and customer. Each interview was recorded on audiotape and transcribed.

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

5.3. Data Analysis

Data were collected in an iterative process as documentation and archival information was extensively analyzed before interviews were conducted. After each interview, data were triangulated against documentation and archival information to determine if additional data were needed from any data sources (e.g., follow-up interviews, additional documentation) before the next interview was conducted. Once the data collection and triangulation was completed for a single case, a 30–40 page case summary was written based on a predetermined case format [Shenhar]. The case summary was then coded and analyzed with the NCTP framework. This resulted in an attribute-versus-alternatives matrix [Scholz and Tietje, 2002] for evaluating the projects (e.g., an attribute in the NCTP framework would be Technology and the alternatives would be Low-Tech, Medium-Tech, High-Tech, and Super High-Tech). The cross-cases analysis followed an iterative process where the completion of a subsequent case was followed by an analysis to gain familiarity with the data and evaluate or reevaluate the proposition.

5.4. Evaluation and Discussion

Once the final analysis was complete, 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 described the results of the evaluation of the cases, provided a case analysis, and offered recommendations based on the investigations objectives and purpose.

6. NCTP FRAMEWORK ANALYSIS

6.1. CONTOUR

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. They believed that they were improving on existing products using technology and concepts from previous missions (e.g., NEAR and Stardust). CONTOUR required a significant level of insight and creativity both technically and managerially built around a core of talented, experienced people to produce a value added product. The NCTP framework in Figure 2 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 qualitative representation of the level of risk associated with the project.

Also presented in the model is how CONTOUR differed in its level of risk. The solid line represents the preferred managerial approach, while the dashed line represents the actual approach. While there is not a linear relationship between the area of the diamonds for preferred and actual, it does represent a qualitative difference in the degree of risk. Choosing the preferred

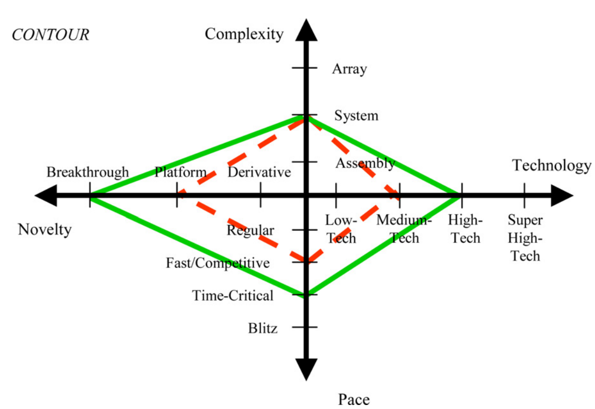

Figure 2. CONTOUR NCTP Classification.

approach in managing a project is a strategic decision that can have significant impact on a project's success, and can be just as important as time, budget, and schedule. CONTOUR represented an attempt to use the FBC approach within an organization that was founded on taking high-level risks, and while sacrificing many of the previous practices to address such levels of risk. Indeed, this reinforces what some have suggested that this culture cultivated the eventual failure of FBC (e.g., CONTOUR) and perhaps demonstrates that FBC could not be used in cases of extremely high risk. In the next sections I will discuss CONTOUR's NCTP classification in more detail.

6.1.1. Novelty

CONTOUR was a breakthrough project. At the time, 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 (key factor in a breakthrough classification). 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. Traveling to a comet incorporated a lot of calculated risks, intuition, and trial and error. In some respects, CONTOUR was new because this technology was being packaged into a new product. CONTOUR believed that they were building upon the success and technology of past missions and approached this project more as a platform 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) because seldom are they repeated. Novelty is related to a product's uniqueness to the market, and 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.

While CONTOUR may be classified as a breakthrough project, it will be discussed later how an organization such as NASA may need a fourth classification between platform and breakthrough. Table III shows the attributes versus alternatives for the novelty classification for CONTOUR and a representative statement of the distinctive factors that characterize its classification. It also indicates the preferred project management style based on project characteristics, compared to the actual style used in the project.

6.1.2. Complexity

CONTOUR was a system project that understood the integration and complexity of that integration to de-

Table III. Novelty vs. Alternatives Matrix

Novelty Attributes	Definition of Novelty Alternatives		Representative Statement
	Platform*	Breakthrough**	
Definition	A new generation in an existing product family	A new-to-the-world product	Integration into a new product with first-time-used systems; no one in history would bring a spacecraft this close to a comet.
Data on Market	Need extensive market research Careful analysis of previous generations, competitors, & markets	Non reliable market data Market needs not clear No experience with similar products	Management believed they were building upon the success and technology of past missions.
Product Definition	Invest extensively in product definition. Involve potential customers in process. Freeze requirements later, usually at mid project	Product definition based on intuition, and trial and error. Fast prototyping is necessary to obtain market feedback. Very late freeze of requirements	The confidence in the inherited technology resulted in CONTOUR waiting until late in the projects development phase to a have focused effort on systems integration.
Marketing	Create product image. Emphasize product advantages. Differentiate from competitors	Creating customer attention. Educating customers about potential of product. Articulate hidden customer needs. Extensive effort to create the standard	The scientific community played a key role in the approval of CONTOUR and its scientific goals, and maintained their involvement throughout the project.

* Indicates the actual (measured) approach. ** Indicates the preferred approach.

Table IV. Technology Attributes vs. Alternatives Matrix

Technology Attributes	Definition of Technology Alternatives		Representative Statement
	Medium-tech*	High-tech**	
Technology	Some new technology	New, but existing technologies	Significant improvements were made to the technology to develop CONTOUR from its original design.
Typical industries	Mechanical, electrical, chemical, some electronics	High-tech and technology based industries; computers, aerospace, electronics	NASA was the primary funding source with Cornell at the lead, supported by APL.
Type of products	Non-revolutionary models, derivatives or improvement	New, first of its kind family of products, new military systems (within state of the art)	Approached as a non-revolutionary improvement to past missions, and assuming a lower level of uncertainty.
Development and testing	Limited development, some testing	Considerable development and testing. Prototypes usually used during development	The inability to test the assembly of the SRM with the spacecraft did not allow for the implementation of rigorous testing; the MIB stated that there was "reliance on analysis by similarity."
Design cycles and design freeze	One to two cycles. Early design freeze, in first quarter	At least two to three cycles. Design freeze usually during second quarter	CONTOUR was basically the same spacecraft by design and budget at the time of launch as was proposed; the MIB stated that there was "inadequate systems engineering process."
Communication and interaction	More frequent communication, some informal interaction	Frequent communication through multiple channels; Informal interaction	Linkages and oversight of APL with the SRM subcontractor was defined by the MIB as "inadequate."
Project manager and project team	Some technical skills. Considerable proportion of academicians	Manager with good technical skills. Many professionals and academicians on project team	CONTOUR was a PI-Led Mission (Cornell University) supported by APL (Johns Hopkins University).
Management style and attitude	Less firm style. Readiness to accept some changes	More flexible style. Many changes are expected	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.

* Indicates the actual (measured) approach. ** Indicates the preferred approach.

velop 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 of 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, this confidence 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.

6.1.3. Technology

CONTOUR was a high-tech project. The technology was mostly proven but being 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 properly 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 one of 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. Table IV shows the attributes versus alternatives for the technology classification for CONTOUR and a representative statement of the distinctive factors that characterize its classification. It also indicates the preferred project management style based on project characteristics, compared to the actual style used in the project.

6.1.4. Pace

CONTOUR was a time-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 FBC at the time of CONTOUR built a confidence in Discover Program missions and gave the appearance that they could be managed as fast-competitive projects. While management understood that 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, inadequate risk analysis 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 FBC projects. Table V shows the

Table V. Pace Attributes vs. Alternatives Matrix

Pace Attributes	Definition of Pace Alternatives		Representative Statement
	Fast-Competitive*	Time-Critical**	
Definition	Time-to-market is a competitive advantage and has an impact on business success	Time is critical for project success. Delays mean project failure (e.g. crisis situations, war, fast response to natural disasters, fast response to business related surprises)	An inflexible launch date and any error in time or schedule meant project cancellation; team members for most of the project lifecycle worked 40-hour weeks until close to launch.
Organization	Matrix, teams, subcontractors	Pure project, special task force	While the team at APL was predominantly collocated, many of the people came from matrix organizations and thus kept to their functional organization for the duration of the project.
Personnel	Qualified to the job	Specifically picked	"What you have available is kind of your field and sometimes at APL there was only two people in the availability groupings."
Focus	Strategically focused on time to market	Swift solution of the crisis	"Even with all the testing there was still uncertainty between teams."
Procedures	Structured procedures	Shortened, simple, non-bureaucratic	"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."
Top Management Involvement	Go ahead at stages	Highly involved and constantly supportive	"My concern wasn't to make sure that somebody was putting in the right number of screws;"

* Indicates the actual (measured) approach. ** Indicates the preferred approach.

attributes versus alternatives for the pace classification for CONTOUR and a representative statement of the distinctive factors that characterize its classification. It also indicates the preferred project management style based on project characteristics, compared to the actual style used in the project.

6.1.5. Implications on CONTOUR

After the failure of CONTOUR, two independent review boards came to similar technical conclusions on the failure of CONTOUR. While the technical failure believed to be related to the ignition of the SRM and its integration with the spacecraft, this will never be able to be confirmed because of incomplete information during the launch phase. Irrelevant of the technical failure, the analysis presented in this paper indicates that CONTOUR's management style and approach did not fit a project of this classification. Therefore, the conception of CONTOUR's technical failure may not have occurred during launch and operation but during the project planning and initiation phases. While we may never know exactly why the chosen management style and approach were used for CONTOUR, it is the conclusion of this investigation and has been shown in other studies that as FBC progressed, it created pressures of working under constraints that were impossible to achieve under the combined requirements of FBC and high project risk. FBC was pushing the enveloped of doing high-tech projects cheaper, and NASA had begun to produce a line of FBC successes. CONTOUR management believed that they were building upon these successes. This may have led to a false sense of confidence by CONTOUR management based on the successes of past missions. To compound this, the implementation of the NASA Integrated Action Team's (NIAT) recommendation from their investigation of two failed FBC missions, the Mars Climate Orbiter and Mars Polar Lander, 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.

6.2. Additional Cases

Table VI shows how the analysis of the three other projects resulted in their NCTP classification and one showing an incorrect approach. In all the projects analyzed the team members interviewed said they had to modify required project management and systems engineering principles and practices to be successful. Team members used heuristics to make determinations on what to cut to meet time and budget constraints. These heuristic decisions in some cases resulted in a costly failure (i.e., CONTOUR and MCO). The analysis used by the NCTP framework showed inconsistency in the actual to preferred classification and thus appropriate management style. An analysis such as that of the NCTP framework or any applicable systems engineer-

Table VI. NCTP Classification for Other NASA Projects

Mission	Novelty	Complexity	Technology	Pace
Mars Pathfinder	**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.	**Time-Critical** Schedule, cost, and technology had limited margins with a fixed launch window.
Lunar Prospector	**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.	**Time-Critical** Schedule, cost, and technology had limited margins with a fixed launch window.
Mars Climate Orbiter	**Breakthrough (Platform*)** Integrated mature technology with a new and untested spacecraft. Cost constraints resulted in fast prototyping that compromised testing and reviews.	**System** A complex interaction of subsystems and elements that would function in Mars' orbit and with the Mars Polar Lander	**High-Tech (Medium-Tech*)** Pressures to push the boundaries of FBC affected costs, testing, reviews, communication, and technical skills.	**Time-Critical** Time was critical for project success and delays would only equal cancellation

* Incorrect managerial style applied by project team.

ing management framework may have revealed that the projects could not have been successful under the planned approach. 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 can value from a unique framework for project management and systems engineering, the exact principles to define that framework are not clear.

7. SUMMARY

7.1. Implications on NASA

These projects represented the maturation and evolution of FBC, and Perrow [1999] states that as one becomes more comfortable with a technology (in this case FBC), one is more willing to take the risks that may ultimately lead to failure. In the case of FBC, NASA continued to push projects to faster, better, and cheaper and Dan Goldin, former NASA administrator, later stated that NASA pushed the "envelope too far." Paté-Cornell [1990] stated that organizational error generally is caused by factors such as excessive time pressures, failure to monitor hazard signals, and often caused by or encouraged by rules and goals set by the corporation. 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 FBC was destined to fail over some period of time. Could a framework have obverted or delayed the failure in FBC and mitigated the risk of this type of project?

To address the risk associated with a mission, a common term in NASA for defining and mitigating risk is "mission assurance." Mission assurance is defined by the safety and enhancement of success of all NASA activities through the development, implementation, and oversight on a project. One of NASA's most pressing challenges since the loss of Columbia, and the CAIB stated since Challenger, has been in how to effectively achieve mission assurance. In any organizations these same issues related to mission assurance are defined by its ability to realize effective and efficient performance, reliability, maintainability, supportability, and process. Therefore, can a systems engineering management framework help an organization such as NASA achieve mission assurance? While it may not be able to guarantee mission assurance it can provide an objective analysis to support a mission assurance decision, and no framework should ever be the comprehensive answer to mission assurance. It was stated earlier that an effective framework could help project managers rely less on heuristics to make decisions about a project. Why this may be true, no framework will ever or should ever completely confine a project manager or systems engineer from using their heuristic knowledge.

The NCTP framework defined the projects well and could provide a fundamental framework for planning and managing projects. Currently within NASA there are few frameworks for classifying a project, and none of these frameworks makes a distinction among different project types, or how to tailor project or systems engineering management to project characteristics. Some of these frameworks, like Technology Readiness Level (TRL), classify a technology based on its developmental maturity and readiness in relation to being acceptable for launch. While TRL may give some indication as to a technology's developmental state, it does not allow for the interplay between multiple technologies, does not correlate to any specific management principles or guidelines and only indicates where you are and where you need to be, not how to get there [Mankins, 2002].

Likewise NASA's risk classification system is predominately used to make executive approval decisions by management, and not how to manage a project. This framework classifies projects into classes A to D (A equals the highest level of risk) by using criteria such as project priority and acceptable risk, national significance, complexity, mission lifetime, cost, launch constraints, and achievement of mission success criteria. At JPL the Strategic Systems Technology Program Office has developed a systematic approach for selection of NASA technology portfolios called the STrategic Assessment of Risk and Technology (START) [Weisbin et al., 2004]. START offers a systems analysis for quantifying the feature of each development system, assessing its risk, and calculating its probable return-on-investment. NASA has identified the need for a project categorization scheme, but this was not reflected in the new release of their procedures and requirements on program and project management. Some of these suggested distinctions on how to differentiate among projects are based on a maturity hierarchy for product line management with five levels, or a distinction based on investment and risk, which is based on a 3 by 3 matrix [Buschmann, 2003]. While all of these principles and practices have proven to be successful, they are not all used agency-wide on all projects, and they do not correlate the classification with an appropriate management approach.

7.2. Implications on Systems Engineering and Systems Engineering Management

This paper presented a framework that used a contingency approach to analyze an appropriate fit between project characteristics and project type to define a managerial approach or style. While a contingency approach or fit to managing projects is not new, it has not been used to understand project failure and provide the practitioner with the tools to make an informed decision on effectively managing a project. This paper aimed to show that an effective framework for system engineering management using a contingency approach could take the practitioner past heuristics and guidelines, toward understanding the results and consequences of their actions to reduce managerial error. Using a contingency approach to study project success and failure need define if a project used good or bad management, but if it was the right management to the situation, the task, and the environment. What works well in one situation may be the wrong approach in another. Since almost no project is done in isolation and most organizations are involved in more than one project, organizations would benefit from developing their own organization-specific frameworks and teach managers to adopt the right approach to the right project. Future investigations could seek additional variables of situation and management and explore richer and wider opportunities for analyzing the fit of styles.

One of the underlying contentions of this paper is that a project is a system; therefore, a framework for systems engineering management should take a systems approach. This is a fundamental reason why the NCTP Framework was used and viewed as a well-developed representation of a systems engineering management framework. Despite the advanced developments of the NCTP framework, it still does not answer all of the questions in defining the management of a system project or systems engineering management and still leaves issues unanswered such as:

- How do you know when you have correctly classified a project and how can this be verified to some level of confidence?
- How do you determine the most effective and efficient cost and resources to a project classification?
- How can a correct or incorrect classification quantitatively correlate to project risk?
- What is the consistency in using the framework among different practitioners (e.g., project managers, program managers, partners, system engineers)?
- How do you address discrepancies in a classification, and who is held accountable?
- What is the significance or impact of an incorrect classification on any single dimension?
- Do individual classifications have weighting factors?

With these questions in mind, a systems engineering management framework should be organization-specific (no project or organization is the same), maintain simplicity for a universal use within an organization, and provide two fundamental functions, definition and arrangement. Definition is the determination of classes of entities that share characteristic attributes; and arrangement involves a systematic ordering of classes that expresses conceptual relationships within the overall structure [Jacob, 1991]. The next step is the correlation of the framework to organizational practices and an appropriate managerial style.

7.3. Research Limitations and Future Directions

Despite the analysis 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 projects and systems engineering management. The sample set covered only unmanned space projects performed under the constraints of FBC. NASA's projects cover a multitude of technology developments at ten 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 did not represent all of the 144 possible project scenarios of the NCTP framework. This can cause limitations in generalizing the conclusions to other projects, not only in NASA but also across the discipline of systems engineering. This research stated that without a framework, the projects were unable to properly identify a correct approach. These projects were viewed in retrospect; therefore, the framework was imposed upon the projects. While this allowed for a more extensive data collection pool, further research would have to validate the effectiveness of the NCTP framework. A retrospective view also can create some bias in the analysis as some interpretations of the interviewees may be based on popular opinion and not objective analysis.

Finally, all four projects were classified as breakthrough products. Novelty is related to a product's uniqueness to the market, and is defined based on a comparison to the market history. NASA projects are rarely repeated and thus are almost always unique to the market. It is believed that NASA projects that are unique to the NASA vision of exploring and extending life into the universe could fundamentally not be classified as derivative. Therefore, it could be concluded that most NASA projects are breakthrough. In this study it was challenging for the interviewees to make the distinction of a NASA product based on the current definitions for product novelty, thus it may also be possible that NASA projects require a third classification between platform and breakthrough, or a refined definition of Novelty.

8. CONCLUSIONS

The failure of some of these projects to perform some fundamental project and systems engineering management practices, as identified in this study, can be identified in project failures across the discipline of systems engineering management and do not enhance our understanding of performing these types of project. The value in this investigation is the significance in being able to indicate a relationship between a framework or project classification system to an appropriate managerial style with corollary contingencies. The analysis using the represented systems engineering management framework supported the premise that despite a projects technical failure, project failure is ultimately a managerial error. The failure of almost any system can be traced back to the operator of the system (e.g., project manager, systems engineer) and rarely is independently related to the technology. Eliminating or replacing the technology does not solve the managerial problems and sometimes can even complicate them. Therefore, the fundamental value in a systems engineering management framework or any management framework is being able to correctly associate a correct management style to a project classification, thus reducing the ultimate failure point (i.e., managerial error) and risk in a system. In the academic literature and in practice, this contingency approach for project and systems engineering management is still unexplored.

9. ACRONYMS AND DEFINITIONS

APL: Applied Physics Laboratory—a division of The Johns Hopkins University—is a research and development organization dedicated to solving a wide range of complex problems.

FBC: Fetter, Better, Cheaper—a way of doing business within NASA in the 1990s, which was intended to decrease time and cost for missions and increase the number of missions and scientific return.

Discovery Program—focused on launching smaller missions with fast development times, each for a fraction of the cost of NASA's larger missions.

MIB: Mishap Investigation Board—established by NASA after a mission failure to determine root and probable causes.

Mission Assurance—defined by the safety and enhancement of success of all NASA activities through the development, implementation, and oversight on a project.

NASA: National Aeronautics and Space Administration.

NEAR: Near Earth Asteroid Rendezvous—developed by the Johns Hopkins Applied Physics Laboratory—was the first spacecraft to orbit an asteroid.

PMI: Project Management Institute—the leading project management professional discipline and the publisher of the *Guide to the Project Management Body of Knowledge* (PMBOK).

SRM: Solid Rocket Motor.

Stardust—developed by the Jet Propulsion Laboratory, Stardust was dedicated solely to the exploration of a comet, and the first robotic mission designed to return extraterrestrial material from outside the orbit of the Moon.

TRL: Technology Readiness Level—a metric/measurement system that supports assessment of the maturity of a particular technology and the consistent comparison of maturity between different types of technology.

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