

# Team Structures and Processes in the Design of Space Missions

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*Abstract*—We consider team dynamics a component of the engineering design process for space missions and explore the possibility of improvements in management of team dynamics to gain additional efficiencies.

At the conceptual level, design times have been reduced by properly defining the required design depth, understanding the linkages between tools, and managing team dynamics. Team structures such as concurrent engineering, tool linkage and a scripted team process have been demonstrated to cut concept-level engineering design time from a few months to a few weeks. Costs are substantially

Design methodologies in implementation-phase design can be revised along similar lines using a similar process. System requirements can be held in crosscutting models which are linked to subsystem design tools through a central database that captures the design and supplies needed configuration management and control. Mission goals, which may be thought of as the rough equivalent of level-one system requirements, are then captured in timelining software that drives the models, testing their capability to execute the goals. The team dynamics revolve around the use of three teams, each of which is managed in ways similar to those mentioned above.

Metrics are used to measure and control both processes and to ensure that design parameters converge through the design process within schedule constraints. Where traditional linear waterfall design methods require management of an ever-reducing margin as the design proceeds to an anticipated endpoint, the methodology described here manages margins controlled by acceptable risk levels. Thus, teams can evolve risk tolerance (and cost) as they would any engineering parameter. This new approach allows more design freedom for a longer period, which tends to encourage revolutionary and unexpected improvements in design.

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## 1. INTRODUCTION

The methodology of engineering design has undergone a revolution in the past two decades. Existing pressures to maximize performance have been joined by pressures to control costs, decrease design time, increase technology development, and others. The field of space mission design has not escaped these pressures. More recently, NASA and its contractors have even been challenged to lead US industry in this revolution. The response to this challenge has led to fundamental redesign of the space mission design process [1], and work has begun to specify an underlying architecture [2].

In this paper we very briefly summarize the space mission design process. We introduce team dynamics as applied to space missions and show how we have produced remarkable productivity increases in the conceptual design phase. Next we describe an effort underway at JPL to extend team structuring to the implementation design phase, and we present a model of that process. Finally, we use the model to predict savings in design time that can be realized through the application of team dynamics management.

## 2. FUNDAMENTALS OF SPACE MISSION DESIGN

Civil space missions are designed in two distinct phases, the conceptual phase and the implementation phase. In the conceptual phase a design is prepared for customer approval, either through a proposal process in anticipation of a solicited proposal announcement (NASA Research Announcement, Announcement of Opportunity, etc.) or as a funded sponsor study in preparation for an unsolicited mission opportunity. Conceptual designs are typically developed to some limited level of engineering depth, as specified by some stated need for accuracy of estimated cost and schedule. They are inspired by a set of science or technology goals. A traditional approach to concept development would begin with the assembly of a design team, who through a series of regular meetings or work sessions dissect the goals into system requirements on

hardware, software, operations teams and the like. These are given to designers, who may spend several weeks developing designs and providing cost information. Costs may be grass roots (developed by the designers based on costs of parts and labor), parametric (developed through a software model that uses cost of past designs as a basis and estimated from some design parameters that historically drive cost), or both.

Conceptual designs are incorporated into a proposal submitted to the sponsor for evaluation. If the design is sound and the cost acceptable, the winning proposer is awarded the job and implementation, the second design phase, begins.

As in the conceptual phase, implementation-phase designs are driven by requirements derived from goals. In the implementation phase, however, some method of managing and controlling requirements is necessary, as there are usually frequent updates. Traditionally, system requirements are captured and held in a set of documents which are parsed into increasingly lower level requirements until they are at the level where a single engineering team can design to them. As the design proceeds, requirements are either accepted or modified, and designers proceed to implement the design as soon as all requirements are accepted. This process involves testing hardware and software as it is developed, and it concludes with the integration of all elements into a whole for final testing and launch of the mission. Testing the system as a whole is seldom successful the first time, and both design errors and fabrication errors are uncovered and returned to the appropriate designer or fabricator for rework. The last phase of the mission is operations, where the system is used to carry out the science or other goals, and data is returned and analyzed.

This basic design scheme has been used for many space missions and has produced many successes. However, recent pressure to make the design process faster, better and cheaper has inspired revolutionary changes. Among these are process-based organization, model-based design [3,4], revised leadership and training, and system modeling [2,4, 5,6]. Concepts already in use in industrial systems design have also been adopted for use in space missions. In particular the concept of concurrency in teams has received attention as a significant time saver in teams [7,8,9,10,11].

Effectiveness of teams and their relationship to the surrounding organizational culture have been discussed in many environments [e.g., 12,13,14]. Methods to measure and increase innovation in teams are reviewed in [15], and specific metrics for innovation are available [16,17]. The design and measurement of teaming relationships are shown to be an important subject when improving efficiency of a human or human-machine combined process.

### 3. TEAMING IN THE CONCEPTUAL PHASE

Traditionally, conceptual studies have been produced by

small, dedicated design teams. Each proposal was produced by a unique team that developed and implemented its own unique process. Typically the teams met weekly to report status, review action items, and establish new actions and deliverables. However, the emphasis on different aspects of the design/proposal differed among the teams (e.g., cost/performance trades, ground systems/operations concepts, mechanical design, electrical design) as did the analytical tools employed to address these issues. Furthermore, since each team member served on only one or a few such teams, there was little opportunity to apply lessons learned and little incentive to develop tools and methods that could improve the capabilities of future proposal teams. In addition, since the teams were funded with internal development funds, resources were not available to develop new tools or tools that could integrate the outputs of each discipline represented on the team. As a result, analytical efforts were disjointed and not integrated with cost estimates, which were usually attempted only after the primary design variables had been specified.

Thus, both the cost and quality of the proposals generated by this process were highly dependent on the team membership, especially the team leader. Some proposals were of very high quality, others were not. The principal characteristics of this approach were as follows. First, each project was designed from the ground up by a dedicated, self-sufficient team. Each product was, therefore, unique and had the quality of being produced by hand. Second, approaches to the concept definition, the work breakdown and cost breakdown structures were likewise unique. Third, the tools used to define missions were unique and often generated explicitly for each mission. For example, a mission concept requires study of the trajectory by which a spacecraft may travel to its destination. Some trajectory options will allow a more massive spacecraft, while others may feature a shorter transit time. Software tools are required to discover options, compare them, and optimize them. Similarly, spacecraft subsystems tradeoffs require tools to manage the comparison of more powerful options against less massive ones.

#### *A New Approach*

In 1994, in recognition of the nation's changing economic and strategic environment, JPL undertook a re-engineering of our project and system engineering processes [18]. The fundamental nature of the change was from a design-to-performance methodology to one of design-to-cost, but the re-engineering team also described other desirable shifts. Those applicable to advanced studies are shown in Table 1. The applications have resulted in (1) the creation of an environment and a team to apply multidisciplinary design optimization, with full consideration of schedule, mission operations, and cost; (2) the ability to use consensus process for real-time problem resolution; (3) the creation of a set of linked tools that facilitate concurrent design by passing pertinent parameters quickly from one member to all others and eliminate the re-entry of designs between design tools; and (4) the use of cost models to quickly demonstrate the fiscal effect of major design changes while still in the concurrent environment.

**Table 1: Changes to the Conceptual Design Process (adapted from [18])**

**FROM:**

Performance-driven design  
Sequential design  
Hierarchical process  
Deferred problem resolution  
Paper data exchange  
Stand-alone tools  
Limited design-space exploration  
Zero-width interfaces  
Requirements-driven approach  
Subsystem engineering models

**TO:**

Cost-driven design  
Concurrent design  
Consensus process  
Real-time problem resolution  
Electronic data exchange  
Integrated tools  
Comprehensive design-space exploration  
Zones of interaction  
Hardware (capabilities)-driven approach  
System engineering models

The Advanced Projects Design Team, universally called "Team X," was formed from members of JPL's technical staff who had participated in previous space mission design and in the missions themselves. Functional design elements common to space missions are each represented by an engineer and a backup. Cost is included as a primary design element. A study leader orchestrates discussions, and a documentarian is responsible for capture of both design trades made, rationales for direction, etc. New mission concepts are brought to the team by individuals assigned by JPL program offices, who are considered a customer to whom the service is provided. Team X participates in three-hour concurrent engineering sessions with the study manager to develop the concept to a level of detail sufficient to proceed with a formal proposal. The customer meets with the study leader to define the basics of the idea (e. g., target planet, cost target, scope of the design effort, risk philosophy) sufficiently to allow some preliminary homework to be done.

Next, sessions are held with the full team. Team X sessions start with a description of the science objectives and how they might fit into the perceived opportunity. Through discussions with the customer, design team members derive a set of mission requirements that will meet the mission objectives as well as possible within cost.

Although each study will vary, a typical Team X session might proceed as follows: The session may begin with a team estimate of spacecraft mass and propulsion requirements appropriate to the mission type based on prior experience. Scientific observation objectives are established (e. g., images to be taken, samples to be returned), and an instrumentation complement is defined. Acquisition data rates are totaled for the instruments. An instrument pointing control requirement is determined and passed to the attitude control engineer. A data collection strategy is derived from the measurement objectives, and acquisition data rates are determined. A data return strategy is worked out and required onboard data storage is determined. After

telecommunications antenna size and pointing control requirement are calculated, the attitude control system (ACS) is sized and the ACS propellant requirement determined. Onboard computer requirements are collected and a data system is chosen.

As the various required functions are defined, preliminary allocations are made to functional elements (although the importance of correct/final functional allocation is restricted to the development of a target cost). Prototypical subsystem components (star scanners, computer processors, propulsion systems and the like) are chosen by the team consistent with the risk philosophy. Component masses and power requirements are totaled by the spreadsheet. For each component chosen, a technology readiness level (TRL) is assigned based on the maturity of the component development at the estimated launch date. Calculated power requirements are used to size the power system, and the thermal control system is defined. The refined spacecraft dry mass total is then used to calculate required propellant mass. A packaging approach is discussed and a drawing of a possible spacecraft structure is produced. The total mass and volume requirements are used to make a final choice of launch vehicle.

A preliminary mission operations concept is prepared by the information system engineer. At this early stage, the operations concept will be very high level and contain many assumptions. Developing the mission operations concept early in the study phase enables the minimization of life cycle costs as well as the determination of the effectiveness of using existing system capabilities. The earlier the mission operations concept is developed, the more leverage there is for influencing the operability of the entire mission system, including the space element. The development of the mission operations concept is most beneficial when done in parallel with the spacecraft design and there is a tight coupling between the two efforts.

An appropriate parametric cost model is chosen for the class

of mission, and selected requirements that have traditionally been strong cost drivers are fed to it. The cost model quickly produces an estimated cost and an estimate of the uncertainty in that cost based on the TRLs and other factors. This cost estimate is used to iterate design requirements and, if necessary, mission goals until the cost goal is met. Similarly, mass or power totals can be quickly iterated against a fixed cost, launch vehicle, or other fixed requirement. Importantly, broad trade spaces involving ground equipment, flight equipment, science objectives and cost can be addressed in the concurrent environment. Infusion of new technology can be balanced against anticipated schedule and cost impacts. After an agreement is reached on a design point each design engineer can provide a grass roots estimate of the cost of his/her function and those estimates totaled. Deviations of the grass roots cost from the modeled cost can then be reviewed and justified.

Team X sessions are summarized by the team members and the documentarian into a final report during the session itself, using a distributed word processor available to all positions. The final form of the design is captured in the report and into a database for later recovery. Text from the final report is made available to the customer for preparation of a proposal.

#### 4. CONCEPTUAL PHASE METRICS

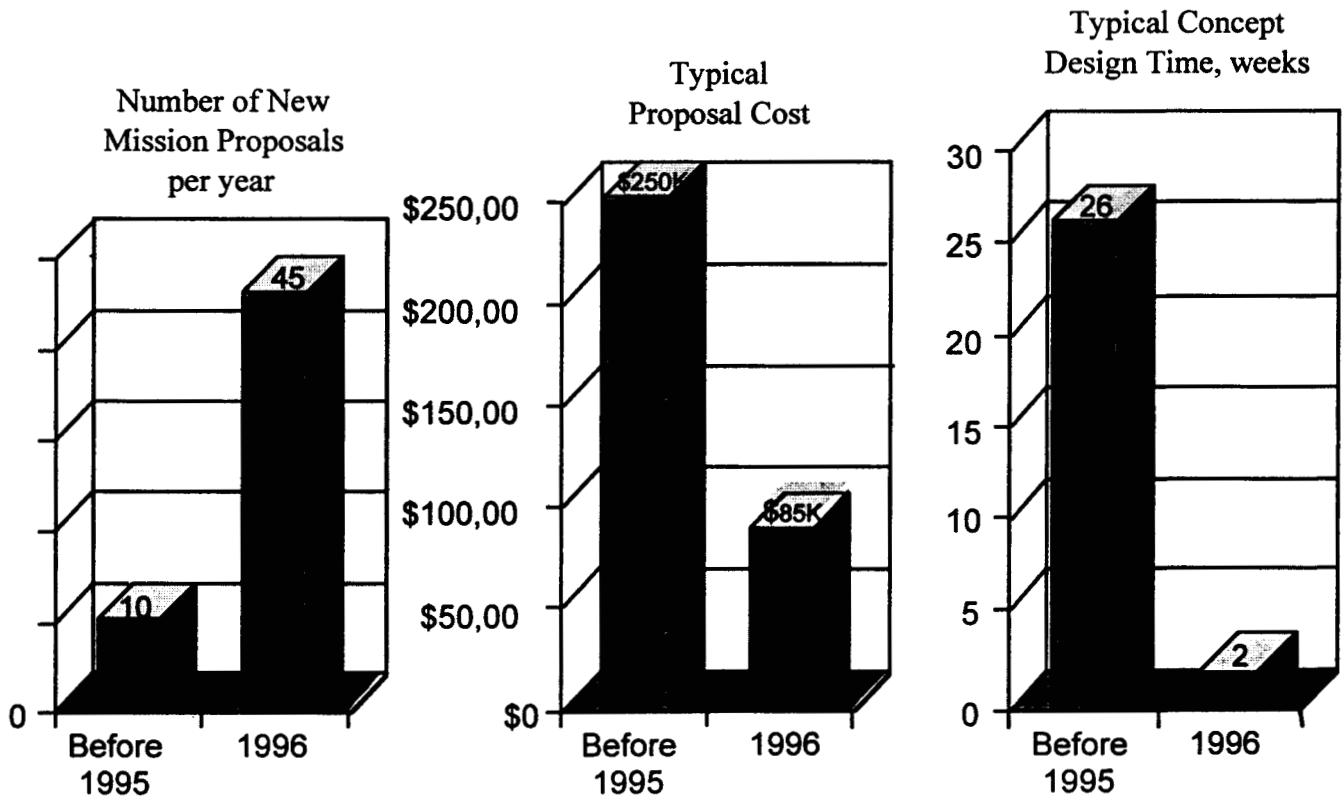
Team X has been in existence for over three years and is now an established part of the conceptual phase design

process. Figure 1 shows the related metrics. Previously, JPL had been able to complete at most ten conceptual designs in one year, requiring 26 weeks to complete and at a typical cost of 250 \$k. With the revised process, engineering designs for more than fifty mission concepts per year are generated in less than two weeks, requiring total funds less than 75 \$k. In 1996, 45 such designs were completed; in subsequent years this number increased to 50 to 75. This increased capacity has been used to enable the creation of candidate mission roadmaps, allowing NASA to choose among proposed mission sets rather than single missions. Some of this time saved is that previously required to assemble a team, relieve them of other duties, establish procedures, and other bureaucratic necessities, but other efficiencies have come from shortened communication loops, computer-to-computer data exchanges, and online report writing. An additional advantage is that the Team X approach has enabled design cycle times measured in minutes or hours rather than weeks. Thus the option exists to allow much broader design space exploration and optimization if desired.

#### 5. IMPLEMENTATION PHASE TEAMING

Compression of the implementation phase design process has also received attention in the past few years. Tools and tool linkages that compress this phase are discussed in [1] and [2], and an overview of a redesigned process has been elaborated in [5]. Here we discuss possibilities for teaming in the implementation phase.

Figure 1 Conceptual Phase Design Metrics



Reference [19] discusses a teaming formulation to augment model-driven design in which three teams, the mission team, design team and test team act in parallel operation, interacting with the central database proposed by [2] to efficiently pass design data between them.

We have implemented and are evaluating such a system for implementation phase design, with the teaming outline and database structure shown in Figure 2. In this scheme, high-level mission constraints are defined by the mission team using the conceptual design described in the previous section of this paper. The mission team includes such roles as the project scientist, mission engineer, and flight and

ground system engineers. These are captured in the timing tool APGEN [20] as rule-based statements of events that must happen together, must not happen together, must follow each other, etc. The team loads rough estimates of power, data, and other resources into APGEN for each event. Mission science teams and mission designers create a mission scenario that describes in high-level terms what activities a mission is to accomplish in APGEN. The program captures the timeline and, given the resource estimates, makes plots of resource usage as a function of time. A mission scenario that is roughly consistent with constraints and resources is output from APGEN.

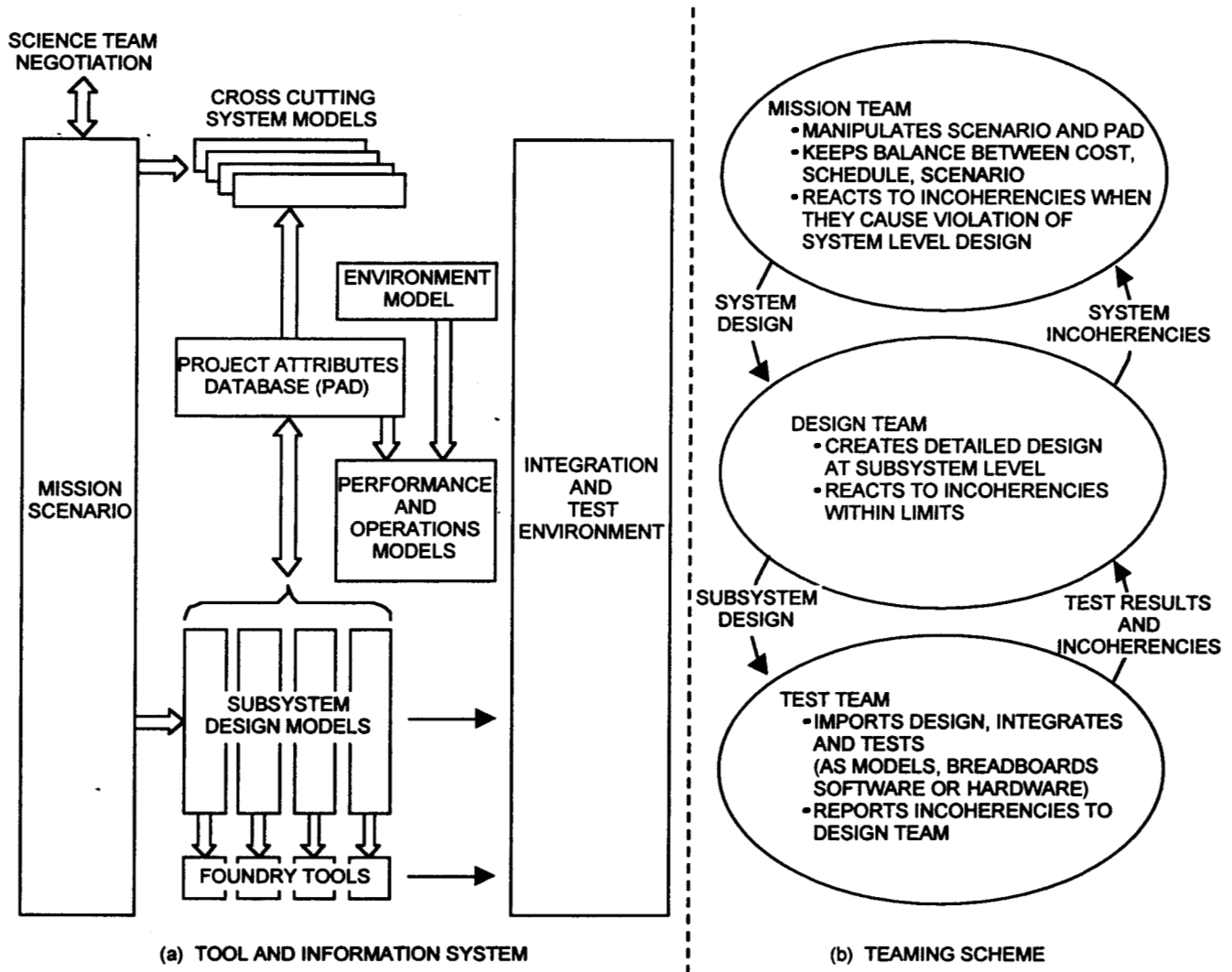


Figure 2. Data and Teaming Flow for Implementation Phase Design

The conceptual design and mission scenario are used to create high-level system requirements and a system design, which are stated in modeling software following [4]. Parameters describing the design are revised from the conceptual design and stored in a central database called the Project Attributes Database (PAD). Parameters are linked to system models, and a product breakdown structure is created that attaches system level parameters (e.g., system mass, cost, and power) to subsystem parameters (e.g., individual subsystem masses, costs, and power). The system models are then attached to the APGEN output and executed to ensure that the scenario can be executed by the designed system. For example, power requirements and power sources are balanced with battery capacity, data sinks and sources are balanced against onboard storage capability and data downlinks, and the like. Note that cost and schedule are regarded as system models and are estimated and balanced like any other engineering parameter. The cost model, for example, may be a parametric model based on past missions that uses some parameters from the PAD to continuously update both life cycle cost and cost profile by year as the design cycle proceeds.

When requirements and scenario are in balance, the mission team's attention shifts to the scenario as subsystem design begins. First, constraints are refined in APGEN in response to the capabilities of the system design. Then the mission scenario is updated and sufficient detail is added to make the scenario useful as a source of test procedures.

To begin subsystem design, the mission team releases the design to the design team, whose job it is to design the subsystems required in the system design. Design parameters and resource allocations are extracted from the PAD and models more behavioral in nature are created of subsystems. In the PAD, a set of parameters parallel to the system design specifications is created so that subsystem design values can be entered for comparison. In addition, the number of parameters is expanded to include subsystem designs, some of which will have no system equivalent. Subsystem models are delivered to the test team, who operates in the system integration and test environment to integrate the modeled subsystems and test them. The test team uses test procedures drawn either from requirements or from the mission scenario to test these models in the first instance of system test (which in the previous paradigm does not occur until much later). For each test cycle, another parallel set of parameters is created in the PAD to represent actual measurements. Test results are used to discover test failures or "incoherencies," which are returned to the design team for design correction. If the design team is unable to resolve the incoherency within the allocations present in the PAD, the incoherency is returned to the mission team. For example, a subsystem engineer in the design team may find that the design requires more power than anticipated, and that there is no solution within that subsystem—this is known in the trade as a "design pushback" on requirements. Such incoherencies are treated as an imbalance in the system models and resolved by readjusting the scenario, rebalancing the system level requirements, or both. Note that in this rebalancing cost and

schedule are continuously updated and obvious, and can thus be treated as independent variables.

The cycle described above is repeated as new system designs translate into new constraints, scenarios and subsystem designs. As the design matures, subsystem models of designs are replaced by breadboards and flight or ground hard- and software, and the test environment proceeds from testing of models through testing of hybrids of models/breadboards/hardware to final test of flight and ground equipment. Thus final integration and test becomes simply another in a series of integrations which lead from models to flight and ground hardware and software.

Imbalances at the system level can, and often do, occur for external reasons. The mission sponsor can direct the mission team to reduce its life cycle cost or readjust costs by year. The science team may respond to recent scientific results or other needs by changing the scenario, or new findings about the environment (radiation levels, for example) may make the mission's task different in some way. Whereas past philosophy has been to resist such changes (freeze the requirements), experience has shown that they are common and probably inevitable. Here, at each rebalance by the mission team (which can be brought on by either a new system design or a new scenario or both) the latest updates from both system and scenario are used, thus accommodating changes to either. Similarly, management reviews are accomplished by witnessing the satisfaction of the scenario by the system models.

We expect three chief advantages of this scheme over traditional design practice. First, the use of three concurrent teams provides a naturally shorter design cycle. Traditional schemes have design cycles limited by weekly meeting schedules, interspersed with manual (telephone, e-mail or paper) data exchanges. This scheme's concurrent teams do not need weekly meetings, and they exchange data through the PAD, enabling design cycle times measured in days. Second, the enabling of fluid requirements encourages creative solutions that reach outside of existing requirements and allow more trade-space exploration during detailed design. Fluid requirements also allow and account for both sponsor-inspired changes and subsystem design pushback, as noted above. Finally, the use of models allows early system test and design error detection, saving rework and reserving final integration and test time for discovery of fabrication errors. In the conceptual design phase we have also noted increased employee satisfaction, higher team innovation and more team loyalty, and we anticipate similar advantages in the implementation phase designs as well.

## 6. A MODEL OF IMPLEMENTATION PHASE TEAMING

The use of a central design database and concurrent teams has not been implemented, so there are no actual metrics. In this section we present a model of implementation phase design and show how such a scheme might operate and show results from that model. The design cycle flow involves a mission team design period (designated MT) followed by a design team period (DT) and a test team

period (TT). Redesigns by the design team are followed by a test team period, whereas redesigns by the mission team (as might be required following a major mission redesign) are followed by both design team and test team periods. Thus a mission requiring  $N_M$  paths through MT and  $N_D$  paths through DT will require total design time

$$\tau = N_M \cdot (f_M + N_D \cdot (f_D + f_T)) \cdot \tau_{obj} \quad (1)$$

where

$\tau$  is the total design time,

$\tau_{obj}$  is the minimum object design time,

and  $f_M$ ,  $f_D$ , and  $f_T$  are relative time factors for MT, DT and TT periods, respectively. This equation emphasizes the need for especially efficient operation of DT and TT; it also points out the common wisdom that minimizing the number of mission system redesigns is particularly important as the design matures, since  $f_D$  and  $f_T$  will inevitably increase with a more mature design.

Using the estimates of relative  $f_M$ ,  $f_D$ , and  $f_T$  values and the observed  $\tau_{obj} = 5$  months from [19], we find the results in Table 2 for typical  $N_M$  and  $N_D$ .

Design times for the parameter ranges shown vary from 17 to 50 months. For reference, JPL's Galileo mission, a large flagship spacecraft, was designed in approximately 72 months, and the Mars Pathfinder in 48 months. Variations

**Table 2.** Implementation Phase Design Time Model Results (varied parameters shaded)

$\tau_{obj} =$  5 months

$N_M$	$N_D$	$f_M$	$f_D$	$f_T$	$\tau$ , months
[shaded]	[shaded]	1	2	3	30
		1	2	3	55
		1	2	3	60
		1	2	3	110
1	1	1	2	[shaded]	25
1	1	1	2	[shaded]	20

with  $N_D$  and  $N_M$  are obviously high, but the value of decreasing both test and design efficiencies are also obvious. We feel that with the benefits of early test and

error detection, both  $N_M$ ,  $f_D$ , and  $f_T$  can be significantly decreased.

## 7. CONCLUSION

This paper reports that management of team structure and processes in engineering design teams is an important factor for decreasing the time required to design a space mission. In the conceptual design phase, a redesigned process featuring management of team dynamics has resulted in significant favorable changes in design time, cost and quality. A proposed change to the design scheme in implementation phase design has potential for similar improvements in time and quality. A simple design cycle model shows that if moderate improvements in team efficiency can be achieved, significant improvements in total design time will result.

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Lynda Koenig received her doctoral degree in clinical psychology in May, 1981, from Purdue University. She has been in private practice in San Luis Obispo, California since 1983. She is partnered in a company involved with re-engineering organizations for enhanced efficiency and quality, Kinetic Stance, LLC. Interests include human behavioral change, systems change, psychometrics, and organizational consultation.

## 9. BIOGRAPHIES

Stephen D. Wall leads the Center for Space Mission Architecture and Design at the Jet Propulsion Laboratory and a former leader of the Advanced Projects Design Team (Team X). He holds a masters degree in Optical Engineering from the University of Rochester (1972) and is a veteran of six planetary and earth sciences remote sensing missions including Viking (1976), Magellan (1988), Cassini (1997) and the Spaceborne Radar Laboratory (1996). For his past work Steve was awarded the NASA Exceptional Service and Exceptional Achievement Medals and seven NASA Group Achievement Awards.