Quantitative Methods for Maturing and Infusing Advanced Spacecraft Technology

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Abstract Today, the pace of spacecraft development has accelerated. Some of this pressure comes from reduced budgets and government mandates to improve efficiency and rely on a greater extent on commercial systems and practices. More importantly, however, and particularly for NASA, the accelerating pace is driven by new opportunities in science and technology. Future systems must respond to requirements to deliver higher resolution, greater responsiveness, and the increased need for interoperability. Additionally, NASA is being asked to field systems in less time and less cost without sacrificing mission reliability. To meet these often contradictory requirements, project managers must find new ways to infuse advanced technologies into spacecraft. As a result, most of NASA's science spacecraft incorporate an unprecedented amount of new technology. The incorporation of advanced technology is indeed a stated goal of some science programs. Announcement of opportunities (AOs) for the Discovery program, for example, encourages the use of new technology. Candidate missions must identify new systems and components, analyze how the risks associated with new designs are to be mitigated, and identify methods for transferring resultant technology within and outside of NASA. Technology infusion in any application is a complex process. Incorporating an unproven new design into the development of an operational system presents significant cost, schedule, and technical risk. Historically, developers of operational systems have been cautious when incorporating new technology. New designs areoften matured independent of operational systems and brought on-line only when they have proven their mettle. In space systems, demonstrator or precursor missions are used to test new designs before the commitment to a new technology is made. This is usually a very slow process; it can take years or decades to move a technology from the laboratory to fully operational status. The result is a stepwise evolution of capability – an approach that minimizes risk. Sometimes requirements evolve at a pace where demonstrator programs are not possible. When this occurs, project managers must accept the task of integrating complex new technologies into the mainstream development of an operational spacecraft. The tools used to assist the project manager with this task are surprisingly fragile. Techniques for measuring the readiness of a technology, for example, are highly qualitative. The importance of the language and culture surrounding the transfer of a technology from the laboratory to the application program is also generally underestimated. This paper focuses on these issues, examining the practice of maturing technology with special emphasis on methods that improve the integration of advanced designs into the development of operational spacecraft systems. Simplified practices are presented that could improve the accuracy and reduce the risk associated with estimating the readiness of a technology for use in space applications. While this paper focuses on the challenges associated with building spacecraft, the authors believe the practices presented here could have broader application to other markets.

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1. INTRODUCTION

One of the most significant sources of risk in any spacecraft development program is the accurate assessment of technological maturity. Many programs have failed technically or far-exceeded cost and schedule projections because of an underestimation of the difficulty of incorporating new designs. Previous RAND research has found the failure to account for the programmatic complexity of integrating advanced technology to be the leading cause of costly overruns and, in many cases, cancellation [1,2,3]. Measuring the maturity of a new technology is, therefore, a matter of considerable importance. Recent Department of Defense (DoD) decisions to base procurement decisions on measures of technological maturity underscore the need to develop measures that are both robust and objective.

Employing new technology on a spacecraft creates a dilemma for a spacecraft program manager. On one hand, spacecraft engineering teams are being placed under more pressure to reduce cost and development time. These teams are relying on advanced technology to meet these goals, as well as mission requirements that are growing in size and complexity. Project managers responsible for delivering a spacecraft "on-cost" and "on-schedule" are understandingly reticent about accepting unproven new designs that represent significant risk to the program - tight budgets and schedules only increase this reticence. Improved measures of maturity could significantly reduce levels of uncertainty.

The adoption of advanced technology is further aggravated by cultural differences that exist between spacecraft engineering teams and technology developers. Concepts for new spacecraft systems are often born in research laboratories, far removed from the pace and pressures associated with a spacecraft flight program. Revolutionary innovations tend to begin in research laboratories. Technologists, anxious to have a new technology used, will often overstate the maturity of the concept. Equally important is the fact that technologist often fail to appreciate the engineering effort required to characterize a new technology and ensure its compatibility with other systems. The tendencies to overstate maturity and provide insufficient engineering data often spurs spacecraft teams to prefer "home grown" technology. Developers tend to rely on local technology application groups, a path that is less risky, but also one that produces technology that is evolutionary, as opposed to revolutionary. More refined measures of technology maturity could help close the cultural gap between spacecraft engineering teams and technology developers by providing firm engineering metrics in place of qualitative assessments.

To generate accurate cost and risk assessments, new, less subjective measures of technological maturity are needed. Current methods, such as the use of Technology Readiness Levels (TRLs), a nine-step index leading to the eventual flight of a new technology, are highly subjective. Variation in assessment techniques increases the risk to the flight project. This variability will be reflected in contractor cost estimates. Reducing this variability is a goal of techniques to reduce subjectivity is assessments of maturity.

The objective of this report is to review the challenges of integrating new technology in space systems and to outline a simple methodology that lead to a less subjective and more quantitative strategy for assessment maturity. *The cases studied in this report assume that advanced technology must be matured during the development cycle of a spacecraft.* Many analysts suggest that technology should be matured outside of the development cycle [4]. This is often not possible, especially in the case of many DoD applications where the rapidly changing threat environment requires that high-performance systems be brought on-line quickly. "Simultaneous engineering" is becoming increasingly important in terms of product effectiveness, in both government and commercial markets [5].

2. THE CHALLENGE OF TECHNOLOGY INFUSION

All new operational spacecraft to some degree rely on advanced technology. This reliance can represent an evolutionary change; for example, the deployment of a new block of units where several new technologies are integrated into an improved system. Other spacecraft represent radical departures from tradition, with systems that utilize advanced sensors or primary systems that represent a new state-of-the-art. Whether an evolutionary or revolutionary step, it is rare to find a spacecraft that is launched without some form of new technology on-board.

For a variety of reasons, including science breakthroughs, decreasing budgets, and national security, the need for higher performance spacecraft has become more pressing. Many analysts overlook the fact that new technology plays a significant role in the cost-performance equation. Advanced technology is usually aimed at boosting performance; reducing development and operating costs is usually considered secondarily or not at all (Smith, K., 1997). Yet all Federal agencies have experienced budget pressures and technology can provide a means of doing more for less (Sarsfield, 2000). A desire for advanced technology does, however, present managers with a dilemma. On the one hand, the manager is driven to employ advanced technology, both to meet performance requirements and possibly reduce cost. On the other hand, tight budgets make it very difficult to mature technology within the framework of a development program; a problem often exacerbated by the inability to maintain a consistent funding over the life of a development program.[1]

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[1] It is worth noting that one reason for shifting to smaller, more quickly developed platforms is to mitigate the effects of budget instability.

The difficulty of incorporating new technology has long been a central challenge of procurement practices in both industry and government. The Government Accounting Office (GAO) has recently recommended that technology development take place separate from acquisition programs citing traditional commercial practice (GAO, 1999c). Certainly, private firms prefer to have technology in hand prior to the production of new models or product offerings. The report notes that, in the government realm, sometimes programs must move forward with imprecise requirements and immature technology. Many NASA, DOD and NRO developments will fit into this category. These agencies typically build complex spacecraft, with low production volumes, and a high premium on reliability.[2] They can certainly increase funding for technology development and employ demonstrator spacecraft to reduce the risk of using new technologies. In the long-run, however, it is likely that they will be faced with acquisition activities with higher levels of technological uncertainty, and developmental risks will increase.

A great deal of the risk of working with new technologies is accurately assessing the readiness of a technology for use in future applications. The GAO has endorsed the use of Technology Readiness Levels (TRLs) pioneered by the National Aeronautics and Space Administration (GAO, 2000a). The TRL index is a scale, ranked from one to nine, that seeks to measure the maturity of a particular technology and the consistent comparison of maturity between different types of technology (Mankins, 1995). It has been widely used by NASA and other agencies in the planning of advanced systems. The GAO's recommendation was followed by actions within the Department of Defense to embrace the use of TRL in procurement practice. New procurement regulations now require the use of TRLs, or some similar measurement schema, in the process of developing and implementing procurement plans for major defense systems (DoD, 2001).

As this chapter will outline, TRLs themselves are problematic and alone are not sufficient to ensure that a new technology will mature along a timeline that ensures ready infusion into a developing spacecraft. Improved means of incorporating new technology are urgently needed. Indeed, new methods for identifying, maturing, managing, and transferring spacecraft technology are as important a set of innovations as the technologies themselves.

The Importance of Infusing New Technology

As argued above, the most important reason to improve the process of infusing new technologies is the need to quickly meet challenging new requirements emerging from the changing science opportunities and from the changing threat environment (Sega, 2002). There are other reasons, however, why the infusion of new technology is a major concern for government spacecraft programs.

There is broad interest within government to extract higher returns from the government's investment in high technology programs. The government invests more that $80 billion dollars in research and development (R&D) annually; the DoD accounts for nearly half of that investment (Fossum, 2000). In many government agencies and within Congress there is concern that this significant investment does not transfer quickly enough, either within government or to the private sector.[3] New legislation requires the Secretary of Defense to monitor the time it takes to incorporate new technology in operational systems, driving toward a 50 percent reduction (U.S. Code, Title 10, 1998). NASA's Administrator labeled the agency's technology programs "hot dog stands" reflecting a frustration they many project were not contributing fast enough to the task of improving the performance of aerospace systems (Goldin, 1996). Improving the infusion rate for new technologies into spacecraft is, therefore, responsive to national policy.

In aerospace, the private sector is more reliant than in many other market segments on government R&D investments. Though difficult to accurately estimate, the ratio of government (civil and military space, but excluding NRO) investment in spacecraft technology to the private sector is approximately 20:1 (Sarsfield, 2000, p. 134). As government acquisition programs continue to push to lower cost space systems, the amount of funds going to long-range R&D could drop (Lorell et al., 2000). Increasing the infusion rate of new technology and bringing about new generations of high-performance spacecraft will likely create "spin-off" benefits that will assist domestic firms maintain a market edge.

Government programs too can benefit. NRO spacecraft are large by comparison to those built by other agencies. This presents an opportunity for smaller programs to leverage the purchasing power of these larger programs. Mars Pathfinder, for example, purchased 40 percent of its Class S (space-rated) parts on shared orders with the larger Cassini Saturn probe (Paté-Cornell and Dillon, 1998a).

A final reason for paying closer attention to the issue of technology is the to realize the promise of increased performance, lower cost, and greater reliability (Sarsfield,

[2] Recent trends of increased failure rates for space vehicles is alarming to program managers. Since 1990, over $11 billion of space assets have been lost due to catastrophic failures (Tosney, 2000).

[3] The 1980 Stevenson-Wydler Technology Innovation Act required Federal laboratories to pursue technical cooperation with industry actively, while the 1986 Federal Technology Transfer Act made the transfer of technology the specific responsibility of all government research laboratories. An internal 1992 NASA review (Creedon, 1992) was highly critical of transfer practices, finding "little commitment from primary research organizations." The importance of technology transfer practices was subsequently emphasized by the White House which specifically directed that spacecraft missions draft technology transfer plans.

1998, p. 40). Improvements on-board spacecraft tend to occur slowly, especially when compared to market segment like consumer electronics where change is rapid and dramatic. New technology includes methods for design, manufacture, test, and operations; it is not confined to systems and components for the flight segment of a mission. Clearly, there is an acute need to improve how the maturation of technology is measured and how new designs are applied to answer emerging requirements. There are, however, many hindrances to addressing this need and these are discussed in the remainder of this chapter.

The Twin Cultures of Technology

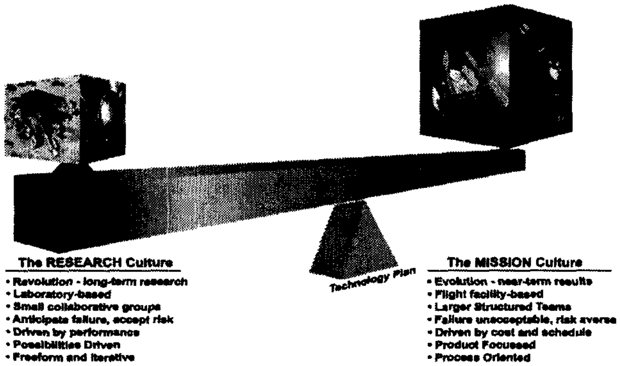

Figure 1: The Spectrum of Technology Cultures

New Technology and Perceived Risk

To meet ambitious performance requirements, each new spacecraft depends to some degree on technological improvement. Incorporation of new technology has, however, traditionally been a cautious undertaking. Satellites have mostly *evolved* in a stepwise fashion, with capability often lagging well behind the terrestrial state-of-the-art. Since the majority of spacecraft are not produced on an assembly line, the term "craft industry" has been coined by one author to aptly describe the spacecraft production process (Tosney, 1999).

A cautious approach to new technology does not necessarily indicate that project managers are innately risk averse. If new technology is not found on the bus side of the spacecraft, it will usually be found on the payload, or instrument, side.[4] Spacecraft project managers could perhaps be more accurately described as preferring to take only the required risk.

It is not clear whether new technology, when first used on a spacecraft, can be traced to mission-limiting failures. Radical new technologies can work very well in a "first use" application *if* adequate testing is done prior to launch. NASA's Mars Pathfinder mission that landed in 1997 employed air bags to cushion landing loads. Air bags were considered a radical departure from proven methods of rocket-assisted deceleration that had been used on prior missions. Yet the method proved successful after the technique was exhaustively tested.

Usually, radical new techniques, like the use of air bags, trace their lineage to earlier proposals that were rejected because of perceived levels of risk. A case in point is the application of an ion engine for primary spacecraft propulsion. The concept of ion propulsion is nearly 70 years old.[5] When NASA first used it for primary propulsion on the Deep Space 1 mission the technology worked very well. Here again, success was achieved after many years of exhaustive ground testing.

Though the risks of employing even radical technology can be successfully mitigated, failures and anomalies on the payload side of a spacecraft have historically been a cause of great concern. Usually new technology is used extensively in the developments of satellite payloads. The bar chart shown in Figure 2, presents a histogram of spacecraft mission degrading failures for recent space vehicles (Tosney, 1997). These data do not specify whether the cause of the mission degrading failure was caused by new or old technology *inside of the payload.*

It is very difficult to establish whether or not a new technology actually failed in space. Yet even if the new technology is the source of failure it can still cause problems. Frequently the attention paid to integrating a new design deflects the engineering team's attention from traditional elements of the system design. From this perspective, even if a new technology is not the direct cause of failure, the complexity of integrating unproven designs leads to other errors being overlooked. Often it is the lack

[4] These definitions refer to the simplest functional breakdown of a spacecraft. The "bus" refers to the part of the spacecraft that contains the systems that provide operational resources. The power generation, guidance, navigation, and control, data communication, and other functional systems comprise the bus. The "payload" side of the spacecraft contains the instrument(s) and sensor(s) that are responsible for meeting the main mission requirements. In modern spacecraft, it is sometimes difficult to identify a clear interface between these two parts of the spacecraft. Highly integrated, small spacecraft are often build "around the instrument" making if difficult to distinguish between these two prime elements.

[5] The concept of electric propulsion is nearly 70 years old. Following the creation of NASA and after a few years of early planning, NASA, in the early 1960s, formally established the Space Electric Propulsion Test program at the Lewis (now Glenn) Research Center. See: Kerslake, W., 1992; and NASA, "Ion Propulsion: Over 50 Years in the Making," NASA Space Science News, Huntsville, AL, April 6, 1999. No NASA science mission used the technology until the launch of the Deep Space 1 mission in 1998. Now the Air Force's Electric Propulsion Space Experiment and the Hughes xenon ion propulsion system are applying the technology for both primary and station-keeping propulsion. It is important to note that the private sector is often equally slow to incorporate new technology if it does not perceive near-term economic advantage. Air bags as a safety device in cars was demonstrated in the mid-1950s, but it took approximately 40 years for them to appear as standard equipment in new automobiles.

of readiness of a new design that consumes the time of engineering teams as they work to deal with unforeseen problems during integration.

Three Central Challenges of Infusing Technology

Cultural differences and varying perceptions of risk significantly slow the infusion of new technologies into spacecraft. This section integrates these observations and attempts to synthesize the issues surrounding technology infusion into a classification scheme that will later be used to outline practices that constitute a potential remedy. Improving the infusion of technology can be characterized in terms of three classic management challenges: 1) defining requirements and measuring progress in attaining them; 2) identifying resource requirements and characterizing the risk involved, and 3) ensuring programmatic continuity during the process.

Establishing Requirements and Measuring Progress

An advanced technology, whether it is a part, component, assembly, subsystem, or turnkey system, is useful to a spacecraft developer when it has matured to the point that it can be incorporated into a flight project with acceptable engineering, cost, and schedule risks. In some cases, a new technology might be pursued because managers believe it offers a significant advantage in terms of performance, cost, or reliability. Technology is, therefore, often *pushed* to potential users who are, in turn, usually skeptical and concerned about potential risks. In other cases, a technology might be urgently needed by a user and is *pulled* from the technology developer. In either case, if the technology is to be included in the design of an overall system it is vital that requirements be generated to guide the technology to its ultimate endpoint. Spacecraft development programs often do a poor job of defining these requirements with significant clarity to be of much assistance to the technology developer. This is the first area where problems occur in the maturation process. The next problem area is the techniques used to measure maturity.

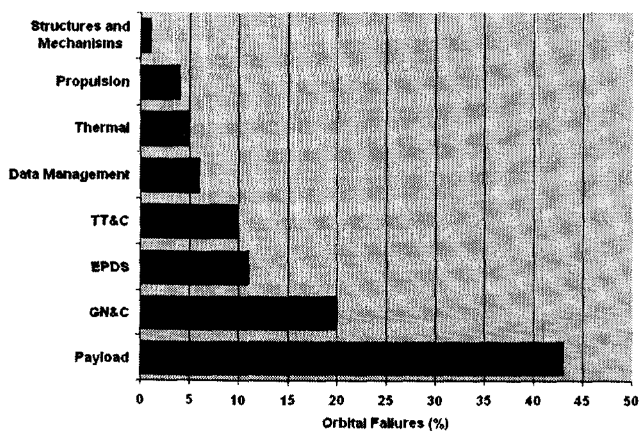

Figure 2: System Level Mission Degrading Failures (1970 through 2000)

The method most used to ascertain the maturity of space technology is captured in NASA's Technology Readiness Levels (TRLs).[6] TRLs are important to the management of technology programs and are essentially a step-by-step schema for retiring risk.

According to NASA plans, funding for advance technology shifts from the developer to user as a concept moves to a higher level of readiness. The user, a science mission for example, would expend only limited resources in Levels 1–4 (mainly to identify and track requirements); begin to pay an increasing share during the demonstration phases, Levels 5–7; and then completely fund the flight phases, Levels 8 and 9. TRLs imply formality in the process of maturing technology. Rigid application would mean, however, that a system could not be considered "flight qualified" (TRL-8) unless an earlier prototype (TRL-7) had flown in space. In practice, few development efforts move sequentially along the TRL continuum.

As the need to do a better job of infusing technology has intensified, limitations with the use of TRLs have become more obvious. More and more, managers rely on an accurate picture of maturity when making critical program decisions. Care must be exercised when using TRLs to describe the maturity of a technology since they are:

Subjective assessments – most often, when TRLs are used few formal methods are employed. The subsequent value, often produced by the technology developer and not an unbiased third-party, represents a subjective assessment of maturity. The definitions provided in Table 1 provide room for broad interpretations of the readiness of a technology.

Not focused on system-to-system integration – TRLs focus on a particular element of technology, for example a new sensor or type of valve. When a technology is to be included in a larger development significant integration challenges can occur. Even "mature" technology can be a challenge to incorporate into new applications. TRLs generally fail to capture the challenge of incorporating a new design into an overall system.

Focused on hardware and not software – TRLs were built with a strong concentration on hardware at a time when software played a much smaller role in the operation of spacecraft than it does today. NASA has recently attempted to create software equivalents for the TRLs.

Not well integrated into cost and risk modeling tools – most cost and risk modeling tools have some means of reflecting the level of maturity of technology elements of a program. Often this simply means that a TRL value is assigned to cost and risk estimating relationships. Errors in the calculation of the TRL will result in significant inaccuracies in program cost and schedules estimates.

[6] A detailed description of NASA's TRL index can be found in Mankins, 1995..

Lacking in definition of terminology – the definitions of what constitutes a given TRL rely on terminology that can be problematic. The phrase "relevant environment" used to decide whether a technology has reached TRL-6 is open to interpretation. There are several space environments that can be simulated (low-gravity, radiation, temperature, vacuum, etc.). The degree of testing and simulation needed to "demonstrate" performance is left undefined. Also, the definitions used within NASA are not universal; DoD and commercial manufacturers have different nomenclatures.

Perhaps the most serious limitation of using TRLs, however, is the ambiguity associated with their relevance in any given application. *It is quite possible to have a technology that is mature in one application and immature in another.* Engineers and designers in selecting components and subsystems for spacecraft often rely on *heritage*.[7] The belief that designs used in prior applications have broader applicability has led to numerous spacecraft failures (Sarsfield, 1998, p. 46). Significant developmental problems can occur if a spacecraft teams assumes that a high TRL value is a clear signal that a technology is ready for use. It is important to assess the performance of a technology in relation to the specific requirements of the mission at hand.

The TRL schema provides a high-level description of a given technology, but it is limited in both accuracy and precision. The schema does allow for the general comparison of technologies. TRLs are, however, being used to for broader purposes including the estimation of resource requirements for large programs. In this role they are limited and cannot provided sufficient assurance that a technology will be ready for use on-time and within budget.

Establishing Resources and Reducing Risks

Maturing a new technology requires all the skills of project management. It requires careful planning including the establishment of clear requirements, the setting of milestones, accurate estimates of cost and schedule, and a method for evaluating and mitigating developmental risks. There principles are often undervalued, however, and the technology development effort proceeds, if part of a larger system, without the tight integration necessary.

Government agencies and commercial firms each have fallen victim to technology development efforts where the resource requirements were wholly underestimated. It is, of course, clear that the risks associated with unprecedented systems are difficult to quantify and, in some cases, unknown. Yet the problems that occur during the maturation of a new technology and infusing new designs into a larger system are often due to poor coordination and a lack of disciplined engineering planning.

Maintaining Continuity During the Maturation Process

Funds for the development of new concepts are usually in short supply. With the number of innovations far exceeding the availability of maturation funds, research groups have to be highly selective in the new projects they will move forward, as well as how far they will push them. Most often, a developer can go only so far and the further maturation of a new technology hinges on making an early connection with an end user with sufficient resources (GAO, 1999a). This means that most technologies are dual-funded. Figure 3 shows the challenge of funding continuity that often plagues technology development programs.

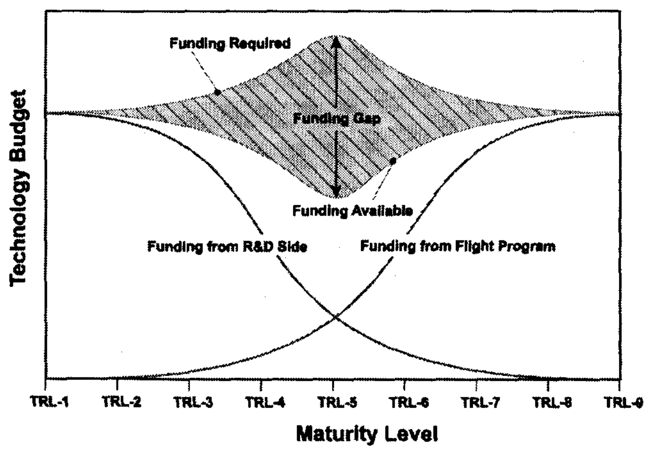

Figure 3: The Technology Funding Gap

The amount of funding needed to begin to move a new idea from the bench to a level of performance of interest to an end user is significant. In practice, funding shortfalls on both sides can lead to a dip in the midpoint of the process of maturing an advanced design. Unfortunately, this occurs at a critical juncture at which a research project undergoes the complex transformation into an engineered system capable of being integrated into a mainstream flight project. Once laboratory viability of a new technology has been demonstrated the costs of proceeding further grow dramatically as additional staff is added and more complex testing facilities are brought into play. Mechanisms for alleviating this "funding gap" would be very helpful in maintaining the pace of technology maturation, and, ultimately, the assuring the successful infusion of a new design.

Clearly there are numerous challenges to integrating new technologies. The challenge is especially sharp when technology development and spacecraft development occur in unison. This requires accurate measurement of maturity and some assurance that technology developer and end user

[7] "Heritage" is a term used by spacecraft engineers to denote prior experience with a design in a space application. This experience could have been gained by another organization, or on-board a spacecraft performing a completely different mission that the one being studied. This can lead to a false sense of security that the performance of a given design, having been demonstrated, can be repeated in the current application. Too often, this has not proven to be the case.

are describing the same things. The measures that are used must not be subjective; instead they should be linked to clear milestones.

3. Quantitative Measures For Maturing Technology

The failure to correctly ascertain the maturity of a technology is a significant source of problems in many missions. In some cases, overruns can lead to cancellation. NASA's Small Spacecraft Technology Initiative Clark spacecraft is a case in point. The project was canceled as a result of cost overruns that were due mainly to a failure to correctly interpret the maturity of the main instrument, a multispectral imager (Cockrell, 1999).

The current TRL schema, while offering a useful means of comparing technology projects, is inadequate for detailed project planning. There is nothing wrong with measuring maturity in a stepwise fashion as long as the milestones associated with each step can be clearly delineated. The measurement also must be meaningful to the specific application to which it is being applied.

Improved methods for measuring maturity show great promise, but there is insufficient evidence that they accurately assess the remaining risk associated with applying new technology. Quantitative methods for measuring technology maturity should be evaluated and efforts made to accelerate their development. The goal of using these methods should be to create a shared language between technology developers and users. Use of maturity models should improve the development of engineering data that spacecraft designers need to work with a new technology. The use of such tools could also assist with the task of identifying high-value technologies, such as those that are reusable and scalable. Care must be taken to ensure that these maturity models can be readily integrated into cost and risk management tools.

Developing Quantitative Methods

Increasing attention is being paid the challenge of developing useful technology maturity indices. Reducing variability is the goal of many techniques under development. Some quantitative techniques begin with TRLs, using them to adjust the cost and schedule estimates provided by traditional parametric cost models (Bearden, 1999). Other methods bypass the use of TRLs in favor of quantifying risk through assessing the influence of a new technology on the overall project architecture (Rynearson, 1999). Fuzzy-logic methods can also be used to validate cost and schedule models according to weighted assessments of technological maturity (Bellagamba, 1999). Decision trees and Bayesian probability models can also be used to predict the impact of uncertainty in measures of maturity of a new technology (Paté-Cornell and Dillon, 1998c). NASA Jet Propulsion Laboratory's (JPL) Technology Infusion and Maturity Assessment system also uses a probability model to establish the cost and risk of inserting an advanced technology (Cornford, 2000).

Many of these methods use statistical analysis to provide a quantitative assessment, but the basis for the initial data set continues to be a set of subjective measures. Most of the existing efforts to quantify technology maturity measurement are also not directed to spacecraft systems. Another shortcoming is that few efforts are aimed at integration into the current set of available management tools.

Interestingly, maturity indices for software development are more advanced than for mechanical and electronic systems. Though an index like the TRL schema is not extensively used, a great deal of research has been conducted on the measurement of software development. There are several reasons for this. First, software cost and schedule overruns for software development projects have been, and in some cases continue to be, legendary. Second, managers realized early that software designs would perform in mission critical applications, including automation in high-risk applications, such as the operation of nuclear power facilities and aircraft flight control systems. Finally, software engineers are familiar with dealing with user requirements. Unlike physical systems, where the rules of physics provide a basic set of initial requirements, software is fluid and the product of intellectual exercise. Without well-documented requirements a software development project cannot get started.

It was clear that software projects presented many unique challenges in comparison to mechanical and electronic systems. Software has only been available for a few decades, so test procedures are commensurately new and often unproven. Humans and not machines produce software, so repeatability and productivity are more difficult to assure. Because software is, by its very nature, extremely complex and interactive, flaws can remain undetected for longer periods.

Government and industry have invested heavily in the creation of measurement techniques for software. Many of these efforts have focused on the development of aerospace systems. Standards have been developed to guide software management practices and extensive training is available. Carnegie- Mellon's Software Engineering Institute is a leading source of maturity measurement practice. For spacecraft systems, NASA's Software Engineering Laboratory has developed guidebooks and standards for planning software developments and for quantitatively measuring progress.[8]

As argued earlier, successful applications of radical new technologies, such as the use of air bags to land on Mars, provide ample proof that tried and true engineering methods can adequately retire risk. NASA and military handbooks and other engineering specifications specify the design and test procedures necessary to access the applicability and associated risks. There are, therefore, well-established technical methods for assessing a new technology and gaining confidence in its performance. The ability to test a new technology does not, however, ensure its acceptance. New technology must be oriented to the requirements of the end user and will be accepted when a benefit is perceived (Creedon, 1992, p. 6). RAND found that spacecraft builders rely on consistent engineering criteria when selecting technology and will employ a new design when it can:

- demonstrate repeatable performance in conditions similar to those expected aboard the spacecraft
- adequately assess all risk factors
- employ high-quality components with lineage to known standards or to test data that establish reliability
- be sufficiently supported (development software, integration and test procedures, parts, etc.)
- promise clear performance gains over existing technology
- present a cost commensurate with performance
- have interfaces that are documented and that can be configured to match other systems.

Developers of new technology must supply the spacecraft development team with sufficient technical data to demonstrate that a) the risks associated with using the new design have been adequately retired, b) that performance meets requirements, and c) that the new design can be integrated into other spacecraft systems.

Technology Development Cycle

Technology matures in three phases; these are outlined in Figure 4. New ideas first require extensive laboratory development. During this phase, physical properties and basic proof-of-concept are demonstrated. This initial phase can only be concluded when performance has been validated and are expectations are confirmed that the new technology can evolve to meet real-world requirements. The phase that follows focuses on the difficult task of engineering analysis and testing to bring the technology to full-scale application. Often the focus of this phase is systems engineering applied to characterize performance in a way that makes the technology useful to an applications team. The final phase is production oriented. Here the focus is on extracting greater performance and efficiency from the new design, as well as modifications that can reduce the cost of producing additional quantities.

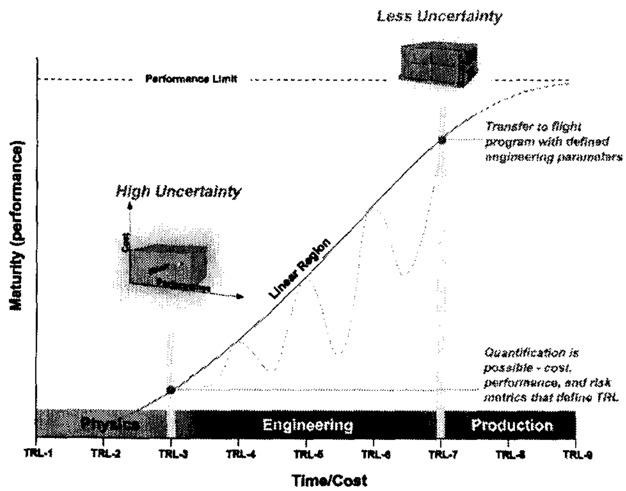

Figure 4: The "Engineering Phase" of Development

The focus of this report is on the second phase: the engineering activities involved in maturing a technology. In Figure 4, this is shown as a more or less linear phase of the product life-cycle. In actuality (as shown in the dashed line) the actual progress can be far from linear. At several stages during development it can often appear that progress in terms of higher performance and increased reliability of the new design has reversed. In practice, moving a technology towards greater readiness means meeting tough engineering milestones.

Critical to the success of this phase two effort is ensuring that a new technology is indeed ready to leave the laboratory. The most important decision that can be made before the "engineering phase" can begin relates to the ability of a technology to evolve. A new design must show, either through analysis or testing, that it can be scaled upward to meet the performance requirements expected in future applications.
"Scaleability" is the primary output of the laboratory phase of development and often this attribute is not accurately assessed. Advanced technologies tend to follow a "hype cycle" where initial high expectations are followed by a trough of disillusionment (Linden, 2002). When a new design is being prepared in unison with an application, problems with scaling-up a design can quickly derail programs. In Figure 5, a notional diagram shows the tendency of new technology efforts to fall short of performance expectations. A new technology is appealing because it promises some positive attribute (higher output,

[8] Several references for software maturity measurement are provided in the bibliography. The reader is referred to the several SEI reports referenced, as well as NASA GSFC, 1993 and 1990.

greater reliability, lower cost, or some combination of these). An application team, once accepting the promise of a new technology will often experience "requirements creep," a growth in needed performance. At the same time, the technology developer often finds (in many cases because of scaleability problems) that the performance of a new design falls short of projections. This can lead to performance gaps at the end of the program that are difficult or impossible to overcome.

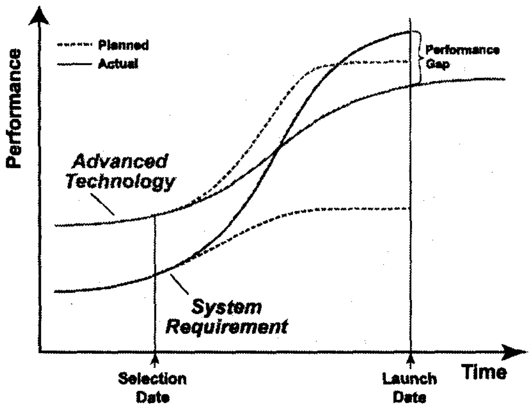

Figure 5: Performance Expectations for New Technology

An Alternative Maturity Index

An index is a useful tool for communicating maturity. The limitation of the TRL index lies in its subjectivity. To counter this tendency, a Developmental Maturity Index (DMI) is proposed to fill the gap. *In the descriptions that follow, DMIs are used in place of TRLs to connote a set of measures that at more closely linked to a specific application and to quantified engineering measures.* Unlike TRLs, which are broadly defined in relation to a given technology, DMIs focus on the specific application the technology is being considered for.

The task of communicating information related to design maturity is often hindered by the different nature of the technology and spacecraft development communities. As discussed earlier, a cultural gap exists between technology developers and spacecraft builders. There is no assurance that the two communities share a common language and the channels through which requirements are communicated often prove inadequate. To improve this process, the notion of employing Key Engineering Performance Parameters (KEPPs) is used in conjunction with the DMI index.

Relying on Engineering Parameters

A KEPP is a technical or operational parameter that can be described as a requirement. For any given new technology, there will be many such requirements that must be met as the design matures. Progress is rarely linear (as shown in Figure 4) and meeting some requirements can stall a development program.[9] The concept of using KEPPs to help quantify the maturity level of a technology is closely akin to the concept of spiral development. As shown in Figure 6, each increment associated with the maturity of technology essentially represents one turn around a development spiral. The practice of using KEPPs would establish the requirements associated with each turn in the spiral early in the maturation process, once the laboratory phase of development is complete. This practice would require that technology developers and spacecraft developers meet to formalize and exchange these requirements. This formalization would help alleviate some of the communication difficulties and false starts associated with many technology development efforts.

KEPPs are made up of three types of parameters. These parameters reflect the challenges of maturing the specific component or subsystem, the variables that affect the new design's ability to operate and integrate with other systems on the spacecraft, and environmental factors that determine operations during ground handling, during launch, and in space. These parameters can be categorized as:

> **Component** – parameters that determine the performance of a given design in relation to its own environment. This can be considered stand-along testing, where the device or component is demonstrated to operate in isolation.
>
> **System** – parameters that measures attributes of the design in relation to other systems aboard the spacecraft.
>
> **Environment** – parameters that establish the performance of the design in the environment in which it will operate. This includes conditions generated on the ground, during launch, and in space.

There are other elements of maturing a technology in a spiral fashion. Each cycle in the spiral requires overcoming significant technical and operational challenges to meeting progressively more challenging requirements. Testing must be conducted to demonstrate that established requirements have indeed been met, reducing the risks of employing the technology. Most projects do not enjoy unlimited time or funding to resolve technical problems and retire identified risks. Technology developers must, therefore, prioritize resources and incorporate the most cost-effective testing possible. The next chapter presents methods for adjusting testing methods to funding, addressing the "testing" part of the spiral shown in Figure 6.

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[9] Spacecraft development teams often maintain a dual-track when risks are high that a new design might not mature. This allows a switch to more traditional systems if a technology is "stuck" in the development cycle. This option is appealing, but becomes costly and difficult to implement as the spacecraft moves into later phases of development.

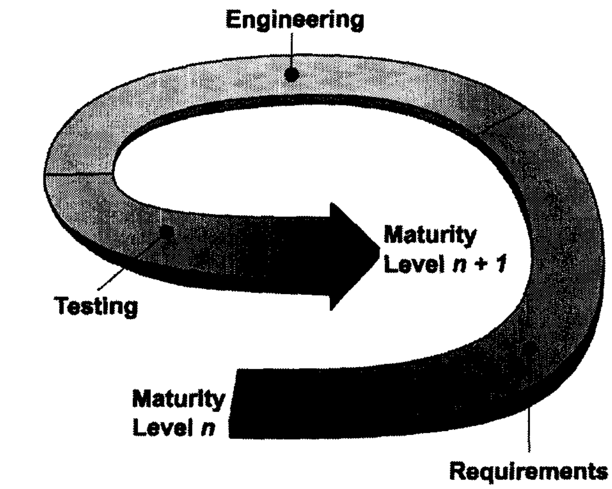

Figure 6: Maturation of Technology in Phases

It should be recognized in discussing the practice of employing KEPPs that spacecraft development teams may not know the requirements with precision early in the process. Usually, requirements become more refined as the design of the spacecraft itself matures. Some degree of refinement in the engineering parameters should be expected, but teams should endeavor for accuracy that can be followed with increased precision as the design of the overall spacecraft matures.

The use of KEPPs provides a simple means of assigning an objective value on the maturity of a technology at any given point in time. In Figure 7, a spider chart is shown portraying the maturity of a notional new electronic component for a spacecraft. The spider chart is a useful graphical depiction of the maturation process that allows a quick means of mapping progress.

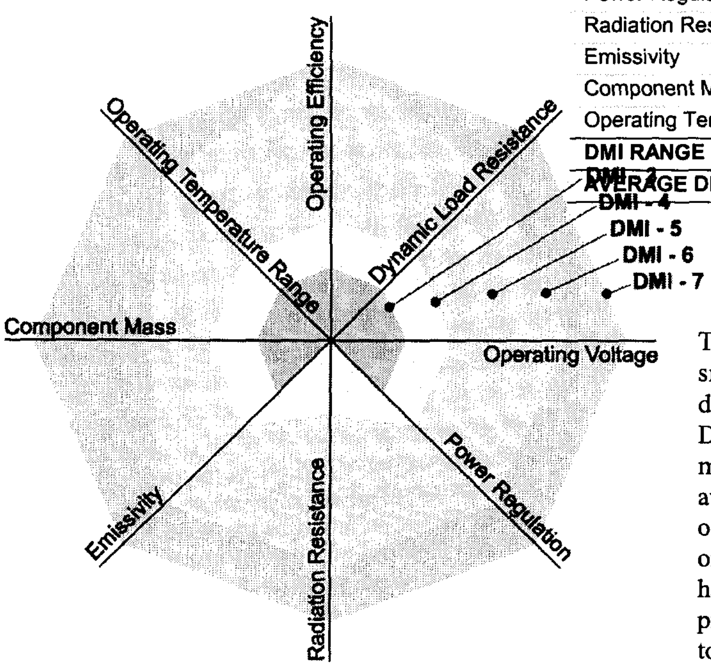

Figure 7: Spider Chart of Developing a Notional Electronic Component

In this notional example, it can readily seen that the component had early difficulty meeting even early requirements for radiation resistance. These developmental problems were overcome at DMI-5, at which point the new design began to have problems reaching mass targets. Before DMI-6 was reached the component demonstrated that it already met DMI-7 requirements for operating efficiency. The progress of this component can be mapped in a simple matrix as shown in Table 2.

This method provides program managers with a simple method to focus resources and identify troublesome areas during the maturation of a new design. It also focuses attention in the areas where trades can be conducted to ease the development burden. Often a spacecraft requirement can be relaxed if a technology is having extreme difficulty in meeting a certain requirement. The spacecraft program manager can assess whether relaxing a certain KEPP to provide relief to the technology developer can be compensated for in other areas of the overall spacecraft design. This simple matrix also assists the spacecraft program manager in creating an "exit strategy' for a given technology. In high-risk developments, spacecraft teams will often maintain a back-up design in case problems are encountered during the technology maturation process. The matrix shown in Table 2 can be translated into decision criteria to help determine when to shift to back-up plans.

DMI	3	4	5	6	7
Operating Efficiency	3	4	5	7	7
Dynamic Load Resistance	3	4	5	6	7
Operating Voltage	3	4	5	6	7
Power Regulation	3	4	5	6	7
Radiation Resistance	2	3	5	6	7
Emissivity	3	4	5	6	7
Component Mass	3	4	4	5	7
Operating Temp	3	4	5	6	7
DMI RANGE	**1**	**1**	**1**	**2**	**0**
AVERAGE DMI	**2.9**	**3.9**	**4.9**	**6.0**	**7.0**

Table 2: Quantitative Maturity Measure for Notional Component

This technique has limitations. The use of averaging, while simple and straightforward, can be misleading. Serious developmental problems can be hidden within the average DMI value. This affect is somewhat mitigated by monitoring the *range* of the spread in addition to the average, but single values cannot communicate a full picture of actual status. The example shown in Table 2 includes only eight KEPPs; in practice complex technologies might have many more. This would further act to disguise problems. More sophisticated methods could be employed to refine this technique. The most obvious is applying weights to the various KEPPs. Some KEPPs may be more important that others and some may be critical to the success of the mission; these can be weighted accordingly. Additional statistical methods can also be used within the matrix to highlight trouble spots.

Applying Key Parameters to Advanced Designs

RAND reviewed technology development projects in industry and government to observe the key factors that influence the maturation and infusion process. Here, two examples have been selected to illustrate the creation of KEPPs.

The first example is a self-rigidizing beam structure. Future spacecraft could deploy large structures in space by using inflatable systems that become rigid in the radiation and temperature environment of space. An example of an inflatable beam is shown in Figure 8. As shown in Figure 8, this beam will form the booms that will carry the load and form the structure of a 70m x 70m solar sail. This mission, under development by Team Encounter, LLC of Houston, Texas, will deploy the largest solar sail ever formed in space and represents the first use of such technology for primary mission propulsion.[10]

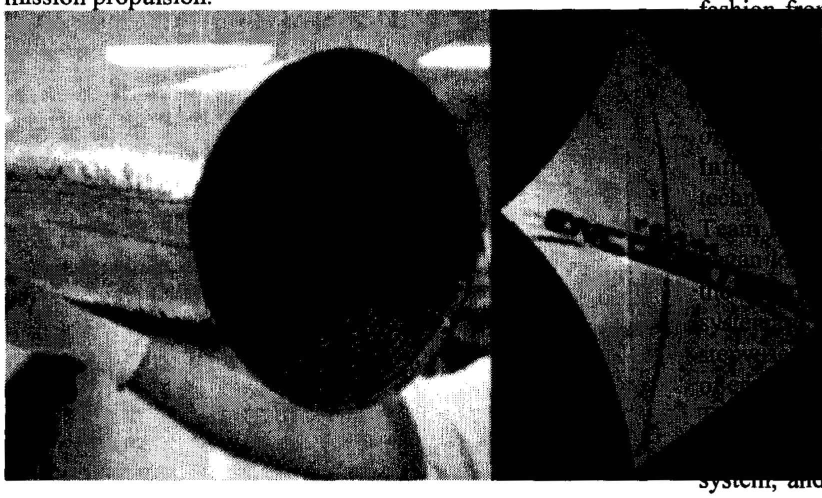

Figure 8: Self-Rigidizing Beam for Use in Solar Sail Spacecraft

Inflatable beam technology has been used in space before. For example, NASA's Inflatable Antenna Experiment, flown in 1996, used an inflatable beam structure to form a parabolic antenna. The beams used to form the structure of the solar sail will be much larger, however, and will have the additional feature of becoming rigid shortly after they deploy in space.

In the case of this mission, a separate firm, L'Garde, Inc. of Tustin, California, is developing the technology for the beams. This mission demonstrates an extreme example of interdependence of a mission on an advanced technology. Meeting the primary objectives of the mission can only be met if the technology development is successful. Further, as a commercial venture, the mission has firm funding goals. The communication of technology requirements between Team Encounter, LLC and L'Garde, Inc. is extremely important. The spacecraft team and the technology team are not co-located and have very diverse cultures. L'Garde is a firm with a strong R&D culture that has pioneered the development and production of inflatable space structures. Team Encounter, LLC is a commercial space firm with a strong entrepreneurial foundation, supported largely by venture funding. The success of the mission is very important to both firms and the technology being pursued is unprecedented in terms of complexity and performance.

Inflatable, self-rigidizing beams are simple in concept but very difficult to deploy in practice, especially at the dimensions needed to support the solar sail. The beams consist of a flexible material that is tightly folded into a stowed configuration for launch. The beam material is coated with a resin that hardens when deployed in the cold of space.[11] Deployment begins with a high pressure gas being introduced into the base of the stowed beam. As pressure increases, the beam slowly deploys in a stable [illegible]n the stowage container. Deployment continues [illegible]l length of the beam is reached and gas pressure [illegible]e beam's shape as it becomes rigid.

[illegible]le also illustrates the wide variation in definition [illegible]nstitutes the "readiness" of a new technology. [illegible]eams have been used in space before and the [illegible] carries a relatively high TRL level. For the [illegible]unter application, however, the beam technology [illegible]n terms of the TRL index. More useful for both [illegible]ogy and spacecraft development teams was a [illegible]neans of evaluating technical performance in a [illegible]nner. Both teams rely on a common definition [illegible]ng parameters to define progress.

[illegible] for the inflatable beam technology are shown in [illegible]he parameters on Table 3 consists of component, [illegible] environmental factors described earlier. Many of the parameters focus on the mechanical properties of the beam, ensuring that the beam, once rigid, can support anticipated loads without buckling. The natural frequency of the beam must also be low and not in the range where bending of the beam is excited by motions of the spacecraft. The packaged beam must also fit within narrow mass allowances. Leakage rates are also critical since the spacecraft carries little extra pressurant and even small disturbances from a venting gas could generate forces destabilizing the spacecraft. Finally, the most important parameter is constructing a beam more than 50 meters long. The project has currently successfully matured the beam technology from DMI-3 to DMI-5.

Another example of technology maturation and the use of DMIs is a holographic memory module, shown in Figure 9. This device stores image data inside of a cubic photorefractive crystal. The images provide a three

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[10] This solar sail mission is being developed by Team Encounter, LLC, a commercial space firm pursuing the use of this technology for a series of missions to carry payloads out of the solar system.

[11] These types of beams can be hardened either by irradiation or by exposure to the low-temperature space environment.

dimensional representation of the data and remain in a non-volatile state until erased (Chao, 2001).[12] Holographic technologies offer the promise to meet all of NASA's spacecraft requirements for large capacity, non-volatile memories. It is possible to transfer data to the holographic memory device at very high speed. These modules are also resistant to radiation and can store large amounts of memory with little power required to transfer data into or out of the device.

evel	3	4	5	6	7
1	2 m	7.6 m	7.6 m	14.1 m	56 m
Density	30 g/m	25 g/m	20g/m	18 g/m	15 g/m
ng Stiffness	9000 in-lbs./in	12000 in-lbs./in	16000 in-lbs./in	16000 in-lbs./in	18000 in-lbs./in
ression gth	150 lbs.	150 lbs.	175 lbs.	200 lbs.	210 lbs.
ng Moment at ng	1500 in-lbs	2000 in-lbs	2500 in-lbs	3000 in-lbs	32[illegible]0 in-lbs
al Frequency	<40 Hz	<40 Hz	<35 Hz	<30 Hz	<30 Hz
ge	5% prior to rigidization	2% prior to rigidization	1% prior to rigidization	.5% prior to rigidization	.25% prior to rigidization
als	IRD-2 Cotton	Kevlar 281	Kevlar 281	Kevlar 281	Kevlar 281

Table 3: KEPPs for Self_Rigidizing Beam Technology

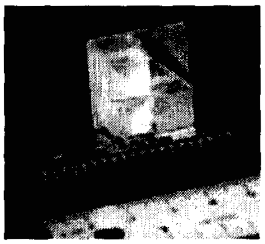

Figure 9: Prototype Cubic Holographic Memory Module

KEPPs for a holographic memory device are outlined in Table 4. The current plan call for a nearly two orders-of-magnitude improvement in memory storage capacity, and several orders-of-magnitude reductions in error rates during successive read/write cycles. These are significant development challenges.

The application of KEPPs is a structured method to bring technology developers and spacecraft engineering teams into close communication at the outset of a project. This is a vital step in the infusion process. It helps ensure that expectations are being realistically established at the outset. The step alone is, however, insufficient to assure the smooth maturation of technology. Technologists must be able to design effective risk reduction strategies. A forum is also needed for effective communication between the technology and spacecraft development teams. These two additional attributes are the subject of the next two chapters.

[12] A volatile memory refers to a condition where data is retained only as long as electrical power is maintained to a device. A non-volatile memory will retain data even when electrical power is removed.

DMI	DMI-3	DMI-4	DMI-5
Memory Storage (GB)	20	100	200
Bit Error Rates	10^{-08}	10^{-07}	10^{-08}
Readout time (μsec)	5000	1000	500
Storage Time (weeks)	2	8	25
Radiation Tolerance (krad)	50	50	50
Bus Type	Any	SCSI	SCSI
Lifetime (years)	0.5	1	2
Thermal Operating Range (°Celsius)	20	30	30
Number of Read/write cycles	1000	1000	10,000

Table 4: KEPPs for Holographic Memory Module Technology

4. Technology Risk Reduction

The process of maturing a technology is, in a fundamental sense, a risk reduction effort. In order to accept a new design, spacecraft engineers must be able to validate performance and understand the residual risks. Since no program has unlimited funds to test performance and reduce risk, some *residual* level of risk remains when a technology is first used. RAND found that uncertainty about this residual risk is a major reason for the reticence associated with using new technology. This is, therefore, an important barrier to raising infusion rates.

Performance targets are outlined in the KEPPs. It is expected that the technology developer has used traditional, and, in some cases, novel, test methods to demonstrate performance and reduce risks. Since funding is usually limited, the technology developer is faced with the familiar problem of crafting a cost-effective test program.

This chapter outlines a strategy for developing a test program that is based on quantitative methods and a historical evaluation of the effectiveness of various test methods. The application of such a structured strategy provides the technology developer, who may be unfamiliar with the methods used to test spacecraft systems, with a tool containing embedded space test algorithms. It is hoped that the application of a such a tool will deliver outputs familiar to spacecraft engineering teams, thereby increasing the likelihood that a technology is readily accepted.

Methods of Reducing Risk

Technology developers are faced with the difficult task of proving the performance of unprecedented designs as well staying within a budget that is often tightly constrained. The technology developer must first prioritize risks and then design a test strategy that ensures a balanced approach to risk reduction. Funds must be directed to retiring the greatest risks first. At the end of the process, at DMI-7 where the technology is finally integrated on the spacecraft, the technology developer must have some way of identifying the residual risks associated with the design. The allows the spacecraft engineering team to develop strategies for mitigating this residual risks, for example, the specific use of redundant systems.

The maturation of an advance designs can be viewed as a process of applying prevention, analyses, controls, and tests (PACTs), a schema shown in Figure 10. PACTs are designed to remove defects and errors. Problems are often traced to poor workmanship, or problems with parts and components used in the design. Particularly in the case of advanced technologies, errors are often traced to the design process itself.

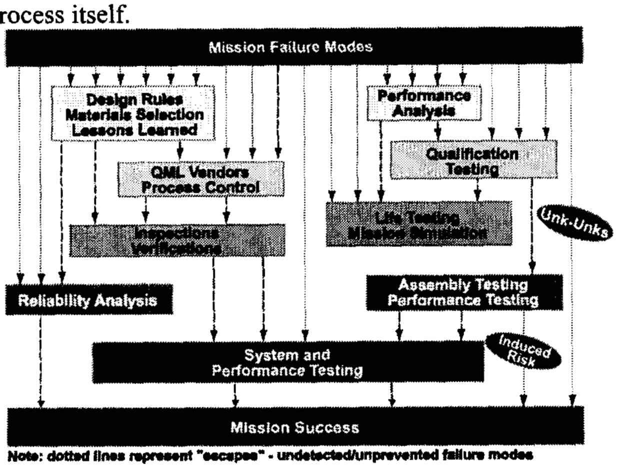

Figure 10: The PACTs Template

The suite of PACTs available to engineers is not equally effective. A given PACT may be highly effective at locating a certain type of defect and very poor at locating others. When a set of PACTs is applied to a new design the odds that a defect will escape (shown in dashed lines in Figure 10) are sharply reduced. Selecting the right set of PACTS for a given type of technology is, however, a significant challenge. For advanced technologies, cases can exist where unknown problems exist and slip through undetected (these are the so-called "unknown-unknowns," or "unk-unks," shown in Figure 10). The PACTs schema is largely made up of engineering tests and these tests can themselves introduce risks into a system. For example, the process of vibration testing, a necessity in spacecraft systems, can introduce mechanical stresses that later lead to failures. This is shown in Figure 10 as induced risk.

Designing a Cost-effective Test Plan

To mitigate risks associated with using a new technology, developers must prepare a roadmap of performance milestones with accompanying PACT activities. Often this process is highly intuitive and ad hoc. Development teams craft a roadmap largely based on experience of team members. For technology development efforts, where in-depth experience with spacecraft development practices may not be available, the process of creating a useful roadmap is fraught with difficulties.

A more structured approach provides technology developer with a framework for using KEPPs to drive toward a set of PACTs with the greatest likelihood of locating defects and retiring risk in a cost-effective way. The strategy outlined here, the Defect Detection and Prevention (DDP) tool, was developed by the Strategic Systems Technology Program Office at NASA's Jet Propulsion Laboratory (JPL) specifically to assist with the development of advanced spacecraft systems.[13]

The DDP tool is a computer-based method of deriving PACTs that are tailored to a given application. The DDP tool provides a mechanism for displaying the risk reduction investment in the form of a Pareto chart, shown in Figure 11.

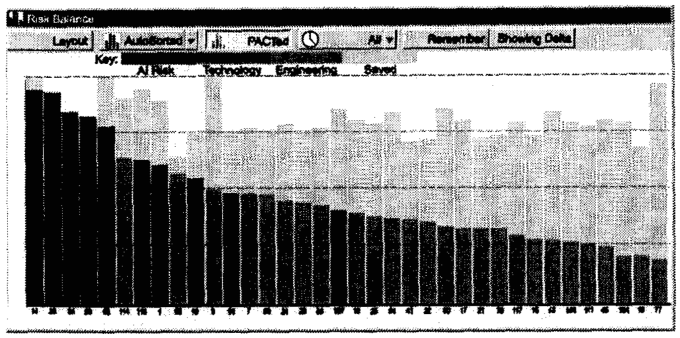

Figure 11: Risk Reduction Plot for Technology Application

The chart shown in Figure is generated by the DDP tool. It depicts the level of risk (determined by the height of the bars) at each DMI increment. Each bar relates to a specific risk identified by the development team. The example shown in Figure 11 represents a case when risk levels have been significantly reduced. The height of the green bars reflects the initial level of risk level. As the process of maturing a technology continues the levels drop. In this example, the majority of risks are associated with "engineering" items, the remaining risks due to difficulties with the technology (shown in purple) have been essentially eliminated. Critical risk areas that have not been significantly reduced are shown in red.

Use of the DDP begins with a decomposition of KEPPs into a matrix of risks. The risk matrix is a portrait of the various problems that could be encountered during the development of a given system – in this case a new technology. The DDP tool contains algorithms that link potential risks with available PACTs. The costs associated with those PACTs are also built into the DDP tools. By linking requirements, risks, test strategies, and cost, the DDP tool allows the technology development team to craft a test plan offering the most cost-effective way of mitigating risks for a given technology.

As shown earlier in Figure 6 , the process is cyclical. The DDP tool is used at each DMI increment, and, as the new design matures, the level of risk is reduced in a stepwise fashion. At each DMI increment, the level of residual risk can be displayed using the DDP tool as a Pareto chart. This sequential reduction of residual risk is shown in Figure 12.

[13] A full description of the DDP tool can be found in Cornford, et al., 2001.

This output provides a ready means for the management team to identify high risk areas, and it provides a clear mapping of where residual risk can be found at each step in the process. This information can be readily transmitted to spacecraft teams.

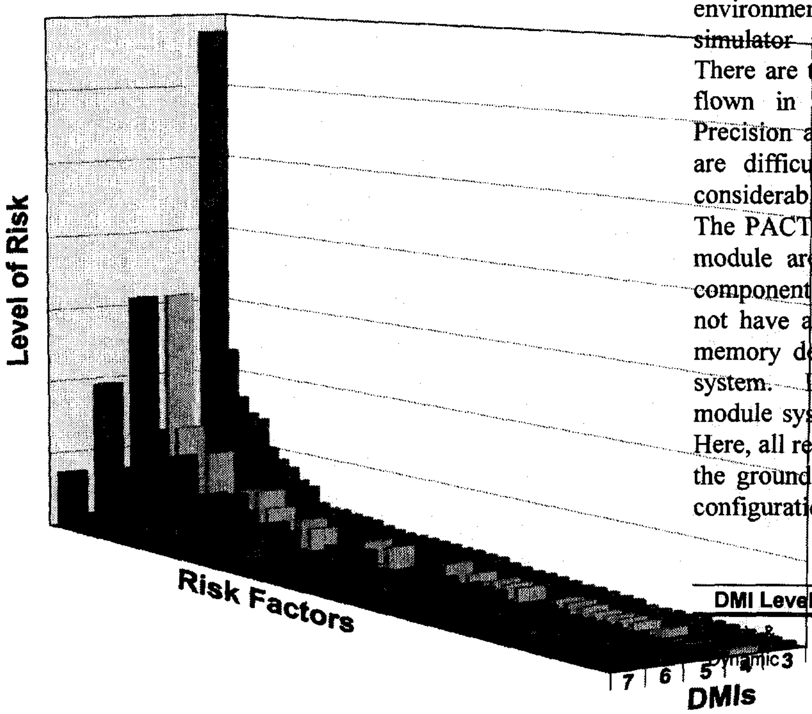

Figure 12: The Stepwise Reduction of Risk

Software instruments designed to assess risk, like the DDP tool, are not fully automated. The DDP tool requires engineering judgement to identify the risks associated with meeting a given requirement, as well as the potential impact on the system if a given risk is realized. The DDP tool does, however, contain a good deal of information to guide and structure analyses. For example, the system contains data generated from NASA's Test Effectiveness Program. This program measured the ability of various engineering tests and evaluation practices to discover defects. By embedding such quantitative data, the DDP tool increases assurance that a selected set of PACTs have a high probability of reducing errors. This assurance is an extremely valuable element of preparing a technology for flight readiness.

Applying Risk Reduction to Advanced Designs

Structured risk reduction strategies, as represented in the use of the DDP tool, result in developmental roadmap consisting of PACTs. In Tables 5 and 6, examples are shown for the self-rigidizing beam and the holographic memory module technologies described earlier.[14] These PACT roadmaps are designed to provide validation that the KEPPs at each DMI increment have been adequately met.

In Table 5 it can be seen that the maturation cycle requires actual testing in space at DMI-6. In this case, there are no available PACTs available on the ground to provide adequate performance validation. Usually, new designs can be adequately matured using low-cost, ground-based environmental simulators, such as drop towers, low-g ~~simulator~~ aircraft, and space thermal-vacuum chambers. There are times, however, when a new technology must be flown in space; deployable systems are an example. Precision apertures, tethers, and inflatable space structures are difficult to test on the ground and they represent considerable technical risk.

The PACTs shown in Table 6 for the holographic memory module are more focused on addressing KEPPs that are component oriented. This is because this technology does not have a large effect on other spacecraft systems. The memory device is, for all intents and purposes, a passive system. It must survive environmental factors, but the module system itself does not tax other spacecraft systems. Here, all required tests and assessments can be performed on the ground, and the technology delivered in a flight-ready configuration.

DMI Level	3	4	5	6
	• Computer simulation • Compression test on sample boom section	• Computer simulation • Compression test on sample boom section	• Control disturbances characterized • Computer dynamics model validated	• Control response visualized ir space environmen • Computer dynamics m validated
Mass	• Mass balance	• Mass balance	• Mass balance	• Mass balaı
Materials	• Tensile/shear testing	• Tensile/shear testing	• Tensile/shear testing	• Tensile/sh testing
Deployment	• Bench testing in ambient environment	• Deployment in water trough	• Extension in ambient water trough • Extension in thermal-vacuum chamber • Deployment in zero-g simulator aircraft	• Vacuum deployment space environmen
Environment Testing	• Sample chilled to rigidization temperature for loads test	• Vacuum deployment at space temperatures • Sample chilled to rigidization temperature for loads test	• Vibration testing of packaged (pre-deployment) beam • Thermal-vacuum testing of packaged and inflated beam • Radiation effects tested in space chamber • Sample chilled to rigidization temperature for loads test	• Vibration, temperature and vacuur testing of packaged (ᵱ deployment) beam • Vacuum deployment space environmen

[14] The tables shown here are high-level representations of actual test plans. Application of the DDP tool will typically produce very detailed test plan that cannot be reproduced in the space of this report.

Leakage	• Leakage estimated through analytical simulation • Leakage rates bench tested	• Leakage rates bench tested • Leaks characterized by observation of inflation in water trough	• Leakage rates measured in vacuum chamber	• Leakage rates measured in space environment	• Leakage rates measured in space environment

Table 5: PACTs for Self-Rigidizing Beam Technology

DMI	DMI-3	DMI-4	DMI-5	DMI-6	DMI-7
Component Performance Testing	• Store/retrieve image • Estimate BER • Estimate # of R/W cycles	• Store/retrieve multiple images • Simulate BER • Measure readout time • Extrapolation of # of R/W cycles	• Store/retrieve multiple images of different types • Measure BER • Measure readout times versus image size • Extrapolation of # of R/W cycles	• Store/retrieve multiple images of different types • Extrapolate BER • Determine readout times versus image size • Extrapolation of # of R/W cycles	• Store/retrieve multiple images of different types • BER measured • Document readout times versus image size • Determine # of R/W cycles
Integrated Performance Testing	• Bench testing of components • Simulation of integrated performance • Identification of key integrated performance parameters	• SCSI bus • Compare nearby images after storage for cross-talk • Compare Readout images after storage time	• SCSI bus • Analyze degradation after writing 'nearby' image • Analyze degradation after various storage times	• FireWire bus • Statistical analysis of degradation after writing different 'nearby' images • Statistical analysis of degradation	• Flight FireWire • Statistical analysis of degradation after writing different 'nearby' images • Statistical analysis of degradation
Environment Testing	• Bench operation (survival at extreme temperatures) • Estimate vibration sensitivity • Estimate radiation tolerance of components	• Bench operation (extrapolate to operation at extremes) • Model/analyze vibration sensitivity • Model/analyze radiation tolerance of components	• Atmospheric chamber thermal testing • Model/analyze vibration sensitivity • Model/analyze radiation tolerance of components • Model/analyze EMC/EMI	• Thermal Vacuum test • Sine survey /random vibration testing • Lab source radiation dose /SEU testing • Component EMC/EMI testing	• Thermal Vacuum test • Sine survey /random vibration testing • Flight radiation dose/SEU testing • System EMC/EMI testing
Materials and Parts	• COTS parts • Prototype materials	• COTS parts • Analysis of flight parts /materials challenges • Prototype materials	• Key flight electronics/materials components • COTS parts • Initial flight part/materials list	• Flight electronics /materials components • Flight-like processes and flight processes defined	• Flight electronics /materials components • Flight processes utilized

Table 6: PACTs for Holographic Memory Module Technology

The DDP tool is an example of a risk management system. It is not clear who should own and operate software tools like DDP. Such tools require training and considerable experience to effectively apply. Technology and spacecraft development teams are typically resource-constrained environments and there is little time to learn and apply something like the DDP tool. The next chapter proposes the use of a technology broker to maintain support tools like the DDP, as well as performing other functions critical to raising infusion rates.

5. MAINTAINING CONTINUITY THROUGH BROKERAGE

The previous chapters discussed the well-known cultural and functional gaps between the worlds of the technology and application teams. There clearly is a need for technology developers to communicate with and understand the users culture (Pacey, 1986). There is also a need for programmatic continuity in the implementation process. The gulf between technology developers and users has been perceived to be as large as to require the creation of a "technology broker" to unite the two cultures. Time is another important factor. Technology development teams tend to be significantly understaffed. A recent management study found that 40 percent of technology teams studied were inadequately staffed (Lucas, 2001).

The notion of employing a technology broker is not new. Brokerage is often used in the private sector, both here in the U.S. and extensively in Europe, to speed the process of bringing new ideas to the market. The large paybacks associated with commercial technological innovation helps fund brokerage houses and they have a very good track record of assisting with new product development.

The Federal government also employs technology brokers, although the main focus of such offices is often technology transfer. Leveraging the large government investment in R&D to improve the performance of the U.S. economy has been the subject of much lawmaking. Seeing to it that Federal R&D investments "spin-off" technology to the private sector has led to the creation of many technology transfer offices within government agencies. More recent attention has been focused on the "spin-on" technologies where the government benefits from private sector technology investments. Small Business Innovative Research and Small Business Technology Transfer programs throughout the government are designed to pull innovation from small private firms into government programs. In each case, these offices exhibit many of the attributes attributed here to a technology broker. Within the context of this report, however, the discussion is narrower. Here, the use of a technology broker is focused on addressing the challenge of integrating new designs into the process of developing main mission spacecraft. The technology being used to meet spacecraft requirements can come from technology developers within the NRO, within government agencies, or from external sources. The source of the technology is less important than the practice that provides a structured mechanism for maturing new designs and ensuring they are used.

The creation of a technology broker function can help assure this structured approach exists within an organization. Creating an internal brokerage signals clear intent within an organization that senior management is committed to the infusion of technology into evolving product lines. Often a desire for new technology requires trading short-term investment for long-term gain. This is a strategic decision made on the part of agency managers and the broker is the tool used to implement this strategy.

Examples of a Technology Broker

The Federal government is using technology brokerage more often and with greater effectiveness. As experience with the use of brokers increases, the role that it plays in organizations is becoming more refined. These organizations are increasingly well funded, often with funds supplied from the end-users. Examples of such organizations within aerospace and military arena include:

> **National Oceanic and Atmospheric Administration (NOAA) Technology Transition Office (TTO)** – this office is focused on locating new technology to meet future operational requirements. It has a broad mandate to seek out technology solutions in government, academia, and industry. It has the mission *and the funding* to identify, evaluate and promote, new technologies through feasibility studies, proof-of-concept studies, and technology demonstration efforts. This activity includes proposing potential interagency working agreements for joint-product development efforts. The TTO presents new technology proposals to NOAA programs ensuring that proposals are adequately defined, technically feasible, and useful for the satisfaction of operational requirements.

> **Marine Corps Systems Command's Technology Transition Office (TTO)** – this organization was established specifically to increase the rate at which innovative technology made its way to Marine Corps operating personnel. The TTO exercises a good deal of financial authority over technology spending to ensure funding continuity and the rapid incorporation of technology. Here too, the organization monitors end-user requirements carefully and has a broad mandate to solve problems that lead to the acquisition of improved products.

> **Office of Naval Research's "Swampworks"** – has a similar charter to the aforementioned TTOs. The goal of the Swampworks is to locate technology solutions and apply them to meet U.S. Navy requirements in far less time than traditional solutions. The Swampworks actively funds new developments, ensuring programmatic continuity and shops broadly for the best technology solutions.

These examples are representative of the notion of a technology middleman who functions to carefully study requirements and find solutions. The focus is on delivering best value and ensuring that requirements are met as quickly and cost-effectively as possible.

The Role of the Broker

A technology broker works 'each side of the street' when it comes to finding and implementing new technology. The broker's job is to create a practice that can repeatedly used to accomplish an unchanging goal – improved infusion rates that lead to better system performance.

As shown in concept in Figure 13, the technology broker's main function is to assist with the performance of the tasks outlined in Chapters 3 and 4. The broker must help interpret requirements, translating them into the KEPPs that are provided to the technology development team. The broker must also understand how to use risk tools, such as the DDP tool, to help build an effective maturity roadmap. The broker must also provide accurate assessments of status to the spacecraft developer. This important assurance helps to reduce risks to the development team, include alerting the project manager if the technology development is experiencing difficulty.

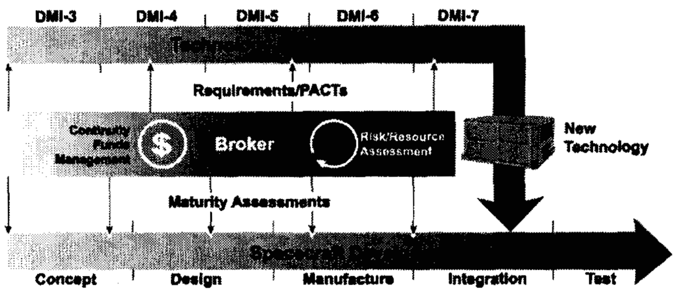

Figure 13: Concept of the Technology Broker Function

The broker serves "pull" and "push" functions, matching technologies from a inventory against ever-changing spacecraft requirements. Technologies are pulled from available sources and pushed to programs with challenging requirements. The broker is serving to form alliances between groups that may or may not be aware of each other.

The brokers job is to perform the functions that neither the technology developer nor the spacecraft team have time to address. These are the very functions that more piecemeal processes often fail to adequately perform, allowing technology projects to languish and spacecraft cost and schedule estimates to grow. The broker does not do the job of either party. Instead, the broker serves to integrate and to provide the management expertise needed to keep the process of maturation on track.

To be successful, the broker must canvass technology programs in the broadest sense, examining and tracking initiatives in civil, military, academic, and commercial space programs. The broker must also be able to accurately assess maturity and the risks associated with a new technology, and is, therefore, a consumer of tools such as those outlined in the previous chapters.

Technology developers often welcome the activities of the broker. Few managers wish to work on technology projects that are not readily accepted by the user community once the promise of a new design has been demonstrated at the laboratory level. Implementation is the goal of the technology developer, as it is the broker. The brokers job is somewhat harder in terms of pushing technology to the user. The ability to accurately assess and communicate performance, cost, and risk to the user is key to overcoming this resistance. In this regard, the broker is better equipped than the technology developer and has a greater chance of success.

A technology broker serves, therefore, to support and guide the many functions that must be performed successfully if a technology is to be infused into a spacecraft. These functions include multiple skills that are unlikely to be found in either the technology development or spacecraft development organizations. Technology brokers must:

Help define quantitative measures – preparing the quantitative measures outlined in Chapter 3 is not a simple affair. Crafting the appropriates KEPPs requires negotiation and the broker must understand the capabilities and motivations of both the technology and spacecraft developers. Evaluating the stepwise progress of the technology through the TRL process also requires independence. The broker is in a position of autonomy and can render an unbiased judgement. This is extremely important in permitting the spacecraft team to move forward with a fair assessment of risk. As the technology matures, opportunities for the application of alternative techniques and systems will evaporate and beyond a certain point it will be very expensive to make a change. The spacecraft team must trust the ability of broker to render accurate quantitative assessments of technology maturity at key milestones in the development process.

Assist with risk management – the broker is in a good position to own and operate risk management software like the DDP tool. Understanding of risk management tools often varies dramatically throughout an organization. Some engineers and managers are adept at using such tools, others have little working knowledge. The broker, skilled in the use of such systems, can help ensure consistency.

Ensure a common language – as previously mentioned, the two cultures involved in developing and using new technology speak different languages. The broker must be an expert in both, with the demonstrated ability to provide information in a form usable by both parties. RAND found that often, in discussions about technology, developers and users think they hear the same thing, only to find later that the meaning of terms was misconstrued. The broker must build a common vocabulary that ensures effective communications and realistic expectations.

Evaluate Requirements – Helping to define and apply KEPPs is one of the most important contributions of the broker. The task of the broker does not, however, end there. The broker may have several technologies that could potentially meet the stated spacecraft requirements and will have to evaluate the cost and risk of these alternatives. Also, during the development process the inevitable difficulties that occur may require refinement of the KEPPs. In some cases, problems encountered in the development of a technology can be dealt with by some relaxation in the KEPPs. The broker must understand the sensitivity of requirements to both the technology and spacecraft developers.

Create standard definitions – the process of technology maturation includes many definitions that unfortunately are not standardized. Within a given organization, the broker must help establish these definitions so that each party understands milestones. The definition of TRL-5, for example, includes the terms "breadboard validation in relevant environment." The broker must create clear definitions for what constitutes a "breadboard" for a given application, as well as the "relevant environment" that will be acceptable to the spacecraft development team.[15]

Provide programmatic continuity – one of a technology brokers main tasks is to work to assure continuity for the technology development effort. Funding stability is, of course, the most important element of this continuity. The broker can act as an escrow agent to retain the bridging funds (including reserves) needed to ensure progress of the technology. These funds can be supplied from a separate pool of money provided by the parent organization to the broker expressly for the purpose of ensuring continuity. Another mechanism for funding is to include brokerage funds in the budgets of both the technology and spacecraft development budgets. These liens on project funds implies that a budget shortfall exists within both the technology development effort and the spacecraft project. This shortfall can only be removed if a) the technology development effort is successful, or b) it fails and the broker releases funds to the spacecraft team so they can

[15] A breadboard is an assembly of parts and components used to prove the feasibility of a device, circuit, system, or principle with little or no regard to the final configuration or packaging.

pursue alternative methods of meeting requirements.

Facilitate planning – technology planning is an important element of building improved spacecraft. Activities like the Space Technology Alliance are, however, difficult to coordinate. The existence of a broker organization, whose single purpose is the successful infusion of technology, can assist with the task of technology planning. Planning of this kind requires an agent with in-depth knowledge of both technologies under development and the user requirements for technology. Often neither the technology developer nor the user has time to adequately address planning and the ability to coordinate planning efforts suffers accordingly. A technology broker is in an excellent position to act as an organization's planning agent. The broker must understand an organization's technology projects and goals, and must rely on information about projects in other agencies in order to respond to emerging requirements.

These functions are very important in the process of ensuring that technology is more quickly integrated into future spacecraft systems. Most importantly, the tasks outlined in Chapters 3 and 4 are difficult to accomplish by engineering teams immersed in the job of meeting challenging technical milestones. The technology broker provides a much needed support function; attending to tasks that busy technical would otherwise treat with lower priority.

6. Conclusions

As the pace of technological development continues to accelerate, new ways to infuse advanced designs will be needed. DoD, partly reflecting this awareness, has begun to embed technology maturity measurement in the acquisition process. The indices used to access the readiness of new designs therefore take on added importance.

The most widely used method in the aerospace community to assess readiness is the NASA-developed TRL. This index is a simple to use device that permits managers and engineering teams to communicate information about a given design. The index is informative and is widely used; including being applied within various cost and risk management computer tools. When applied to specific applications, where precision is needed to assure project integration, the TRL index, as a subjective measurement, is inadequate.

Technology infusion is not simply about having an accurate accounting scheme, however; there are significant cultural barriers that often inhibit progress. Spacecraft engineering teams and understandably reticent when faced with the task of embedded a complex new technology in a product with firm cost and delivery targets. Technology developers are often unfamiliar with the process of building equipment that must operate in the field with high levels of reliability. New techniques for measuring the maturity of a technology must be sensitive to the motivations of the various stakeholders and find ways of bridging this cultural gap.

The three-step process described in this report aims to better integrate technology development and spacecraft development teams. The DMI index provides a point value that is more accurate that a TRL in that it is linked firmly to requirements that are drawn up cooperatively by both technology and spacecraft engineering teams. These requirements, expressed in the form of KEPPs, are much less open to interpretation that the definitions used in the TRL system. The result is a simple index that can still be used in cost and risk calculations.

The process includes two other features that are very important in the process of infusion. First, the risk measurement tool allows technology developers to balance risk to come up with the most cost-effective test plan possible. Second, a technology brokerage provides the much-needed intermediary function that brings together the key elements during the infusion process.

The three elements - quantitative measure, risk tools, and brokerage - provide a means of improving infusion rates, in turn leading to more capable space systems. These new practices can be tested on a small scale to evaluate their broader utility. The application of these techniques does not require large investments; the tools and techniques are in hand and require only modest organizational shifts to bring them into play. It is hoped that their application will help improve the management of complex spacecraft projects and the delivery of more capable systems on-orbit.

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The elements of this research have been conducted within

Discussions with TBD have been most useful in helping us formulate our ideas and bring them to fruition.

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BIOGRAPHIES

Liam P. Sarsfield *is the Deputy Chief Engineer for Programs at NASA Headquarters. He is responsible for the independent assessment of NASA programs, and also efforts to improve Agency project management practices.*

Prior to joining NASA, Mr. Sarsfield was a Senior Analyst at the RAND Corporation's Science and Technology Policy Institute (STPI). While at RAND, Mr. Sarsfield led many investigations associated with the development of advanced aerospace systems. His research involved the development of advanced national space systems and the effectiveness of efforts to streamline spacecraft development practices. Mr. Sarsfield also led a comprehensive review of the National Transportation Safety Board related to the conduct of aviation accident investigations. He is the author of several books on spacecraft development practices and advanced technology development.

Before RAND, Mr. Sarsfield was Deputy Director of the Special Payloads Division of the Lockheed Martin Corporation in Greenbelt, Maryland where he managed the development of research spacecraft for the NASA Goddard Space Flight Center. His technical background is in space physics and propulsion. Additionally he has a laboratory background in fluid dynamics and the low-gravity processing of materials, and has led design studies of ground and space-based facilities for the conduct of scientific investigations, including the implementation of the International Space Station. Mr. Sarsfield's career began at the NASA Glenn Research Center in Cleveland, Ohio. He holds degrees in mechanical engineering and public policy.

Steven Cornford *is a Senior Engineer in the Strategic Systems Technology Program Office at NASA's Jet Propulsion Laboratory. He graduated from UC Berkeley with undergraduate degrees in Mathematics and Physics and received his doctorate in Physics from Texas A&M University in 1992. Since coming to JPL he focused his early efforts at JPL on establishing a quantitative basis for environmental test program selection and implementation. As Payload Reliability Assurance Program Element Manager, this evolved into establishing a quantitative basis for evaluating the effectiveness of overall reliability and test programs as well as performing residual risk assessments of new technologies. This has resulted in the Defect Detection and Prevention (DDP) process is the motivation for this paper. He received the NASA Exceptional Service Medal in 1997 for his efforts to date. He has been an instrument system engineer, a test-bed Cognizant Engineer and is currently involved with improving JPL's technology infusion processes as well as the Principal Investigator for the development and implementation of the DDP software tool. Steve is the one in the middle of the picture.*