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# INTRODUCING NEW TECHNOLOGIES INTO SPACE STATION SUBSYSTEMS

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## I. Abstract

In a cooperative effort between Kennedy Space Center, Stanford University and Lockheed Space Operations Company, a new systems engineering methodology has been developed and applied in the operational world of Shuttle processing. The new engineering approach stresses the importance of identifying, quantitatively assessing, and managing system performance and risk related to the dynamic nature of requirements, technology, and operational concepts. Under the cooperative program entitled, **Space Systems Integration and Operations Research Applications (SIORA)**, the modernization of the processing operations for the Shuttle thermal protection system (TPS) or tiles became the first application of the engineering methodology. This effort adopted an approach consisting of an integrated set of rapid prototyping testbeds in which a government/ university/industry team of users, technologists, and engineers tested and evaluated new concepts and technologies within and in parallel to Shuttle processing operations. The integrated set of technologies introduced included speech recognition and synthesis capabilities, laser imaging inspection systems, distributed Ada programming environments, distributed relational database architectures, in addition to distributed computer network architectures, multi-media workbenches, expert system applications, probabilistic risk assessment modeling, and human factors considerations. The successful operational implementation of the integrated prototype, referred to as the Space Shuttle Tile Automation System, has validated the engineering methodology and strongly indicates that the same approach would be a viable systems engineering and project management tool for Freedom Space Station. This paper will address the lessons learned from the Shuttle processing experience and will present concepts which are applicable to the design and development of the Freedom Space Station.

## II. Introduction

The technology base needed for the efficient and effective design, development and operation of the Space Station is readily available today. Although true, a 1988 Congressional Office of Technology Assessment (OTA) report entitled, "Reducing Launch Operations Costs: New Technologies and Practices", was critical of space-related systems being operated and developed by the Department of Defense (DoD) and NASA. In recent years, the traditional systems engineering and project management approaches utilized by NASA and the DoD have failed to provide a means to incorporate rapidly evolving technologies and operations concepts into system developments or system upgrades. The development of an operationally efficient and productive Freedom Space Station, with its long term utilization goals and rapidly changing technology environment, will severely test traditional systems engineering approaches. This paper will address this issue and describe a systems engineering methodology which will provide a means to accommodate changing user needs, incorporate emerging technology, identify, quantify and manage system risks, manage evolving functional requirements, track the changing environment and reduce system life cycle costs.

## III. Background

Since the Second World War the science of system engineering has evolved to where it now offers a demonstrated methodology for developing very complex, high technology systems. This methodology involves the process of defining systems needs, developing performance requirements, evaluating alternatives for meeting these needs and selecting the best available alternative, and then repeating the process at a more detailed level until a cohesive, integrated set of traceable requirements have been constructed. Detailed designs can then be formulated and implemented. System engineering performs an oversight function to ensure system performance. The impetus for the adoption of this engineering methodology in the aerospace industry has been the fact that aerospace systems must work properly the first time and this engineering methodology has been effective at ensuring this reliability.

This engineering approach was developed in the late 1950's and early 1960's for the development of the intercontinental ballistic missile (Thor, Atlas, etc). It was refined during the development of the Polaris submarine launched ICBM. The civilian space program also used this engineering approach on a number of programs ranging from the first American unmanned satellite launch of Explorer 1 in January 1958, to the landing of the first man on the moon in July 1969. Each mission demonstrated the ability of the U.S. to perform very complex aerospace activities that were remarkably successful.

Recently this same systems engineering approach has been used on a number of government development projects with less success. The Sergeant York air defense gun, the Bradley armored fighting vehicle, the Aquila remotely piloted vehicle, and the NASA Space Shuttle are examples of systems where current system engineering and project management practices have resulted in development delays, performance short falls, and cost overruns. If this engineering methodology has worked so well in the past, why is it now failing to produce similar results on current system development projects? This paper will address key factors that affect system development success and describe a new dynamic engineering process that can assist in the return to a successful system development environment for the Freedom Space Station.

If one had to come up with a common denominator for the earlier successful projects, one leading candidate would be focus. It could be said that the focused objectives were primarily R & D driven where success was measured solely by system performance. In the case of Apollo, it was to put a man on the moon and return him safely to the Earth. This was a very unambiguous top level goal. Another characteristic of the Apollo program was that it was technology limited. Today it is difficult to recall the extent of the technological challenge of the Apollo program. When President Kennedy challenged the nation to send a man to the Moon in 1961, the entire manned spaceflight experience of the U.S. consisted of 17 minutes of suborbital flight time. The key question was whether it was possible to build the systems to meet these challenging goals, everything else was secondary. Another factor this program exhibited was that it progressed very quickly. It was quite possible in 1961 to develop a satellite and launch it within 24 months or less. The Apollo program took only 8 years even with the 18 months lost because of the Apollo 1 fire.

The Space Shuttle shared some of these elements in that the goal of reusability was clear. It was also to be a vehicle that lowered the cost for access to space and increased the availability of space for a variety of uses. In the area of reusability the Shuttle is a marvel of technology, in the area of lowering cost and increasing availability it has not proved to be so successful. A vehicle that was originally designed to be turned around in two weeks and flown for $ 10 million per flight, in actuality takes 12 weeks to turn around at a cost of $ 250 million. One reason is the specter of design to cost loomed large over this project. In addition, this was the first time a major space project was dominated, both technically and budgetarily, by long duration space and ground logistics and operations.

Today's high technology system development projects are typified by diverse goals, resource limitations, large size, complex interfaces, long development schedules, and a dynamically changing environment. Due to the increasing cost of todays systems in relation to the overall budget it is increasingly important to build political coalitions in order to sell programs. This leads to diverse system goals due to the diverse objectives of these coalitions . The Shuttle development is a prime example. NASA needed Air Force support and funding to be able to sell the program. The Air Force finally agreed but only if NASA would modify Shuttle requirements so they would meet Air Force mission needs. This increased the size of the cargo bay as well as the cross range on the Shuttle. Shuttle payload weight requirements were also driven by Air Force polar payload needs. Design to cost is increasingly used as technological capability increases. The question used to be "what can we do?". The question today is "what can we afford?" Design to cost encourages optimistic predictions of cost and schedule. Due to budget constraints NASA was forced to abandon a fully reusable Shuttle because of development costs. Even though this vehicle would have been safer and would have greatly reduced operational costs, the development price tag forced the current Shuttle configuration.

The complexity of today's systems, particularly the Freedom Space Station, require special techniques to ensure proper system level performance. The problem is not just that there are more components in these advanced systems but that the interactions of these components are far more complex and have a far greater impact on system performance than in past systems. A change in one subsystem can have a disastrous impact on the performance of another unrelated subsystem, which in turn can drastically reduce the overall system performance. Understanding and documenting these interactions is becoming increasing important as well as difficult. With the development of systems such as the Space Station Freedom even higher levels of complexity are involved. In contrast, the electrical interface between the Apollo command module and the Saturn 5 booster was only 70 wires. Big is not always complex.

Today's long project development cycle presents problems. For a major aerospace system the development cycle can stretch from 12 to 20 years or more. With the rapid advance of technology this increasingly results in the development of systems that are obsolete before they are operational. Over this extended development period both the user need and the system environment can change. Current systems are also being kept in service longer than ever before. Operations, maintenance, and upgrade of systems over an extended operational life (20-30 years) are an increasingly important consideration. Operations cost of the system over its operational life may exceed the development cost by an order of magnitude or more.

The key to the success of future system development projects, such as the Freedom Space Station, lie in the ability to balance performance, cost, schedule and risk objectives within a dynamically changing environment. The ability of these future projects to meet the operational needs of a wide range of users with conflicting utilization requirements, while remaining within budget and schedule constraints and allowing for future growth and flexibility, will be the challenge. The key issues that need to be resolved are: what are the key driving requirements for these future missions, what is the interaction between these requirements, how do they change as a function of time and what are the risks? The normal system engineering tools and methodologies have not been effective in answering these crucial questions within the cost and schedule constraints. Without a thorough understanding of these requirements, the accurate decomposition of the operational system architecture, both in space and on the ground, from major performance requirements and functions down to the lower level component requirements, is impossible.

## IV. Requirements: Our Accumulated Ignorances

All systems engineering methodologies begin with mission requirements definition and specification. Generally, there are three major players in this initial requirements activity, the systems engineer, the system user (either in person or a surrogate), and the technologist. Most projects use a linear phased approach (Concept Exploration Phase - mission needs and objectives defined, Demonstration-Validation Phase - mission definition and specification, Full Scale Development - detailed design, construction, assembly and test, and the Operational Phase) to carry out the system engineering. Although there may be involvement of all three major players in the Concept Exploration activities, the system users and technologist have minimal involvement beyond this. Systems which use this engineering methodology make the basic assumption that system needs and requirements are fully understood and that the technology is identified during Concept Exploration and will remain essentially static during the other phases. Figure 1 illustrates this linear development cycle. The government procurement procedures are also structured in such a way to formalize the assumption of static requirements, user needs and technology throughout the life cycle of a project.

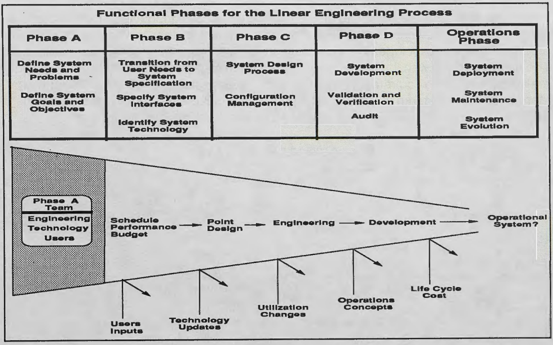

Figure 1. Linear Engineering Cycle

The process moves efficiently along from engineering to design to development whereby budget and schedule are managed carefully. System performance is judged against the initial requirements. As the figure indicates, changing user needs or utilization concepts, evolving technology, and operations cost modeling are not allowed to influence the design or development of the system. If the system requirements are not well known initially and/or the system technology or operations concepts are dynamically evolving, the operational system will not be functionally adequate or cost effective.

Too often the linear approach neglects to define fully what the system is. Design engineers generally believe that the system is the design and development of the hardware while others may think that the primary objective is the functional operation of the hardware for some purpose. This results in optimizing the design for the wrong functions. Optimizing for development efficiencies instead of operational efficiencies can many times lead to costly, unproductive, and unusable systems.

## V. Systems Engineering for a Dynamic Development Environment

The Department of Defense and the Defense Advanced Research Projects Agency (DARPA) has addressed the problems associated with a dynamic development environment by initiating an industry-university-government program, called concurrent engineering. The driving force behind the concurrent engineering methodology is the consideration that requirements and technology will be evolving throughout the life of a project. This requires the formulation of a engineering methodology which allows this dynamic evolution of requirements and technology to influence the system design, development and operations. Figure 2 indicates the SIORA Project's concept of the concurrent engineering process. The figure includes the engineering process through Demonstration/Validation. The process begins with the formation of an engineering-users-technologists team to begin preliminary system requirements definition from a best guess of user functional needs. Membership of this team is derived equally from the university, industry and government sectors. Each sector gains unique benefits from this working level interaction.

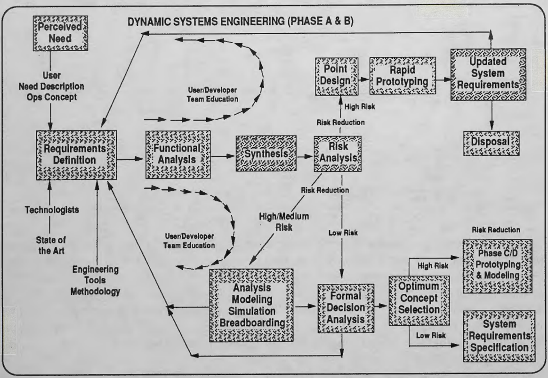

Figure 2. Concurrent Engineering Process for Dynamic Systems

Concurrent engineering, as developed and practiced by the SIORA Project, has its foundation rooted in identifying, quantitatively assessing, and managing system performance and risk. This process starts with a performance model of the system that defines not only the functions but the interrelationships between the functions. A detailed probabilistic risk assessment (PRA) of the system elements and their inter-relationship is also performed. Risk analysis techniques include functional scenario scripts, system problem studies, expert knowledge capture and consequence assessments. Risk probability distributions are then derived for the system in terms of performance attributes (e.g. money, time, safety). These probability distributions are then formally applied to the choices-risk management-decision theory process. This allows the systems engineer to derive a maximum utility function (maximized for operational efficiency and productivity) based on attribute priority. The formal process allows the systems engineer to evaluate design alternatives and set priorities for resource (money, time, manpower) allocations. This process will also identify those system requirements, elements or operations concepts which require additional work by the engineering-users-technologists team before they become fixed system specifications.

At this point the team establishes a set of evaluation criteria for various proposed concepts which were formulated to meet the preliminary requirements. The concepts which have high risk values can take one of two paths. With either path, the primary objective of the process is to validate the concepts in terms of satisfying the preliminary requirements and to educate the team. Both work to reduce risk. Some concepts can be functionally tested in a modeling or computer simulation environment while others must be placed in a rapid prototyping testbed where "quick and dirty" point designs can be operated in a hands-on mode by the team. With both paths, rapid iteration is essential to the success of the methodology. When several competing concepts satisfactorily meet the system requirements, then a formal trade-off process must occur to arrive at the optimum concept. Quantitative risk assessment techniques can be a useful tool for this formal trade-off process. Before formal specification can begin, care must be taken to distill all design specifications from the concepts such that vendor specific specifications from the point designs are removed. It should be stated that not all requirements will be fully specified at the end of Demonstration/Validation Phase in engineering design terms. Any Request for Proposals (RFPs) for Full Scale Development should fully identify which requirements have not been fully specified (those with high risk probabilities) and proceed with additional prototyping to fill in any additional information that will be needed to complete the system design. The present procurement system used by NASA must be totally restructured to accommodate this dynamic nature of requirements, end user knowledge of system functions and technology. The Freedom Space Station phase C/D procurements were constrained by using the traditional linear engineering process for formation of the system specifications.

The implementation of the dynamic system engineering methodology during the Full Scale Development portion of a project is constrained and hampered by the considerable cultural change which must occur for engineering personnel who are trained and are experienced in the traditional linear systems engineering techniques. The primary problem arises in dealing with evolving requirements, specifications and operations concepts. Traditional linear systems engineering provides techniques to carefully manage and control schedule and cost risks by ignoring or constraining the dynamic (time dependent) aspects of the system. This process works well, in terms of career advancement, for engineering managers whose system responsibilities end at the end of the development phase. Few managers of Full Scale Development activities ever transition to become the managers of the operational system, thus, inefficient and nonproductive operational systems have little or no impact on the managers final success or failure. Under this management scheme, design decisions will never be significantly influenced by whether a system is operationally productive or cost effective. Any implementation of concurrent engineering during the Full Scale Development period has to be accompanied by the understanding that managers will have system performance and operational efficiency as two critical elements of the managers performance evaluation. At present, Space Station has few or no incentives in place to encourage and reward managers to incorporate design features which optimize operational efficiencies and productivity.

A key to good system engineering and management during the design-development phase is the ability to keep the design process open to evolving requirements and technology as long as practical. The fundamental tools to assist the systems engineer in this process is the system performance model and quantitative (probabilistic) risk analysis. The performance model will allow the impact of the changing requirements/environment to be quantified and documented. This information is then input into the risk analysis. While the risk analysis during the Concept Development Phase dealt with user ignorance of needs/requirements, technology readiness, and system evolution, now the risk parameters of time, budgets, and schedules must be assessed and managed. It should be stated again that this risk analysis process is not a casual "seat of the pants" effort but one in which formal quantitative probabilities are determined for each individual system element along with the joint probabilities between elements. These quantitative assessments will provide an exacting means to determine when further prototyping will reduce risks and when system technology and specifications must be rigidly fixed for development. It will also provide a quantitative means to determine where architectural "hooks and scars" (system hooks allow for software evolution while scars allow for hardware evolution) must be designed into the system such that evolution can occur gracefully during the operational phase. In recent years, NASA has incorporated this modular approach to spacecraft design so that on-orbit maintenance, upgrading, and repair could be accomplished. In general, this has not ever been a design concept for the overall operational (both ground and space segments) system of any NASA program. The risk assessment analysis can provide a quantitative way to evaluate which systems are susceptible to rapid technology evolution and utilization concepts and could benefit from the introduction of architectural "hooks and scars".

Several important hooks and scars techniques exist for communications and information system elements for operational systems. These include standard bus architectures where functional applications are modularized on individual bus-compatible plug-in units which can evolve with the technology. In the software area, the development of software standards (i.e. UNIX, Ada, X-Window displays, etc.) and interface standards and protocols (i.e. ISO, IEEE, etc.) provides the architectural hooks which permit easy evolution during the operational phase of any program.

## VI. Theory Meets Reality — Space Shuttle Tile Automation Project

Although many of the concepts for the SIORA Project's concurrent engineering process were theoretically formulated by the early part of 1986, the opportunity for a practical application of the methodology did not appear until December, 1986. The Space Systems Integration and Operations Research Applications (SIORA) Program was initiated at that time as a cooperative applications research effort between Stanford University and NASA Kennedy Space Center (KSC). One of the major initial SIORA tasks was the application and introduction of automation and robotics technology to the most labor intensive operation in the Space Shuttle program, the Shuttle thermal protection system (tiles) processing and inspection. This effort adopted the concurrent engineering approach in which a government-university-industry team of operations personnel, technologists, and engineers tested and evaluated new concepts and technologies within the operational world of Shuttle. The integrated set of technologies introduced included speech recognition and synthesis capabilities, laser imaging inspection systems, distributed Ada programming environments, distributed relational database architectures, in addition to distributed computer network architectures, multi-media workbenches, expert system applications, probabilistic risk assessment modeling, and human factors considerations.

The labor intensiveness of the Shuttle Thermal Protection System (TPS) processing can be traced back to the early design phase where only secondary consideration was given to long term operations and maintenance issues. This has resulted in a TPS whose maintenance program can be characterized as being labor intensive, antiquated and time consuming. This is due to the fact that the maintenance program (based on initial development phase specifications and procedures using linear engineering techniques) uses manual techniques for inspection and measurement, mostly paper databases, no networking between pertinent electronic databases, manual scheduling of operational flows and a quality control and reliability program based on a paper information system.

An important part of the SIORA effort was to understand the organizational dynamics involved in evolving the TPS operations from its present labor-intensive state to one in which functionality and operational efficiency and productivity where primary drivers. Although SIORA began as a systems engineering and technology transfer program, it was soon realized that no implementation progress could be achieved without educating the operations "culture" at the working level, the mid-level manager level and at the upper management level. The existing culture was composed of NASA and its prime operations contractors with work functions ranging from engineering to quality assurance to technology development.

Introducing new technologies and operational concepts into such a culture is constrained by the lack of time available to interact with operations personnel. This is due to the fact that TPS processing was so labor-intensive due to manual operations that the work force had no time to think about or to attempt to improve the operational system by themselves. Any technology transfer process must take this into account and provide an efficient venue to expose operations personnel to the new concepts and technologies. A hands-on prototyping environment, in parallel to the ongoing operational process, was chosen as the vehicle to rapidly educate the operations personnel. Industry was invited to participate as cost-sharing affiliates of Stanford so state-of-the-art, but commercially available, technologies and technical experts could be made available to the prototyping environment. The participation of industry, in terms of personnel and equipment, considerably reduced the risk involved in selecting appropriate technologies and integrating them into a functional system.

Developing an understanding of the initial perceptions of the various organizations was an important first step in the application of the engineering methodology. From a NASA vantage point, this brought together three diverse organizational divisions, Shuttle Engineering and Operations, Safety, Reliability, Maintainability & QA, and Advanced Technology. Each is driven by different goals and responsibilities and by different schedules and budgets. Historically, Shuttle Engineering & Operations and SRM & QA have had a working engineer - inspector relationship rather than a team attitude. The advanced technology group has traditionally been considered "sand box types" where technologies are developed that, although designed to address a perceived functional operational requirement, have low probability of ever being implemented into the operational environment.

From the operations prime contractor (Lockheed Space Operations Company (LSOC)) point of view, the project was initially looked at as an interesting concept with some potential to give long term relief from the labor-intensive tile processing problems. Historically, as part of the prime operations contract, contractors do not have contractual authority to pursue studies for implementing new operations concepts or technology. In addition, the present budgetary, man-power level and schedule climate (post-Challenger) in the Shuttle processing environment made LSOC very conservative in its expectations for the project. The initial response from LSOC was to dedicate several personnel to the project which had considerable experience with Shuttle tile processing but were not part of the flow schedule for Orbiter 103, Discovery.

Stanford University was also playing a historically non-traditional role. Stanford saw the SIORA Project as a means to provide students and faculty with an applications environment to test and evaluate systems engineering techniques and newly developed technologies. Although close university-industry-government ties for cooperative research is not new to Stanford, applications research in an operations environment is. Providing a "real" systems engineering educational experience for students within the Shuttle program is also new to the School of Engineering at Stanford. The cooperative agreement between KSC and Stanford was also the first of its kind at KSC. This agreement allows KSC and Stanford to jointly share personnel and facilities and also closely coordinate and manage the joint project. The agreement also allows industrial partners of Stanford to participate on a cost sharing basis on the rapid prototyping efforts. This feature of the program allows the placement of state-of-the-art prototype equipment (loaned, gifted or heavily discounted to Stanford) in the middle of NASA operations without violating or jeopardizing future competitive procurements to acquire the operational system.

With the participants in place, the tile automation project was ready to begin. It is important to realize that all Shuttle tile processing operations or potential operations come under the management and review of the Shuttle TPS engineering review boards. To initiate the tile automation project, Stanford and LSOC submitted a project plan to the engineering review board. With review board approval, funds were allocated from the Shuttle operations budget to prototype, test, evaluate and finally specify the functional configuration for the operational system. The project plan laid out a 15 month scheduled for completion of the prototype evaluation and for functional specifications to be documented. A follow-on period of nine months was allocated for the competitive procurement and, in parallel, to develop training models and simulation capabilities for the operational system.

The first step in the engineering process was to establish a general architectural framework in which all of the operational concepts and technical elements could be evaluated. One of the more important architectural decisions made in the initial phase of the program was the selection of an Ada software environment. Although NASA had already made the decision on Ada for the space station core software environment, no one had attempted to put Ada into an operational Shuttle program. With a crash training program in Ada at Stanford, the prototyping team developed the programming skills quickly. The efforts were aided by the recruitment of a software company (CRI) which provided a relational database system which was programmed in Ada and easily ported to a number of different computers including DEC and IBM. Our experience on the project has shown that Ada provides a good software environment for quality and quantity of code while remaining hardware independent.

Another important architectural decision was the implementation of a distributed network configuration. This is a concept where nodes on a network each serve a specific function. This is opposite to the "mainframe" concept where a large mainframe carries out a number of functions in a centralized location. The distributed concept takes advantage of the decreasing cost of specialized hardware for unique functions. This allows for high performance, good access from anywhere on the network, and a graceful, both in terms of budget and functionality, evolution as technology evolves. The distributed network concept also allows for the tailoring of workstations to meet the unique needs of classes of operations personnel. The workstations can be developed in a modular manner which can respond to the particular functions of each job. This makes the task of creating training/simulation system much easier.

The two architectural decisions above allowed the team to progress rapidly. Our success became very visible which, in turn, lead to NASA management requesting that we modify our objectives and schedules. The opportunity was presented to the team to join the operational personnel to assist in processing the orbiter, Discovery. This is quite a challenge for a research/prototyping team. Questions arose as to whether we could get the prototypes certified for use, whether we could meet such condensed schedules, and whether this would drastically interfere with our initially assigned responsibilities. We chose to accept the challenge. We first assessed which of the prototype elements would best aid the work flow for Discovery. It was determined that the speech recognition system and the relational database were the only ones that could make an impact. Through hard work and dedication from the entire team, the systems were delivered to the tile processing personnel working on Discovery. To our surprise, we found minimal acceptance of our labor saving tools. This was later determined to be due to the fact that none of the work force had an opportunity to get hands-on experience with the tools and, therefore, had no confidence in its use under time critical constraints. With that lesson learned, we have now scheduled blocks of time in the process to acquaint the tile processing personnel with the prototype system in a hands-on manner before any the system is put into operational service. Although the excursion into the operational world delayed our original schedule, the information gained from the effort has convinced the team that this should be part of the systems engineering methodology for upgrading operational systems. To do it successfully, rigorous detailed scheduling is essential and appropriate allocation of resources (time and personnel) should be provided.

Although rigorous use of quantitative (probabilistic) risk assessment was not employed in the SIORA program to date, its importance in providing systems engineering personnel with a quantitative means of establishing schedules and resource allocations is readily apparent. Follow-on activities have now incorporated probabilistic risk assessment as a baseline tool to be employed in the dynamic engineering process.

## VII. Conclusion

The systems engineering methodology, concurrent engineering, for the development of a long term, inexpensive, and efficient space operations capability has been described. The methodology asks us to consider a cultural change in the way we define, specify, manage and satisfy system requirements. It also asks us to change the way we have historically viewed design goals. We must evolve from having solely hardware goals to where the goals reflect the efficient and productive operations and utilization of the system. We must also begin to understand the design ramifications of doing full life cycle cost modeling which includes the operational phase of projects. This concept must be reflected in the way the government does system procurements. Unlike the linear engineering approach, the concurrent engineering process forces the user-technology-design engineering team to continuously iterate throughout the full life cycle of a project.

Throughout the life cycle of a project it is important to maintain an iterative engineering process to be able to incorporate dynamically changing requirements and technology. The process is driven by information derived from risk assessment analysis and rapid prototyping testbeds which are carried out by technology-user-design engineering teams. These teams should have equal representation from the university, industry, and government sectors and each sector must give proper consideration to the long-term coordinated support for the training and education of the next generation of engineers and scientists that will lead the concurrent engineering process for future projects.