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As space agencies around the world develop plans for scientific and technological advancement they must concurrently manage contracting budgets and other resource constraints. To increase efficiency in space programs some key issues must be addressed in future project management. Three semi-retired senior NASA test laboratory directors, J. C. Blair, R.S. Ryan, and L.A. Schutzenhofer, have identified key technical management issues based on their combined experience that dates to the beginning of NASA. In interviews with these three senior technical managers and in reviewing documents that they have compiled, root cause technical management issues are identified. These include ownership and accountability, normalization of deviances, critical thinking failure, decentralized authority, and managing organizational complexity. The most prominent issue lies in integrating systems. It encompasses the variety of a project's components, from design to external operating environment, making reintegration from compartmentalization by necessity, a continuous effort throughout the life cycle. Specific integration processes affect project development at each level and by definition narrow future decision options, so this process requires highly effective communication networks. These communications networks would be utilizing the T-Model to create a seamless design process to address both ownership and authority issues. Risk management also integrates the information from differentiated processes to evaluate and forecast future performance using the Risk Matrix and PRA. These considerations are investigated within the context of life cycle management. Using the information obtained in collaboration with Marshall Space Flight Center we link past lessons learned to current management research. Analyzing the past projects leads to an understanding of research and development management techniques that identify specific areas of improvement and ways of changing the management to affect the overall performance of the end project. The organizational learning from NASA-MSFC historic analysis will provide greater insight into efficient use of resources and improved technical management.

INTRODUCTION

Increasing the efficiency of large scale aerospace projects requires an internal analysis of the management processes that are currently being utilized. NASA projects often encounter high risk-reward scenarios that make efficiency even more paramount but ever more difficult as well. Efficiency not only reduces the engineering development and production schedule and cost, but it encourages innovation when there is a continuing demand for improvement in processes. Considering the current resource constrained environment, it is important to make space missions as affordable as possible. To illustrate the nature of this challenge, during the Space Shuttle Main Engine development, approximately 70% of the cost was due to problems encountered subsequent to the initial design phase of the project. Much can be learned from the development phase of previous NASA programs. Organizational learning is the transferring of knowledge from one project and applying that knowledge in subsequent projects. Technology transfer is generally well documented. However, the transfer of technology management knowledge is generally less well documented. At Marshall Space Flight Center (MSFC), NASA has developed innovative approaches to organizational learning and the transfer of knowledge from past programs to current programs. The result is improvements in development processes and efficiency.

At NASA-MSFC the innovative approach to organizational learning and the transfer of technology management knowledge includes the retention of retired senior managers as expert resources. These managers are then employed on a part-time or

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temporary contract basis and utilized in the professional development of new entry-level NASA engineers. In this investigation J.C. Blair, R.S. Ryan and L.A. Schutzenhofer were interviewed. These individuals served in positions including director and assistant director of the Structures and Dynamics Laboratory at NASA-MSFC. Their combined experience in design and test activity includes Saturn I, Saturn IB, Saturn Apollo, Skylab, Space Shuttle, Spacelab, Hubble Space Telescope, Chandra, X-33, and the International Space Station. Of the numerous lessons learned, several critical issues were identified for this investigation. These included the problem of critical thinking failure and the need for decentralization, achieving integration through both formal and informal means, and lessons learned in the management of organizational complexity. These issues are central to the space exploration challenge, which is to "conceive, design, build and operate, safely, high performance, high power density, highly interactive space systems at reasonable cost and schedule efficiency"[1].

CRITICAL THINKING FAILURE AND THE NEED FOR DECENTRALIZATION

Critical thinking failure is a particularly insidious problem because it is often so subtle that managers can make decisions without realizing this failure has occurred. This is a potential problem in many professions and engineering management is no exception. Human judgment and analysis will ultimately be what moves the project forward. Requirements documentation should give direction and convey the overall technical performance objectives (or targets) that are to be reached but should not be unnecessarily over specified. Though specificity acts as a risk deterrent, this can limit the ingenuity which is paramount in being innovative; to solving problems creatively and efficiently. Each project requires necessary procedures and processes but these should not be excessive. Blair, Ryan and Schutzenhofer observed a trend within NASA where the flexibility of the Von Braun era gradually gave way to greater formalization and even bureaucratization. They concluded that the aim should always be brevity and this is an underlining theme of every process; to create as little unwarranted restrictions as possible to leave room for appropriate creativity. Creativity is central to innovation. It is also partially critical thinking and this is inherently necessary in devising new ways of looking at existing processes and efficient ways of solving problems as they arise.

To illustrate this issue, the Silicon Nitride ball bearings, or SiNi bearings, which were used in all of the Space Shuttle turbopumps were initially created under an eminent project cancelation threat. The designated team was unable to solve the design problem. However, an engineer who was not directly involved in the design effort came up with the innovative concept, then used various demonstrations to convince management, and created a solution that was ultimately adopted. Thus, the planned steps should be taken in solving a problem, such as forming a designated team to work on the solution. However, if the organization is operating under the Von Braun era assumptions of an organic structure and there exists sound interaction between teams, then the solution can come from many different sources, meaning that the designated team formation is just the first step in the multi-faceted process[2]. Robert Ryan observed that no specialized team should be isolated and the teams must be open-minded to other's inputs which could potentially be presenting the solution. As a solution is sought for a problem, all options must be explored in a similar logical fashion. Even if one option looks appropriate, the process must not stop there but investigate all alternatives. It is easy to fall into the "eureka" trap where the process stops due to an attractive initial solution[3]. This in commonly known as satisficing.

If deviations are ignored and are not critically analyzed, then the problems which should have been anticipated will have larger negative impacts downstream. To illustrate this issue, during the Saturn IV project, there was an undesirable side effect of the engine gimbaling actuators interacting with each other, jeopardizing their ability to control the vehicle. However, management was skeptical of the problem's existence[3]. If the project managers do not accept the team's input, it will create an environment where performance deviations are ignored to evade ostracizing by denial from the superiors. An example of where this principle was applied effectively was during the Jupiter program. Following a launch failure, in order to deal with propellant sloshing in the second Jupiter launch, the team used one engineer's experience from his youth on his farm moving water wagons to construct floating containers. These were later adapted to create baffles and eventually resulted in reducing the total weight. The solution was creative and was made possible by an organizational culture that encouraged critical thinking in the form of "thinking outside the box." This also illustrates an organizational culture of decentralization, ownership and accountability.

Another dimension of critical thinking failure is perhaps even more profound. This is the actual dismissal of data, sometimes known as selective perception. To illustrate, in 1975, a high ignition overpressure from the Space Shuttle's solid rocket motor was deemed acceptable, after running the test[3]. The risk was underestimated, which caused the first flight to experience a buckled tank and unexpected vibrations, impacting the vehicle loads. The corrective engineering design changes took 40 model test runs, all of which the team could have anticipated given the accurate data they had initially obtained. Once more, though the main issue was deficient risk management, it combined with perceptual dismissal of data generated by the test, subsequently resulting in a larger problem. In high performance requirement and high cost projects the effects of critical thinking failure can have very large consequences.

The history of NASA space projects offers multiple examples of both well managed and poorly managed test results. For example, one of the anomalies that occurred with Space Shuttle STS-1 was shown during the initial launch test. The results showed that some points on the wing were experiencing 100% of the design load, versus 65% predicted. What turned out to be accurate data was initially dismissed as improperly placed stress gauges and this caused a problem which could have potentially delayed the program by as much as two years. Though a timely solution was devised, it caused a 5,000 pound payload loss. Once such a large problem is identified, it becomes difficult to meet the original technical performance objectives. Normalization of deviances is one of the challenge areas that projects can face. Due to the nature of a project, tests can always have outlier results that may reflect improper modeling of the test itself and this desensitizes people from seeing such anomalies. This necessitates a test design that is reliable, where its limitations are understood so that the results it produces always have meaningful implications. Not all tests can emulate the desired conditions but then the uncertainties must be identified based on historical data or sound judgment.

To illustrate further, a model was created to determine how a diffuser functioned on the Space Shuttle Main Propulsion System, and it passed all the tests. But in actual operation, it failed after several hours because it could not stand up to vibrations induced by the system as a whole. The results were partly due to uncertainties and partly due to an inadequate model which had more stress absorbent gages than the actual system. The environmental conditions that applied to the particular scenario had to be replicated in a test. However, an EPA regulation on insulations changed how the Shuttle External Tank was insulated, but in the subsequent test, the same high temperature and low pressure conditions had not been replicated properly. This resulted in a pop-corning of the insulation versus an even coated layer. These problems all stemmed from failing to prepare a test adequately and failing to analyze the test results adequately.

Sometimes, the failures are simply due to lack of knowledge in the field, such as the flow environment on Space Shuttle Main Engine (SSME) which initially caused failures of numerous components. The solution required funding applied research on computational fluid dynamics and waiting for the research to generate more insight. The cost savings were estimated to be hundreds of millions of dollars but the time delay was the most serious cost. With SSME development, there was considerable technological uncertainty. This translated into high costs and the necessity of innovating as research progressed. The final result was that the SSME did become the only reusable rocket engine approved for human missions.

THE NEED FOR BOTH FORMAL AND INFORMAL MODES OF INTEGRATION

One of the greatest challenges in a large scale aerospace project is systems integration. In complex projects integration is difficult to achieve because the essential specialization or division of labor must also be fully utilized. The resulting compartmentalization is essential for component and subsystem design. However, it is important to make sure that the boundaries that are formed by compartmentalization are not inhibitory and that there are organizational modes of integration to traverse these artificial boundaries[4]. One of the ways to facilitate integration is to prioritize the overall project. Technical professionals are assigned to specific tasks associated with specific components or subsystems. However, larger periodic meetings of multiple teams can facilitate a full understanding of the project in its entirety. This helps to guard against suboptimization in decision making.

Systems engineering governs the lifecycle of the project while technical integration focuses on the unity of the project. Most problems in large scale aerospace projects have not arisen due to lack of ability, but more as a result of systems engineering or technical integration problems. The entire lifecycle is marked with compartmentalization where there is fragmentation into design function, disciplines and so on. Then the subsystems must be integrated and the requirements of each subsystem must be optimized by giving up less essential requirements of each subsystem in order to maximize the performance of the entire system. These design interfaces, and the complex interaction effects that are created, is the most pivotal part of the integration. There are numerous ways in which each subsystem interacts with other subsystems. Robert Ryan observed that in NASA's experience most of the downstream project problems trace their roots to one of these interactions.

At NASA-MSFC the T-Model is used to illustrate and combine the formal (structural) and informal aspects of integration[5]. The T-Model has the shape of the letter itself, which conveys the unity of all the subsystems at the top level as well as the relatively separate specialized subsystems. The formal or top level integration depends on the project managers who must optimize the overall project's technical performance, cost and schedule. If an overemphasis is given to formal modes of integration, then informal forms of integration may suffer. Informal integration takes place between the engineering teams in the form of personal interaction across units, informal meetings, phone calls, or other forms of electronic communication. Informality is important because it is maximally adaptive and flexible. More emphasis is given to formal modes of integration but informal integration is often underestimated and is usually thought of as an aspect of the organizations' culture. Blair and Ryan observed that the lesson learned in NASA'a experience is that the formal modes of integration are necessary but not sufficient. Informal integration, as an aspect of the organization's culture, is important to achieving systems integration.

To illustrate, during the Skylab program there was a need to undergo extensive payload recovery missions because of earlier failed integration of manufacturing with the design engineers. The testing for the auxiliary tunnel venting, precluded a sealed end of the tunnel but during manufacturing the tunnel was inadvertently sealed because of a cross-functional integration failure with the structural design team[6]. Such failure should not have occurred by any standard if the requirements of the system were properly communicated.

Blair, Ryan and Schutzenhofer[3] observed that because there are multiple requirements on multiple levels, an individual functional requirement must consider other functional requirements which are all part of a subsystem. These in turn must maintain compatibility with the parallel requirements of other subsystems. This means that the process must be repeated with each set of requirements, and balanced, before the design can be finalized. As an example, the design of a propulsion subsystem is broken down further into various design functions. The requirements for each team range from safety to performance, encompassing for example, thrust to weight balance and thrust to engine number ratio which are two separate requirements but at the same time, inexorably bound. When all of the elements of the subsystem are integrated, they must then be integrated into the entire system. This is where there is the inevitable discovery of new interactions involving the various subsystems that must be addressed. This process of balancing is central to the integration problem because the ideal environment for each subsystem is generally unachievable. This is why the combination of both formal modes of integration and informal coordination are so important.

LESSONS IN MANAGING COMPLEXITY

Every new compartmentalized subsystem adds a complexity layer as well as further interface requirement documents and interface control documents which track and manage the subsystem. Such documentation creates another but separate need for subsystem management and once more, the complexities increase. Complexity is defined here as how various component interaction changes affect the outcome. Just as integration complexity increases with the level of compartmentalization, system uncertainty inevitably increases with the level of complexity. Blair, Ryan and Schutzenhofer[7] observed that in NASA's experience, the test-fail-fix cycle usually accounts for at least 70 percent of the development cost. The test-fail-fix cycle includes the preliminary testing which is commonly followed by seemingly unforeseen failure in the system which must then be corrected. This cycle typically repeats enough times to expend three quarters of a development budget. The problems are caused by the high level of uncertainty which the engineering teams are unable to reasonably predict in advance. High uncertainties include the unforeseen results of subsystem of component level interfaces as well as sensitivities.

An example of this problem was clearly observed in the Space Shuttle Main Engine (SSME) developmental process which had 38 significant corrections with a mean cost of $30 million[7]. Blair, Ryan and Schutzenhofer believe that this process can be significantly reduced by initial design decisions that involve lower technological risk. In the original fuel turbopump housing on the SSME, which when redesigned, had half as many parts as the original, with no welds. Thus, the redesign reduced uncertainty. The design process can be improved if probability density functions (PDF) and risk matrices are utilized. This is essentially an estimated quantification of technological risk. This approach takes into account both demand factors and capability factors, mapping out potential interferences, or potential failure regions.

The stage in the project lifecycle will determine which options are available at that particular point. Though every requirement must be balanced throughout the project, the design decisions that occur earlier will have great impact on decisions that occur later in development. Lifecycle considerations serve many purposes, including acting as a test to the project's requirements. Robert Ryan observed that in NASA's experience, most of the design compromises must be made as early as possible because if the problems are temporarily ignored, the solutions will still have to be made later at greater expense or more severe consequences.

A simple example of the role of the project life cycle can be seen in the design decisions related to the problem of wind bias during launch when contrasting the Saturn V with the Space Shuttle. In both programs the wind bias problem was taken into consideration during the initial design process and thus affected original design decisions[3]. There were few options in addressing the wind bias problem and each option had its own consequences. Once early design decisions were made to accommodate wind bias, subsequent design decisions were affected. If the wind bias had been accounted for by an annual wind speed mean, then the design would be required to withstand the large deviation from the mean, but if the wind bias were measured the day of launch, then the design could be adjusted accordingly. Utilizing the day of measurement though, increased cost and operational complexity. The Saturn V utilized a more robust design to accommodate the wind speed problem. However, the Space Shuttle required actual day-of-launch wind biasing, though monthly mean wind bias was initially planned. This was a less robust approach but allowed other design compromises to occur. Thus, every decision must not only consider the system as an entirety but must anticipate downstream consequences for cost, schedule and technical performance.

The Law of Unintended Consequences states that any and every change will produce a change on the whole system, all of which cannot be calculated[3]. This requires technical managers to consider all the possible scenarios and to assign objective probabilities where possible, and subjective probabilities where there is no known data. To illustrate this, the NASA Large Tethered Satellite System missions were cancelled due to two failures. The first Tethered Satellite was unable to complete the mission due to an incidental bolt change out that jammed one of the mechanisms. This mission failure was based on human error. Every change must be verified but in this case there was no verification. The test was not completed and this resulted in system failure. In this case the scenario was not considered, no probability to this event was assigned, and a necessary test was not conducted. In the second Tethered Satellite mission the satellite was lost and the concept was abandoned. However, the opportunity was lost due to circumstances that perhaps could have been anticipated from the start. Again, there was inadequate development of possible scenarios without the assignment of probabilities. There was no subsequent testing and design changes.

CONCLUSION

In conclusion, aerospace projects face unique technical challenges due to the scale, complexity, and the pioneering of new technologies in these projects. They also provide an opportunity for the development of new technology management knowledge and the transfer of that knowledge throughout the industry. As J. C. Blair, R. S. Ryan and L. A. Schutzenhofer observed, much can be learned about technology management from the NASA experience. At Marshall Space Flight Center, NASA has developed innovative approaches to organizational learning and the transfer of knowledge from past programs to current programs. This knowledge has applicability not only within NASA and the aerospace industry, but for large scale engineering projects in general.

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