Systems Engineering and Integration Management for Manned Spaceflight Programs

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The development of systems engineering and program management in NASA manned space programs has grown in a largely uncoordinated manner over the last 30 years; however, the systems and practices that have been developed form a proven pattern for successfully integrating large technically complex programs executed in several geographical locations. This development has not been recorded in a comprehensive manner, and much of the reasoning behind the decisions made is not obvious.

Although there is no generally accepted definition of SE&I, for the purposes of this discussion systems engineering is defined as the interdisciplinary engineering that is necessary to achieve efficient definition and integration of program elements in a manner that meets the system-level requirements. Integration is defined as the activity necessary to develop and document the system's technical characteristics, including interface control requirements, resource reporting and analysis, system verification requirements and plans, and integration of the system elements into the program operational scenario.

This paper discusses the history of SE&I management of the overall program architecture, organizational structure, and the relationship of SE&I to other program organizational elements. A brief discussion of the method of executing the SE&I process, a summary of some of the major lessons learned, and identification of things that have proven successful are included.

History

NASA, then the National Advisory Committee for Aeronautics (NACA), participation in the management of major aerospace programs began shortly after World War II with the advent of the X-series research aircraft. In these projects, essentially all of the technical responsibility was delegated to one of the NACA Centers. At this time, the Centers were primarily expert in the technical areas being explored (i.e., aerodynamics, stability, control, and structures) but did not have experts in the development of hardware. Accordingly, NACA entered into agreements with the Air Force or Navy to manage the actual development of the aircraft, while the NACA Centers focused their direction on the technical requirements and performance characteristics to be demonstrated by the aircraft. The contractor's responsibility was similar to that for the development of any aircraft, and the contractor usually furnished test pilots for early demonstration flights.

With the formation of NASA and the start of major manned space programs, it was necessary for NASA to develop the capability to manage complex development activities. Very little SE&I capability existed within the functional organizations of the NASA Centers. As a result, SE&I expertise was developed within each of the program offices. In particular, the Gemini program office was set up with autonomous capability to manage SE&I and direct the development contractor.

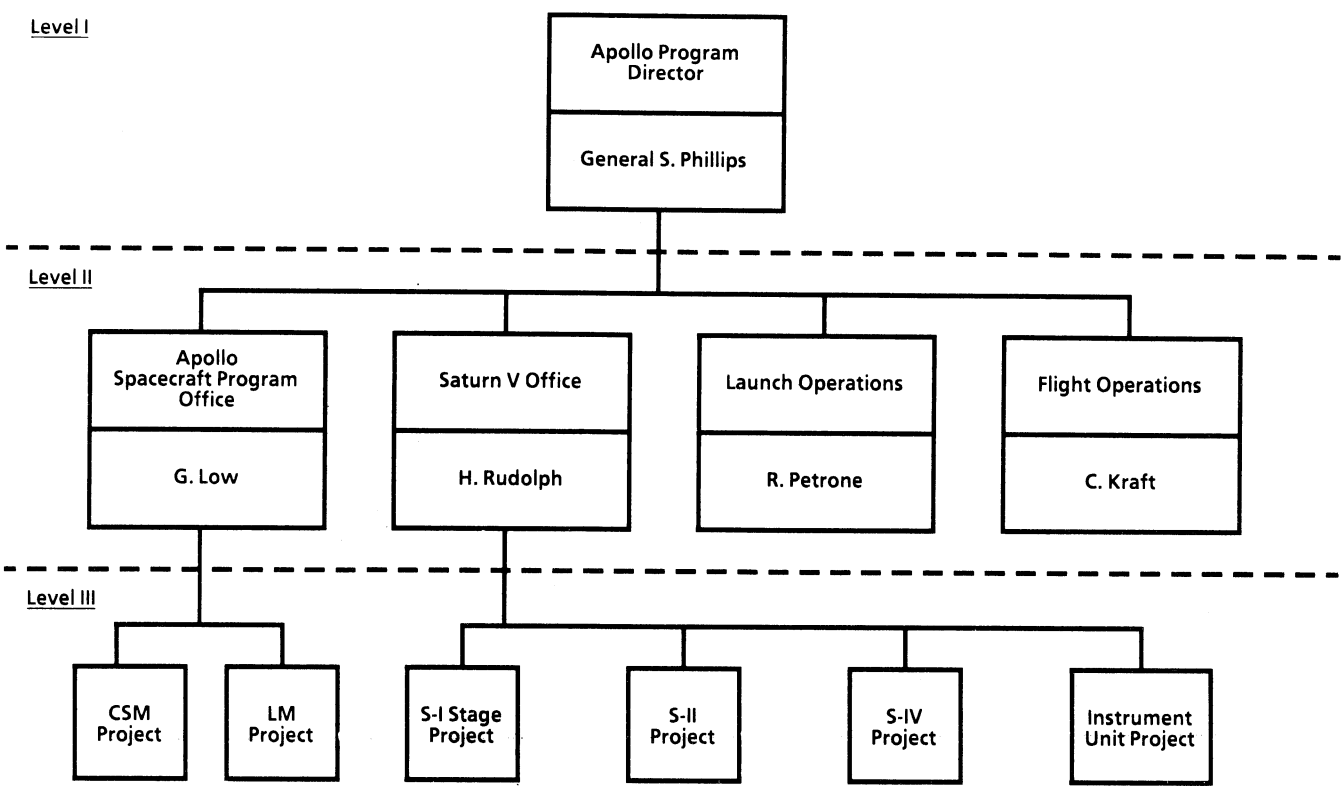
With the advent of the Apollo program, SE&I was again managed from the project offices at the development Centers. The project offices used specialized technical capability from the Center functional organizations and prime contractors and initiated the practice of hiring support contractors to assist in implementing SE&I.

After the Apollo I fire, a review committee was established to determine the cause of the fire and recommend modifications to the program. One of the recommendations made was that NASA acquire a technical integration and engineering support contractor to assist in accomplishing SE&I activity. The Washington program office selected Boeing as the contractor and managed the contract for this activity; however, a large portion of the manpower was located at the development Centers. The contractor's responsibilities included monitoring the development and operational activities at the Centers, forming integrated assessments of the activity, and making recommendations to the program director for improvements. As the program matured, the contract focus was changed, and the contractor provided a significant number of personnel to directly support the centers in SE&I and systems activities.

With the initiation of the Space Shuttle program and the adoption of the lead Center concept, it was decided to manage the Level II integration activity, including SE&I, by providing a small management core within the program office and using many of the Center's functional organizations to provide technical support in a matrix fashion. At the Johnson Space Center (JSC), the lead person from the functional organization was generally a branch head or an assistant division chief. Therefore, JSC had a relatively large staff to draw from to provide the specific technical expertise and the level of effort needed to accomplish a given task.

The Space Station Freedom program was started using the Space Shuttle program as a model. As the lead Center, JSC managed integration. Later, the Level II function was moved near Washington, D.C., under the deputy program director, and an independent contractor was brought in to assist the integration process. The Space Station Freedom program's management organization is discussed in more detail in the next section.

Figure 1 - Apollo Program Organization

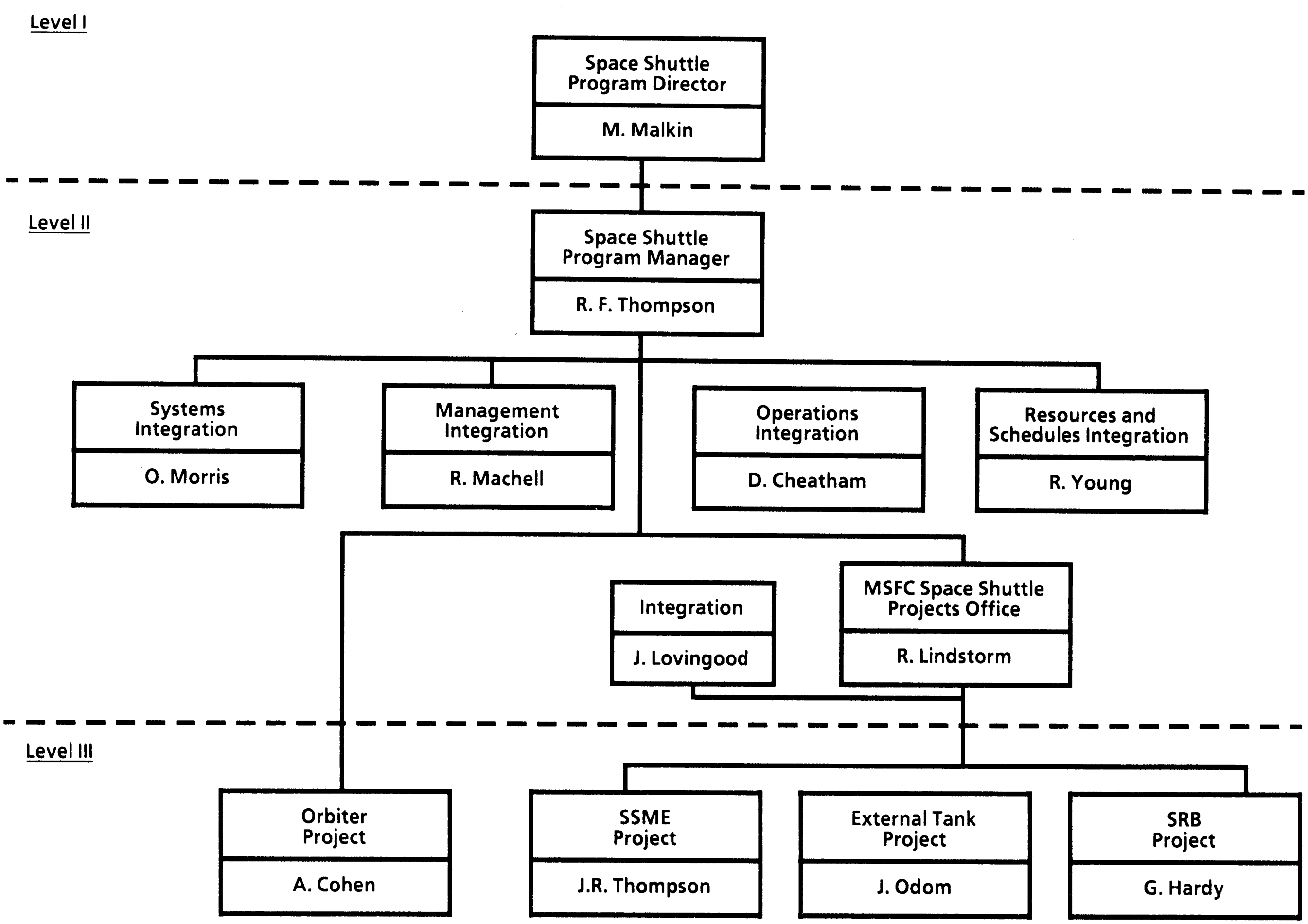


Program Management Organizational Structure

A single NASA Center largely managed early NASA manned space flight programs, which allowed for a relatively simple organizational structure to accomplish program integration. JSC, then called Manned Space Center (MSC), managed both developmental and flight operational aspects of the Mercury and Gemini programs with the checkout and preflight testing being performed by support elements at Cape Canaveral.

The Apollo program became organizationally more complex (see Figure 1). The spacecraft development was managed by JSC; the launch vehicle development by the Marshall Space Flight Center (MSFC); the prelaunch activities by the Kennedy Space Center (KSC), by then an independent NASA Center; and the flight operations by JSC. In all of these programs, the responsibility for the development of the flight hardware was delegated to the Centers, and the interfaces between projects were intentionally kept as simple as possible. The Washington office, under direction of the program director, was responsible for overall direction of the program including budgetary allocations, congressional relations, and management of development issues between the project offices at the different Centers. The actual integration activity (SE&I) was coordinated by a series of panels and working groups in which individuals from the Washington program office served as either chairperson or members, with the program director overseeing the activity. In the early programs (Mercury and Gemini), this activity was the responsibility of a single Center, and the Washington office was coordinated in an informal manner, but by the end of the Apollo program, the management of the panel and working group activity was relatively formal. In all of these programs the Center directors took an active part and personally felt responsible for the technical excellence of the work performed by their Centers. This in-

Figure 2 - Space Shuttle Program Organization



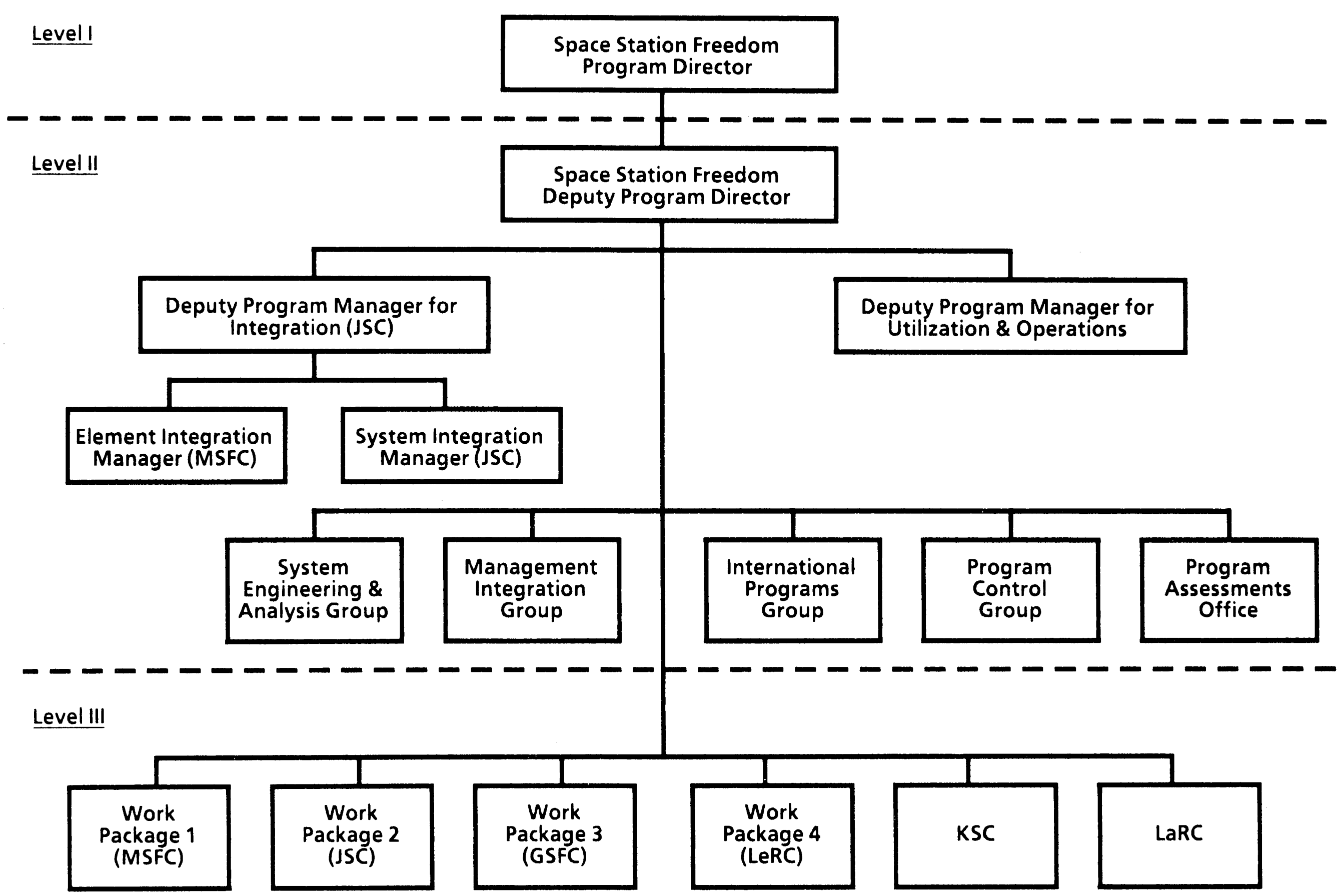
tercenter involvement was accomplished primarily through the management council and major program reviews where Center directors personally participated in major decisions.

In part of the Apollo program, the Washington office retained the responsibility for performing the SE&I activity with actual work being led by Bellcom, a division of Bell Laboratories. Ultimately, this approach was abandoned in part because much of the Center director's responsibility was lost, and an adversarial relationship between the program director and the Center organizations developed. The execution of the SE&I was returned to the Centers with management and coordination of intercenter activities achieved through the use of working groups, panels, and management reviews.

At the outset of the Space Shuttle program (see Figure 2), the management of SE&I was changed. Some of the more important changes were: adoption of the lead Center management concept, in which one of the participating Centers was delegated the management of program-level integration including SE&I activities; the adoption of a configuration with functional and physical interfaces of much greater complexity; and the employment of one of the major hardware development contractors as the integration support contractor. The complex interfaces made SE&I activity voluminous and involved and required the commitment of a larger percentage of the program resources to this activity.

The Space Station Freedom program was structured so that the interface activity between the work packages was even more complex than that of the Space Shuttle program. Initially, the lead Center approach to SE&I activity was adopted, but the implementation was not effective. As a result of recommendations made by study groups and the committee reviewing the Challenger accident, it was decided to transfer the responsibility for program integration activity, including SE&I, to the deputy program director in Reston, Virginia, and to bring on a con-

Figure 3 - Space Station Freedom Program Organization



tractor to provide program integration support (see Figure 3). Contractors having significant hardware development contracts were excluded from the contract competition. The first approach was to provide detailed management of SE&I activity by the Reston civil service personnel with the integration contractor providing support in executing the activity. Additionally, it was thought that much of the technical integration activity could be accomplished by having the work package contractors negotiate the definition and execution of much of the detailed integration process directly between themselves. This proved ineffective, however, because there was no clear lead responsibility and no clear way to resolve differences. As a result, because of the complexity of the program integration and the lack of in-depth backup capability, this management approach has not been completely effective.

Recently, it was decided to give the integration support contractor direct responsibility for the integration of the program but without authority to directly manage the work packages or their contractors. In an attempt to obtain more in-depth capability, the program director and deputy program director decided to execute the systems integration portion of the SE&I activity at two of the field centers with the deputy director for integration physically located at one of the Centers. Since these functions were still retained organizationally within the program office, they were under the control of the deputy program director and, at the same time, had the advantage of drawing from the technical capability residing at the Centers. Simultaneously, the integrating contractor's personnel at the Centers was materially increased in both responsibility and quantity.

Growing Program Complexity

One of the major factors that determines the efficiency of the integration of a program is the methodology used in delegating the engineering and development responsibilities to the project offices at the field Centers. It has been found that less complex organizational structures and simple interfaces are extremely important to allow efficient management of the SE&I activities. Each of NASA's manned space programs has been organizationally more complex than its predecessor and has had more complex interfaces. In both the Mercury and Gemini programs, the flight elements were divided into two parts, spacecraft and launch vehicle, and the physical and functional interfaces between the two were quite simple. The induced environmental interfaces were somewhat more complex but readily amenable to experimental and analytical determination.

The Apollo program involved a major increase in program complexity. The spacecraft was divided into two project offices while the launch vehicle was divided into four project offices. By assigning the four launch vehicle projects to the same development center (MSFC), the integration between launch vehicle stages could be accomplished at the Center level. Similarly, both spacecraft projects were assigned to one Center (JSC) for the same reason. The physical and functional interfaces between the spacecraft and launch vehicle, and hence between development Centers, was relatively simple. In a paper written in 1971 titled *What Made Apollo a Success*, George Low stated:

> *Another important design rule, which we have not discussed as often as we should, reads: Minimize functional interfaces between complex pieces of hardware. Examples in Apollo include the interfaces between the spacecraft and launch vehicle and between the command module and the lunar module. Only some 100 wires link the Saturn launch vehicle and the Apollo spacecraft, and most of these have to do with the emergency detection system. The reason that this number could not be even smaller is twofold: redundant circuits are employed, and the electrical power always comes from the module or stage where a function is to be performed. For example, the closing of relays in the launch vehicle could, in an automatic abort mode, fire the spacecraft escape motor. But the electrical power to do this, by design, originates in the spacecraft batteries. The main point is that a single man can fully understand this interface and can cope with all the effects of a change on either side of the in-*

terface. If there had been 10 times as many wires, it probably would have taken a hundred (or a thousand?) times as many people to handle the interface.

However, the operational complexity of the Apollo vehicle demanded a more extensive integration activity between the Centers, and for the first time posed the problem of accomplishing detailed technical coordination between Centers.

One of the basic tenets of the Space Shuttle program was to have an integrated vehicle that would recover the most expensive elements of the system for reuse. This led to a design concept that placed a great majority of the electronics and major components of the main propulsion systems in the orbiter. This design concept led to very large increases in interface complexity between the program elements and, more importantly, between development Centers. For instance, the number of electrical wires running between the external tank and the orbiter was more than an order of magnitude greater than between the spacecraft and launch vehicle of Apollo, and for the first item, major fluid systems ran across the interfaces. This represented a formidable increase in the effort required to successfully accomplish the SE&I activity. As previously noted, the new program management structure, shown in Figure 1, was adopted to accommodate the increase. The accomplishment of program level SE&I was given to a "lead Center." The program director at headquarters was still responsible for program budgetary control, Congressional relations and a technical staff sufficient to assure that the program technical activity was being properly implemented. At JSC, which was the lead Center for the Space Shuttle program, a Level II program office was established totally separate from the Level III orbiter project office, located at the same Center.

The development of the flight hardware was delegated to four project offices with the orbiter office located at JSC, as mentioned above, and the other three, the Space Shuttle main engine office, the external tank office, and solid rocket booster office, located at MSFC. In addition to the hardware development project offices, a prelaunch processing office was formed at KSC. All of the project offices reported to the Level II program manager for all programmatic direction except budget allocation, which was retained by the program director at headquarters.

The SE&I activity was delegated to the Systems Integration Office located within the JSC Level II Office. The orbiter contractor, Rockwell International, was selected to be the integration support contractor, but to increase objectivity, the integration activity was made a separate exhibit to the contract and technical direction was delegated to the Level II Systems Integration Office. The MSFC Space Shuttle Project Office appointed an integration manager to manage the integration of the Marshall Space Shuttle Projects and to serve as the primary interface to the Level II Systems Integration Office.

The flight hardware developmental delegation of the Space Station Freedom program was formulated in an even more complex manner (see Figure 4). End-to-end developmental responsibility for each of the major functional systems was delegated to one of four project offices called work package offices; the responsibility for assembling and delivering the flight hardware was broken down by launch elements, again assigned to one of the work package offices. Each of these launch elements incorporated components of most of the distributed systems, necessitating the transfer of an extremely large number of hardware and software items between work packages prior to their delivery to the government. This resulted in another major increase in the complexity of the program-level SE&I process and directly contributed to the difficulty of implementing a satisfactory SE&I process in the Space Station Freedom program.

SE&I Scenario

As a program develops from concept to operational status, the characteristics of the SE&I activity vary greatly. Early in the program, conceptual stage SE&I is intimately involved in defining systems that will meet the overall program objectives and in evaluating the

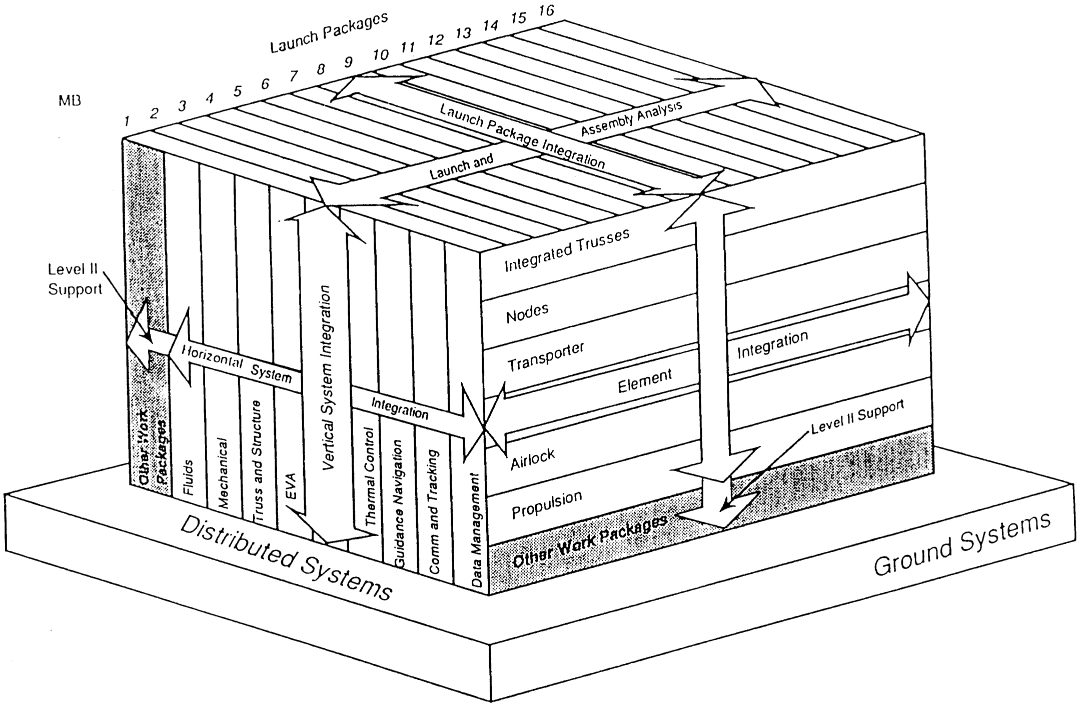


Figure 4 - Space Station Freedom Integration Activities

relative merits of each. This is usually accomplished in NASA manned programs by the civil service organizations, often in concert with Phase A/B contracts with industry.

After the general systems specification has been developed and a detailed evaluation of system concepts completed, SE&I provides a lead in the preparation of the procurement specifications for the Phase C/D activity and is usually directly involved in the source selection process. After award of the Phase C/D contracts and final selection of the design approach chosen for implementation, SE&I is responsible for preparing system level technical specifications, which define the performance requirements to be satisfied by each of the major program elements.

SE&I then develops the system characterization process to be used (discussed in more detail later) and starts an initial analysis cycle. The results of this cycle are extremely important in verifying the validity of the system technical specifications and providing a technical basis for conducting the Program Requirements Review (PRR). After completion of the PRR and updating of the technical specifications, SE&I starts the definition of the interface control document tree and the initial drafts of the documents. Another system characterization cycle is started based on the updated specifications and the hardware/software concepts chosen to assess the adequacy of the proposed preliminary design approach.

By this time in the program, the ad hoc organizational structure should be well in place and functioning on a routine basis. The communication and management overview provided by this structure of working groups, panels, and reviews is central to accomplishing horizontal integration among the project offices and is discussed in more detail in a later section.

In preparation for the preliminary design review (PDR), SE&I defines the minimum content required in the PDR data packages and is responsible for preparing system-level documents supporting the Integrated System PDR. During the PDR process, SE&I representatives participate in the project-level reviews with particular emphasis on the compliance of the project to the system-level requirements. During the integrated system PDR, emphasis is placed on assuring that the preliminary designs meet the operational requirements of the program. The SE&I organization is intimately involved with the evaluation and disposition of review item discrepancies (RIDS) that are submitted during the review.

As a result of the PDR process, changes to the requirements and modifications to the preliminary design of the elements are incorporated. A new characterization cycle is then initiated to evaluate the compatibility between the modified requirements and proposed system capabilities. At this time, the drafts of the interface control documents are expanded and quantitative detail added to assure that they are mature enough to become baseline requirements in the program. This maturation process inevitably adds a significant number of changes to the baseline.

In a similar manner, the verification plans of the elements and the integrated system are refined and baselined. The responsibility for executing the test and analysis required by the integrated system verification plan is delegated to appropriate organizations who then prepare detailed plans for accomplishing the assigned portions of the verification.

Detailed mission operational scenarios and timelines are prepared by the operations organizations, and the operations and SE&I organizations jointly conduct an analysis of the system capabilities to support the scenarios. Concurrently, the acceptance test and prelaunch operations requirements and plans are prepared and delegated for execution.

In preparation for the critical design review (CDR), another system characterization cycle is performed based upon the detailed design of the elements. This cycle typically uses mature models to synthesize the hardware and software systems and also incorporates the results of tests performed to that time. SE&I participates in the conduct of the CDR in a manner similar to that of the PDR. After completion of the CDR, the system requirements and design changes resulting from the CDR are incorporated into the documentation, and another complete or partial system characterization cycle is performed to validate the decisions made during CDR.

After CDR, the primary activity of the SE&I organization is to analyze test results and conduct analysis to verify the capability of the system that is being manufactured. Particular emphasis is given to verifying the interface characteristics of the elements as defined by the interface control documents. This activity directly supports the preparation for the design certification review (DCR) and provides interface information necessary to allow acceptance of the system hardware and software by the government.

The DCR is conducted similar to the PDR and CDR but addresses the as-built hardware and software. Successful completion of the DCR certifies the acceptability of the as-built elements and the ability to be integrated into an overall system that will satisfy the initial program operations requirements. Final operational certification of the system is obtained by a combination of the DCR process and analysis of information obtained during early flight operation of the system.

SE&I organization participation throughout the program development cycle provides them a unique capability to support operational planning and real time operations. SE&I is the repository of corporate knowledge of the details of the system capability, which is vital to the effective and efficient operation of the system.

Relationship of SE&I to Other Program Functions

To effectively accomplish the SE&I task, the SE&I management organization must maintain good communications and obtain the support of other program office organizations. Some of the more important interactions are discussed below.

Configuration Management

The interaction between SE&I and configuration management is particularly strong. As the developers and keepers of the systems specifications, SE&I has an interface with the configuration management function that is extremely active throughout the life of the program. The SE&I office recommends the baselining of the technical requirements as they become sufficiently mature and then serves as the office of primary responsibility for defining and evaluating most of the proposed changes to this baseline. The SE&I office, after proper coordination throughout the integration function, also recommends the processing of non-controversial changes outside of the formal control board meetings, where appropriate. This results in significantly reducing the board's workload and conserves the time of the key managers who are members of the Change Control Board. Significant issues are referred to the board, and the SE&I office presents its analysis of the issues involved and makes appropriate recommendations.

Program Control

SE&I supports the program control function in the development of program schedules and budgets. The key to making this support effective is the use of SE&I logic networks and estimates of the manpower required to accomplish activities. Because of its interdisciplinary nature, SE&I can assist in planning activities in many program areas.

Early in the program, SE&I helps define the content and schedule milestones for each of the projects so the coherent development of project-level schedules and cost estimates can be achieved. In addition to supporting program control, SE&I provides program control with the engineering master schedules (EMS) and associated budget estimates for incorporation in the overall schedule and budget system. SE&I also works with program control in the planning of major program reviews, provides technical leadership during the conduct of the reviews, and frequently chairs the screening groups and preboards.

Operations

In all of the NASA manned space programs to date, the SE&I function has been managed in a different organization from the operations definition and planning function. Although this is undoubtedly the best choice in the later phases of the program, it may result in a less thorough incorporation of operational requirements in the systems specifications and other SE&I products early in the program. It may be desirable to consider combining the management of SE&I and operations in the same office early in the program and then separating them at a later time, such as completion of the predesign review (PDR). The stated reason for separating the functions in the past has been that they serve as a check-in-balance on each other; however; this causes disconnects in the detailed interfaces between the two functions.

SR&QA

The interactions between SE&I and the System Reliability and Quality Assurance (SR&QA) functions depends on how the delegation of responsibility for executing the program is approached. If a large part of the SR&QA activity is accomplished within the SR&QA organization, then the interface with SE&I is mostly that of using SE&I as a reservoir of information or to perform specific tasks as requested by SR&QA. However, if the SR&QA office is responsible for setting the requirements for the SR&QA activities and evaluating the outcome while other organizations such as SE&I are delegated the responsibility for executing the work, then the interface becomes one of SR&QA defining and obtaining baseline approval of task requirements, monitoring execution of the task by SE&I, and evaluating the results to assure satisfactory achievement.

The former mode of operation was exemplified during early portions of the Apollo program, where the SR&QA activities were largely accomplished within the SR&QA office using basic engineering information obtained from SE&I and other program organizational offices. Later in the Apollo program, the second mode of operation was adopted, in which engineering offices, primarily SE&I, actually performed the work and made a first-level analysis prior to formally transmitting the results to SR&QA for authentication. This latter mode of operation was felt to be more effective primarily because problems and discrepancies were often discovered by the originating engineering office and corrected even before the task was completed.

SE&I Execution

Many techniques have been developed in past NASA manned programs that have proven effective and have become an integral part of implementing SE&I activities. The following paragraphs describe some of the more important techniques to assist those planning and implementing new programs.

Importance of SE&I Early in a Program

Comprehensive SE&I support is crucial in the early stages of complex programs to assist in determining the architecture to be used in delegating project responsibility. This is accomplished by dividing the program into the next lower level of management, the project offices. The primary outputs are comprehensive and clear program requirement specifications, identification of major programmatic interfaces, development of the ad hoc SE&I management structure, definition of operating concepts, and preparation of initial specifications for the hardware to be delegated to each project office.

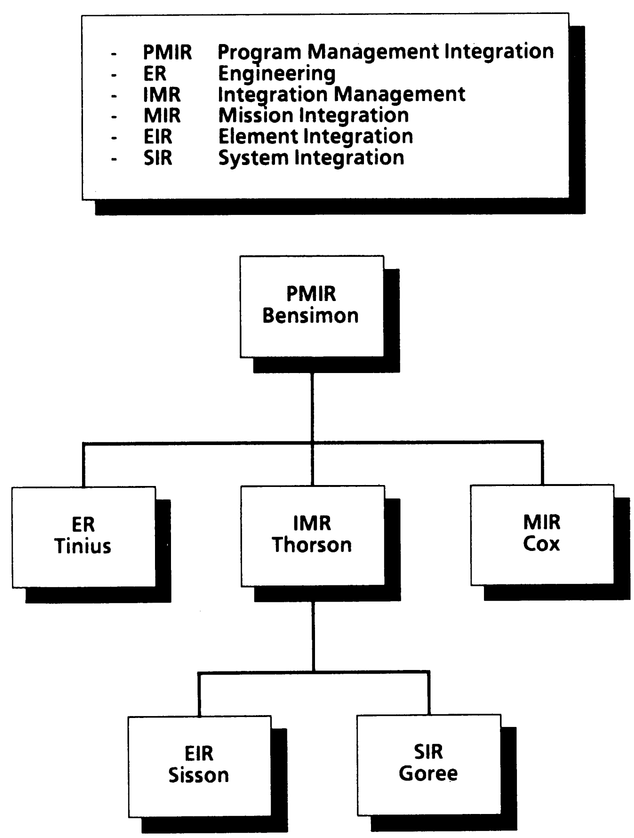
The SE&I organization is responsible for managing technical integration both vertically between different levels of the management organizational structure and horizontally across the organizations at each level. To efficiently achieve both dimensions of integration, it is necessary to develop logic diagrams of the major SE&I activities to be accomplished by each of the organizational elements and then to determine the interrelationships between them. By developing these diagrams and playing them against different organizational structures, it is possible to evaluate the proposed organizations in simple terms and easily define the interactions between the organizational elements, thus helping to choose the most efficient management structure. The importance of the logic diagrams will be discussed later.

Development and Use of Ad hoc Integration Structure

To manage the definition and implementation of the SE&I activities in manned space programs, NASA has developed an effective ad hoc organizational structure. The structure consists of a series of reviews, panels, and working groups that address the definition and management of integration functions throughout the program. Each of these organizations has membership representing all of the organizations interested in the particular integration function being managed. In the Space Station Freedom program, the working group structure is formed by technical disciplines and distributed systems, such as Guidance, Navigation and Control (GN&C), Robotics, and Loads and Dynamics. The panels are formed to address specific programmatic management areas (i.e., assembly requirements and stage definition, system design integration, and element design integration) that span a number of organizations. The reviews are formed to address relatively broad program areas as shown in Figure 5.

Each of these organizations is responsible for developing the integration plan in its area of responsibility, monitoring the execution of the tasks, identifying problem areas, and either re-

Figure 5 - Station Technical Review Structure 1990



solving them or submitting them to the overall program management structure for resolution. Many benefits result from the face-to-face meetings and interchange of information among peers in these organizations. Although these organizations by their nature do not perform work, the members, by working back through their functional organizations, greatly influence the work being accomplished in their particular areas of expertise. As rapport is developed between members, many potential problems and issues are identified and resolved without the need for referral to the formal management decision channels. In addition, the quality of the work materially improves. This ad hoc organizational structure also provides obvious places for program elements to present issues of any given nature for deliberation and resolution. All of the panels and working groups support each of the reviews as needed and submit their open issues to the most appropriate review for resolution.

The reviews address broad issues and serve as a communication channel between the panels and working groups. Since the reviews are broad and cover all of the panels and working groups, they provide an excellent way to assess and recommend activities that address the interdisciplinary aspects of the program.

Chairpeople of the panels and working groups are the best qualified individuals available in the particular discipline, and only secondary consideration is given to selecting a person from a specific organizational element. As a result of their recognized stature, the chairpeople provide leadership, which makes their recommendations and decisions more readily acceptable. The panels and working groups also request outside expertise when needed; such outside inputs are filtered by the panels and working groups prior to making a recommendation to the reviews or other management organizations.

Internal vs. Matrix SE&I Staffing

As already noted, SE&I activity was staffed and accomplished in different ways in the different NASA manned programs. At times, in the early manned space programs, the personnel required to accomplish the SE&I activity were assigned directly to the program and project offices. At other times, during the Apollo and Shuttle programs, the program office had only the people necessary to manage the SE&I activity, and most of the work was accomplished by technical experts assigned from the Center's functional organizations in a matrix fashion.

Although each had its advantages and disadvantages, the matrix approach in general appears to have had more advantages, one of the most important being that the manpower can be increased or decreased as needed by pulling support from the matrix organizations without requiring reassignment of the people involved. The primary disadvantage is that the leader of a particular area does not report functionally to the program or project office; therefore, the line of direction is not as strong, a factor that is inversely proportional to the working relationship between the organizations.

In the Space Shuttle program, this relationship and the matrix approach worked well. In other programs, the relationship was not as good and direction through the matrix was less effective. On occasion, program management appointed all panel and working group chairpeople from the program office staff, giving less regard to the personal qualifications of the individuals. This has led to a marked decrease in the stature of the ad hoc structure, which resulted in a lack of support from the functional organizations and a decrease in the quality of the integration activity and products. As in many areas of SE&I, effective implementation relies heavily on the quality of the leadership and the maintenance of free and open communications between the organizations involved.

Logic Networks

As the NASA manned space programs have become increasingly complex, it has become difficult to define the specific content and tasks needed to accomplish the SE&I function. Central to the development of a comprehensive SE&I plan is the development of detailed logic networks. These networks form the basis for planning, executing and evaluating SE&I activities.

As used in the Space Shuttle program, these logic networks covered all of the SE&I activities that had to be accomplished by all elements of the program organization. Thus, these networks were able to interrelate SE&I activities both vertically and horizontally throughout the program management structure. The basic summary logic networks were developed for the entire program duration to identify all major activities required as a function of time and were instrumental in developing cost and manpower forecasts for the entire duration of the program. Detailed logic networks were then prepared in the Shuttle program for 12 months, identifying in greater detail the specific activities to be accomplished by each organizational element during that period. The networks were revised every six months to extend the detail planning horizon, and in addition, the summary networks were reviewed and modified as needed on an annual basis. The logic networks were a primary input to the development of the engineering master schedules discussed next.

Engineering Master Schedules (EMS) and Associated Dictionary

The activities identified in the SE&I integration logic networks were then assigned to specific organizations for execution and presented as a schedule for each organization involved. By using a numbering system for the activities, a correlation between the logic network and the schedule could be easily provided. Preparation of the schedules allowed cost and manpower estimates to be prepared for each organization and provided an excellent means of updating and managing the activities in real time.

Associated with the engineering master schedule (EMS), a dictionary was prepared with an entry for each activity. Each entry identified all input information required to allow the accomplishment of the activity; described the contents of the products; and identified the primary user of each product, the scheduled completion date, and the person responsible for preparing the product. The EMS and the dictionary were the primary tools for defining and communicating SE&I activities throughout the entire program structure.

As would be expected, the basic content of the EMS changes character over the life of the program and accordingly requires a varying mix of technical capabilities as a function of time. Early in the program, the activities are primarily of a design nature and involve a large number of trade studies and the development of synthesis tools to be used in evaluating the capabilities of the proposed design. As the program matures and the design solidifies, the activities become more involved with exercising the system models, conducting tests, and analyzing data. As the flight phase approaches, the activities are predominated by operational considerations, including the development of operational data books, mission requirements, certification of system readiness, and support of mission planning and real time mission operations.

System Characterization Process

A major SE&I activity throughout the program life span is the assessment of the capability of the system to meet specified requirements. In the NASA manned space program, this has been accomplished primarily by synthesizing the vehicle characterizations in the form of either models or simulations and then developing detailed performance characterizations by exercising the models against selected mission timelines and significant mission events.

The methodology used in performing the system synthesis is central to the development of the logic networks and schedules described earlier. An examination of the system usually reveals scenarios useful in conducting the overall system evaluation, and after selecting the most desirable scenario, it is used to form the nucleus of the overall SE&I logic. In the Space Shuttle program, the scenario chosen was (1) developing the necessary models and simulations, (2) determining the structural modal characteristics, (3) determining the loads on each of the system elements, and (4) performing stress analysis of the system when subjected to these loads. Using this scenario it was relatively easy to define and interrelate the SE&I activities of other disciplines, such as GN&C, propulsion, and thermal, among others. After definition of all of the required acthe models to be used, the mission events to be analyzed, and a definition of the configuration to be used. The sequence described above formed an analysis cycle of a specific configuration subjected to specific operational requirements and, in the Shuttle program, was termed an integrated vehicle baseline characterization cycle (IVBC). In this article, the capability assessment is referred to as a system characterization cycle. As previously described in the SE&I scenario, several characterization cycles are needed during the life of the program. As the program matures, the cycles are characterized by having additional synthesis detail, more definitive configuration information, and better operational information.

At the completion of each of the characterization cycles, system deficiencies are identified and modifications to either the system specifications or the requirements are made. For program management purposes, it is usually convenient to schedule the completion of one of the characterization cycles to occur just prior to each of the major program level review milestones.

Program Reviews

SE&I has a large input to each of the program-level reviews, such as system requirements review, predesign review, critical design review, design certification review, and flight readiness reviews. As mentioned above, completion of one of the system characterization cycles is an excellent indicator of whether the system design meets the specified requirements, and the engineering master schedule gives a graphic representation of the integration progress being achieved. Reports produced by the SE&I activity—such as resource allocation status and margins interface control document status, design reference mission maturity, and system operational data books—give a good indication of the maturity of the element participation in the system-level SE&I process.

Design Reference Missions (DRM)

Most of the manned space programs had to be capable of performing a relatively large number of diverse missions, and the specifications are written in a manner to provide hardware and software systems and elements that are flexible enough to satisfy all of the missions. For analytical purposes, however, it is convenient to define and adopt one or more design reference missions (DRMs) that stress all of the system's capabilities to a significant extent. The DRMs are used as the primary mission requirements in the system characterization cycles, and in evaluating the ability to meet performance specifications. In addition to evaluating the baselined configuration against the DRMs, other specification requirements are evaluated by the accomplishment of specific analyses or tests as necessary.

The DRMs also allow the user community to evaluate whether the system is capable of meeting specific user needs and whether these needs are specifically in the system specifications. The DRM is also used by mission planners to determine the system's capability of performing any specific mission under consideration.

Verification

Verification plays a major role in program planning and in the ultimate cost of the system. Most of the verification is delegated to projects; however, SE&I is responsible for identifying overall verification requirements and specifically, identifying system-level verification test and simulations, which frequently require specialized facilities and significant amounts of system hardware and software. These system-level verification tests are frequently both complex and expensive, and planning for them needs to be started very early in the program. The system-level verification network is developed as an integral part of the program SE&I logic networks and baselined early in the program.

Final verification of some system requirements can only be accomplished in the real flight environment, and these are demonstrated in early operations before final certification of system operational capability is accomplished. It is also important to integrate the system-level verification planning and the operations planning to gain the maximum possible synergy between system verification and operational training.

In the manned space programs, all of the major system-level verification tests were assigned to program or functional organizational elements other than SE&I for implementation. This helps assure that the management of SE&I can remain objective in the evaluation of overall certification adequacy.

DCR Process

One of the more significant activities of SE&I is its role in the design certification of the system prior to the start of the flight operations and then again later, prior to committing the system to operating throughout the entire design envelope. SE&I is instrumental in setting the overall requirements for the DCR and is directly responsible for the system-level portion of the review. This process uses synthesis of the as-built vehicle hardware and software capabilities and results of tests and analysis. The results of the design certification process also form the basis for the system operational data books that are used in planning and conducting the operational phase of the program. The DCR requires that all system requirements be evaluated against all of the as-built system capabilities, and where possible, the system margins are quantified to assist the operations organization in planning and conducting flight operations.

ICD Development

As the program management organizational structure and the delegation of the responsibility for developing hardware and software are made, it is necessary to start the development of the interface control document (ICD) tree, which identifies each required ICD and the content to be presented. As previously noted, the division of program activities to minimize the number and complexity of interfaces has a strong influence on the overall program cost and the ability of the program to meet schedules. The early development of strawman ICD trees can greatly assist in optimizing the overall program management structure.

As the program progresses and the system configuration becomes better defined, the content of each ICD is developed in more detail and ICD working groups are formed to quantify the environmental, physical, functional, and operational characteristics in detail. In most of the manned programs, the ICDs have been baselined at a relatively early point in the program and have usually contained a large number of TBDs (to be determined). After baselining the ICDs, working groups then continue their work to arrive at specific values for each of the TBDs and to continually assess the adequacy of the ICDs as the design matures.

The ICDs are primary documents at each program review and provide a basis for evaluating the adequacy of the items being reviewed to satisfactorily function as part of the total system.

Program Management Organizational Structure

The efficiency of program management is greatly influenced by the organizational structure selected. Organizational structures that are compact and simple are essential to promote effective program management. Compactness is measured vertically by the number of levels of the program management organization and horizontally by the number of organizations at each level. Each organizational element added significantly increases the manpower and costs of achieving program integration, including SE&I. If each organizational element must interface with all others in the program, the number of interfaces increases rapidly as organizations are added. Adding management levels increases the complexity for delegating the execution of the program. This factor was evident to the Augustine Commission in their recent summary report *The Future of the U.S. Space Program,* in which they recommended that "multicenter projects be avoided wherever possible, but when this is not practical, a strong and independent project office reporting to headquarters be established near the Center having the principal share of the work for that project; and that this project office have a systems engineering staff and full budget authority."

In addition to keeping the management structure compact, it is also very important to select an an architecture that divides the program into project offices so that the interfaces between projects are as simple as possible and that the delegation is all encompassing. In so far as possible, all of the deliverable hardware assigned to a given project should be the responsibility of that project to design and manufacture. In all of the manned programs prior to the Space Station, there was little transfer of hardware and software between projects with one exception, that being the development flight instrumentation in the Apollo program.

Early in the Apollo program, a decision was made to establish a civil service project office to develop, procure and deliver the specialized development flight instrumentation to the prime spacecraft contractors for installation and integration in the early spacecraft. Coordination of the very large volume of interface information required the development and maintenance of the complex bilateral schedules and support required.

The complexity of providing support after the transfer of instrumentation was a significant management problem throughout the entire time that the development flight instrument was used. In view of the extremely large number of hardware and software items that must be passed between work packages, it will be difficult for the Space Station Freedom program to develop, coordinate, and maintain all of the interface information required.

Objectivity in Management

To promote objectivity in managing SE&I, one of the basic ground rules in the Space Shuttle program was that the SE&I function would not be responsible for the development of any flight hardware or software products; thus they had no conflicting pressure to make their development job easier at the expense of another organization. It was found that any bias, either perceived or real, immediately brings the objectivity of management into question and rapidly destroys the confidence between organizational elements.

Need for Good Communication

The nature of SE&I is such that most of the program elements and many other agency organizations are involved in the execution of SE&I tasks. To facilitate accomplishment of the work, the importance of free and open communication cannot be overly stressed. One of the ways of accomplishing this is "to live in a glass house." All decisions and, of equal importance, the logic behind those decisions must be communicated to all parties involved if they are to understand their role and how it fits into the overall picture. All parties must feel that their inputs are included in the decision-making process.

This openness, and the accompanying feeling of vulnerability, is not welcomed and requires faith and confidence between the organizations involved. The fact that mistakes will be made must be accepted, and all organizations involved must constructively assist in correcting them. Frequent open meetings of the ad hoc organizational elements described above have proven to be an effective tool in developing rapport between peers and communicating information and decisions throughout the program structure. As noted earlier, however, such meetings become increasingly time-consuming and expensive as the complexity of the organizational structure is increased.

Importance of Margins

At the time programs are initiated, they are frequently sold on the basis of optimistic estimates of performance capability, cost, and schedules. This often results in reducing margins to low levels at program initiation and solving early program costs and schedule problems by reducing weight, power, and other resource margins. As a consequence, margins are reduced to zero or negative values early in the program, making it necessary to modify the program to either reduce requirements or introduce program changes that will re-establish positive margins.

The recovery of the margin inevitably leads to significantly higher ultimate program costs in both dollars and days. Minimum life cycle costs are achieved by holding relatively large margins early in the program and then allowing them to be expended at a prudent rate during the program life cycle.

Things That Have Worked Well

In the management of the manned space programs' SE&I activities, several approaches have been particularly successful. Some of the more important, briefly summarized below, have been discussed previously in the paper but are readdressed here because of their assistance in the management of SE&I.

Ad hoc Organizations

The use of ad hoc organizations to coordinate SE&I activities has proven to be a valuable tool. The effectiveness of SE&I depends heavily on good communications between organizations and the assurance that a common approach to the implementation of SE&I is being taken by all organizational elements. This is difficult to accomplish using the normal program office organizations because they cannot directly address interorganizational communications and have difficulty in managing across organizational lines. The ad hoc organizational structure, on the other hand, is made up of specialists from each of the affected organizations, and their activities directly promote interorganizational communications. Using this technique, technical peers can plan and monitor the execution of specific SE&I activities. When a resolution cannot be reached within the ad hoc organizational structure, the issue is referred to the proper program management office.

Common Organizational Structure Within the Program and Project Offices

During the Apollo program, the program director decided to have all of the program management offices at both Level II and Level III adopt a standard organizational structure. Five offices reported to the program manager and to each project manager. This technique assured that the work breakdown structure was similar for all offices, that direct counterparts could be identified in each of the offices, and that budget allocations flowed down in a uniform and predictable manner. All of these features resulted in less cross-linking between organizations and made the required program management activity more rational and predictable. Although the specific office structure chosen would be different for each program, the concept of having uniformity between the Level II and Level III management offices should be considered for future programs.

System Characterization Cycles

Constructing the SE&I plan and identifying the required tasks is a very complex undertaking in large programs, and as previously described, it is best to meet the specified requirements. Analysis of the results reveals deficiencies and allows modifications to either the requirements or the system design to be identified, thus assuring an adequate margin of performance. Building on this core analysis cycle, it is relatively easy to plan the other SE&I tasks around it in a consistent manner, providing a complete characterization of the system capability.

Matrix Management Organizational Approach

The concept of staffing the program management office with a small number of people who serve as managers only and then augmenting their capability with personnel drawn from other Center organizations in a matrix fashion has significant advantages. Personnel can be brought in from the organizations only when they are actually needed, and the makeup of the technical capability can be changed as a function of time to satisfy programmatic needs. The quantity can be augmented to meet program needs, i.e., major program reviews; the personnel involved can be assured of a career path in their parent organizations; and the individuals involved can continually replenish their expertise by participating in the R&D activities in their parent organizations.

This mode of operation has been quite successful and has demonstrated several additional attributes such as reducing friction and undesired competition between the program office and Center functional organizations, improving technical communications across programs being implemented simultaneously, and providing an efficient way of phasing the development program into an operational role. It is noteworthy that the assignment of program-level SE&I to a lead center, coupled with the execution of this assignment using Center functional organizations in a matrix fashion, allowed the program to take advantage of both the quality and quantity of technical expertise available throughout the Center.

Use of a Prime Development Contractor to Provide SE&I Support

In the Space Shuttle program, the SE&I support contractor was also the prime contractor for development of the Space Shuttle orbiter. Although there was considerable concern about the ability of the contractor to maintain objectivity in supporting SE&I, this concern was reduced to an acceptable level by separating the direction channels of the development and integration activity both within NASA and within the contractor's organization. The support contract was also set up with an award fee structure in which SE&I was responsible for providing inputs for the SE&I activities. There were many advantages to having this arrangement:

a) The integration personnel were familiar with one of the major program elements and did not need to become familiar with that element or the general program structure.

b) Expert technical specialists could be made available for both activities as needed.

c) Many of the synthesis tools required by both activities were similar, and frequently one model could be used for both purposes with only minor modifications.

d) Uniformity in approach assured ease of comparison of results from both project and program level activities.

Summary

The management of SE&I in NASA's manned space programs has developed over the last 30 years to integrate complex programs satisfactorily. Some of the approaches and techniques described in this paper may be helpful in integrating future programs. Careful consideration of the organizational structure and systems architecture at the start of the program will largely determine the level of effort required to accomplish the SE&I activity.