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SYSTEMS ENGINEERING & INTEGRATION AND MANAGEMENT FOR MANNED SPACE FLIGHT 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.

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 systems' 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 Centers, which were primarily expert in the technical area 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. 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 work force was located at the 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 development 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 Centers' 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. 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 management organization will be discussed in more detail in the next section.

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 the Manned Space Center, managed both development and flight operational aspects of the Mercury and Gemini programs with the checkout and preflight testing being performed by support elements at Cape Canaveral.

Apollo became organizationally more complex (Figure 1). The spacecraft development was managed by JSC, the launch vehicle development by Marshall Space Flight Center (MSFC), the prelaunch activities by 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 intercenter 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 responsibil-

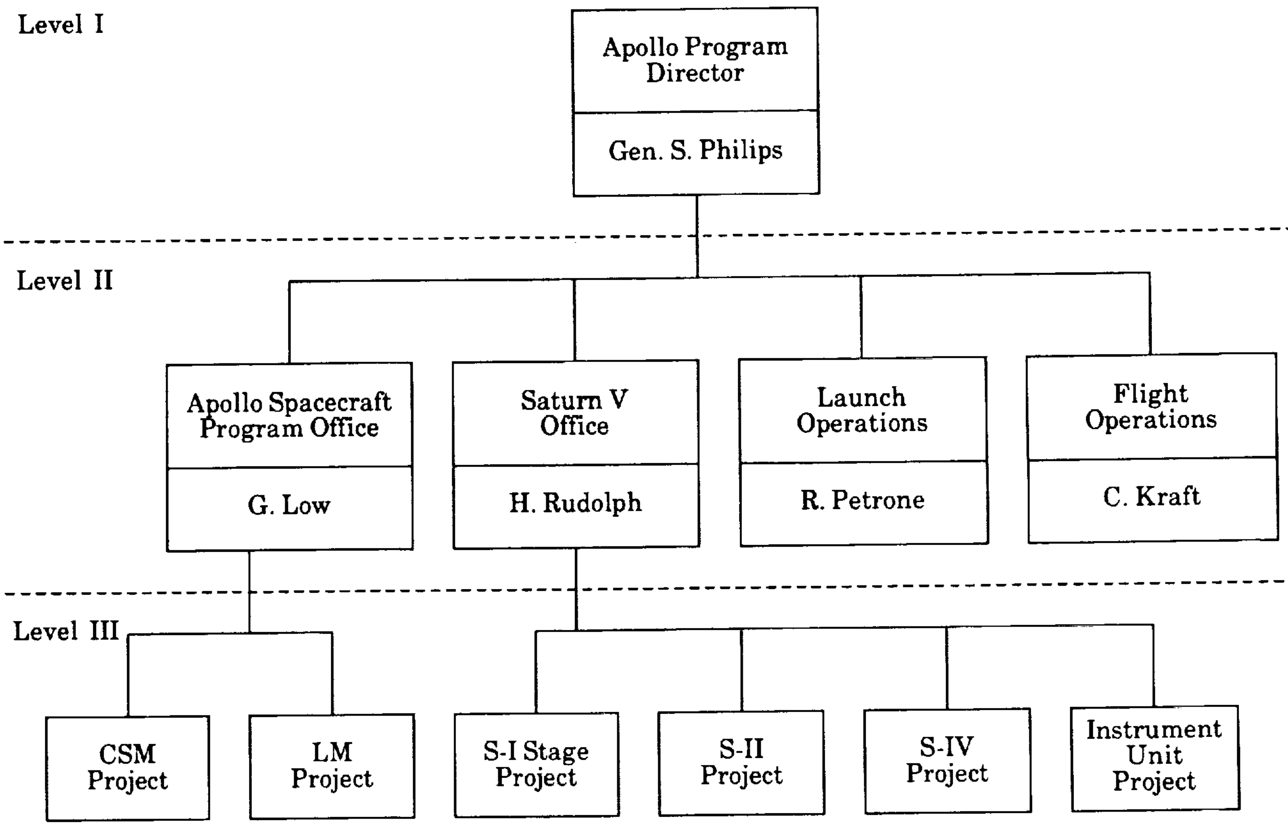

Figure 1 Apollo Program Management Organization

performing the SE&I activity with the actual work being led by Bellcom, a division of Bell Laboratories. Ultimately, this approach was abandoned, at least partly 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 (Figure 2), the management of SE&I was markedly 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 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 contractor to provide program integration

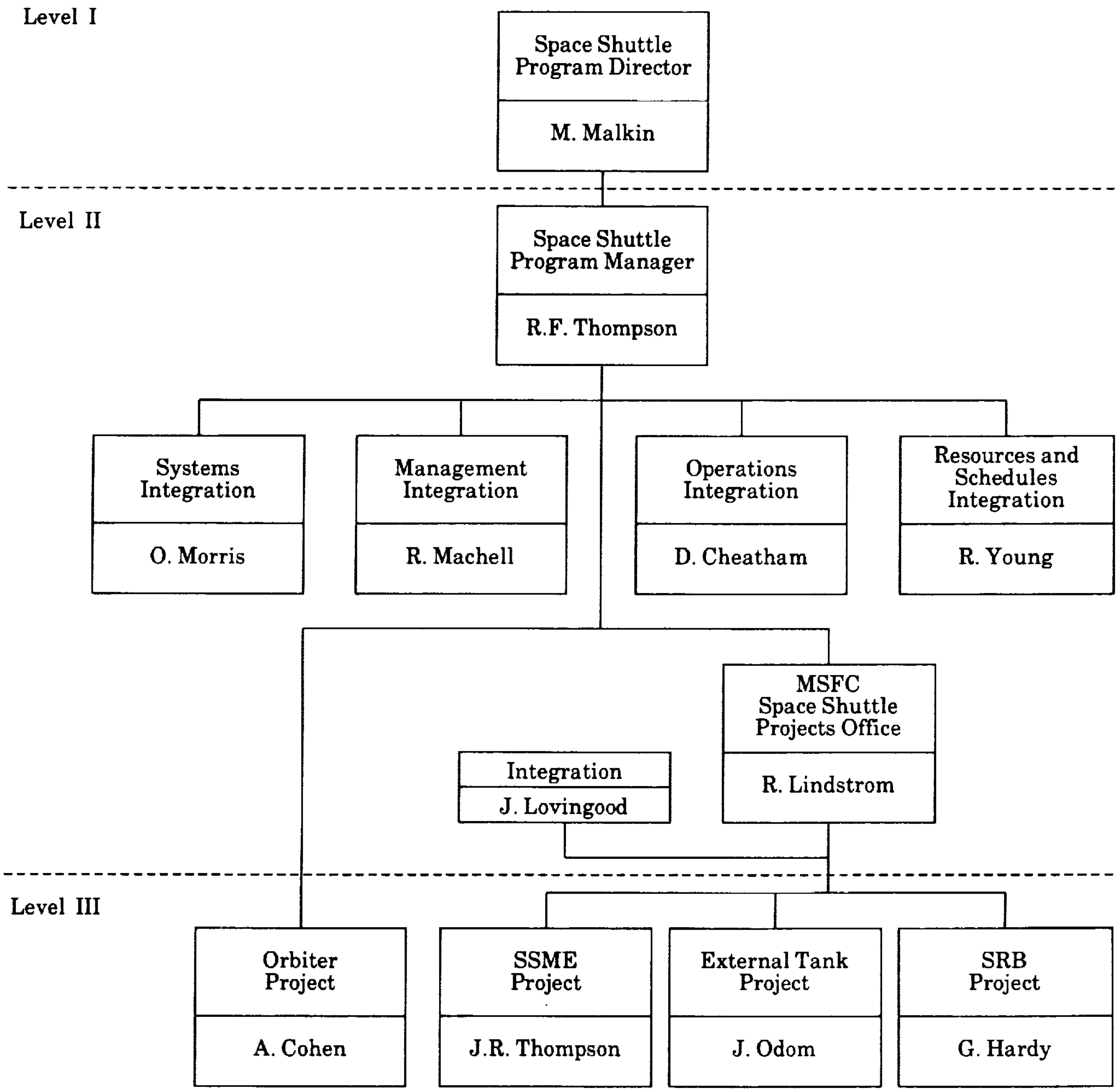

Figure 2 Space Shuttle Program Management Organization

support (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 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 program integration and the lack of in-depth backup capability, this management approach has not been completely effective.

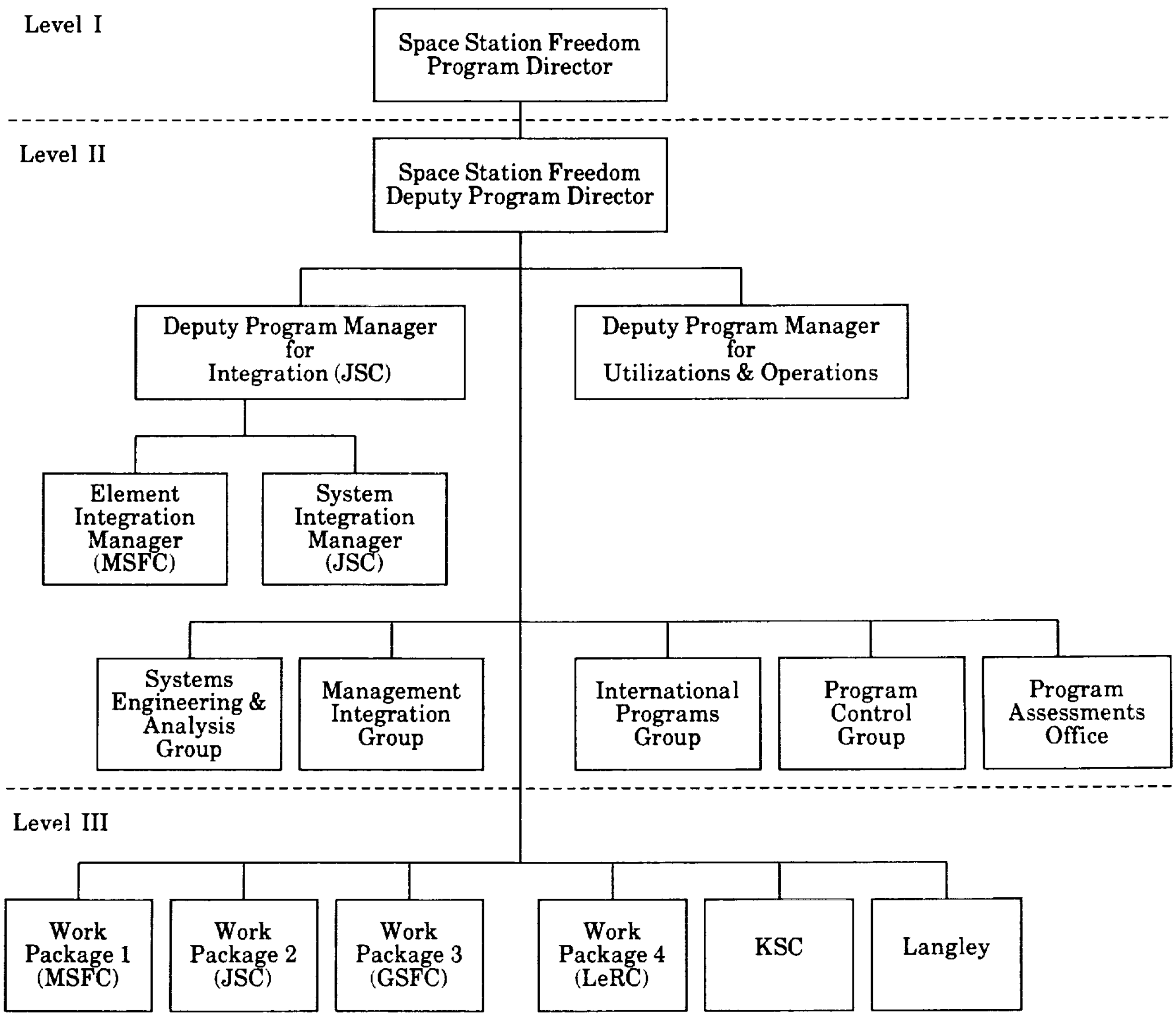

Figure 3 Space Station Freedom Program Management Organization (1990)

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 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 in-depth technical capability residing at the Centers. Simultaneously, the integrating contractor's work force at the Centers was increased in both responsibilities and numbers.

GROWING PROGRAM COMPLEXITY

One of the major factors determining the efficiency of the integration of a program is the methodology used to delegate the engineering and development responsibilities to the project offices at the Centers. It has been found that less complex organizational structures and simple interfaces are extremely important to allow efficient management of 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 and the launch vehicle was divided into four project offices. By assigning the four launch vehicle projects to the same 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 Centers, was relatively simple. In a 1971 paper 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 person can fully understand this interface and can cope with all the effects of a change on either side of the interface. 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 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 the 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 time, 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, a new program management structure (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 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 the 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 (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 in the Space Station Freedom program. 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 incorporates 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.

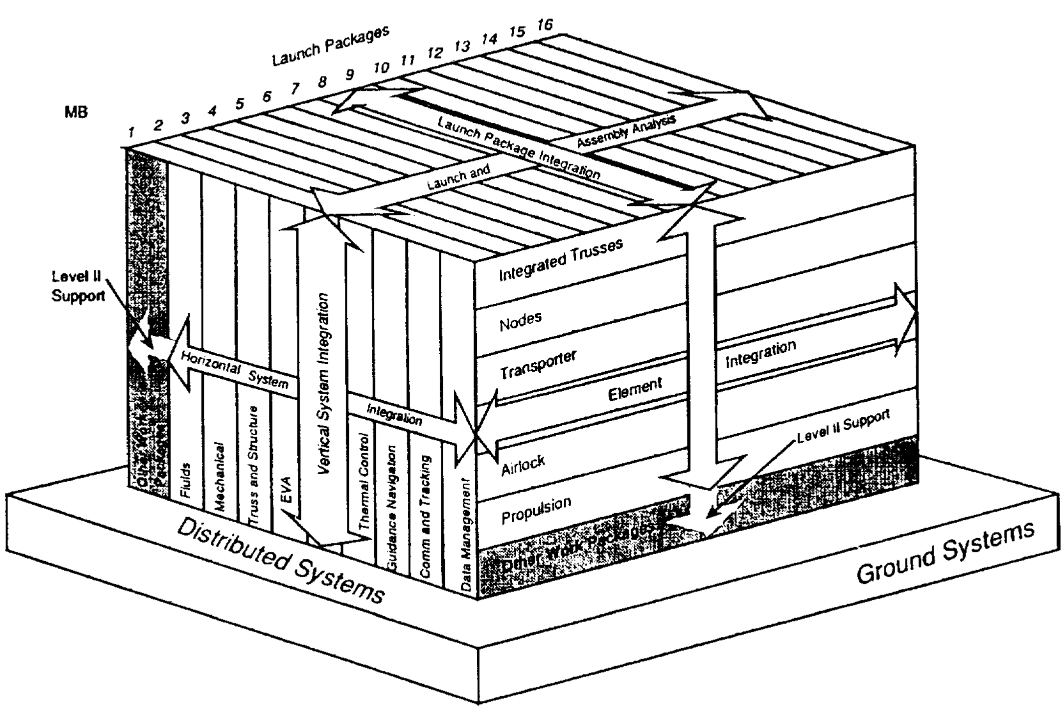

Figure 4 Space Station Integration Job

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 SE&I is intimately involved in defining systems that will meet the overall program objectives and in evaluating the 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 systems concepts has been completed, SE&I provides a lead in the preparation of the procurement specifications for the Phase C and D activities and is usually directly involved in the source selection process. After award of the Phase C and 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 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 document drafts. Another system characterization cycle is started, based on the updated specifications and the hardware and 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 routinely. 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 later.

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 proposed by the projects are compatible across the interfaces and that the integrated system is capable of meeting 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 is added to assure that the documents are mature enough to become baseline requirements in the program. This maturation process inevitably results in the identification of physical and functional disconnects among the elements and in 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 are delegated to appropriate organizations that 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 validates 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 similarly 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 operational 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.

The SE&I organization's participation throughout the program development cycle supports operational planning and real-time operations. SE&I is the repository of corporate knowledge of the details of 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 noncontroversial changes outside of the formal control board meetings, where appropriate. This significantly reduces the board's workload and conserves the time of the key managers who are members of the change control board. As significant issues are referred to the board, SE&I presents an analysis of the issues involved and makes appropriate recommendations for action.

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 the SE&I logic networks and estimates of the manpower required to accomplish the activities. Because of SE&I's interdisciplinary nature, SE&I can assist in planning activities in many areas of the program.

Early in the program, SE&I helps define the content and schedule milestones of each project to permit coherent development of project-level schedules and cost estimates. SE&I also 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 planning major program reviews; provides technical leadership in conducting the reviews; and frequently chairs the screening groups and pre-boards.

Operations. In all of the NASA manned space programs to date, the SE&I function has been managed in an organization different 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 combine the management of SE&I and operations in the same office early in the program and then separating them later, perhaps at the completion of the preliminary design review. The stated reason for separating the functions in the past has been that they serve as a check and balance on each other; however, the separation also disconnects the detailed interfaces between the two functions.

SR&QA. The interactions between SE&I and the system reliability and quality assurance (SR&QA) functions depend on how responsibility for executing the program is delegated. If a large part of the SR&QA activity is accomplished within the SR&QA organization, SE&I is used 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 SR&QA activities and for evaluating the outcomes—while other organizations are delegated the responsibility for executing the work—then SR&QA must define and obtain baseline approval of task requirements, monitor execution of the task by SE&I, and evaluate the results to assure satisfactory achievement.

The former mode of operation was exemplified during the early Apollo program, in which 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 execution was adopted; the engineering offices, primarily SE&I, actually performed the work and made a first-level analysis before formally transmitting the results to SR&QA for authentication. This latter method was considered 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

Techniques developed in past NASA manned programs have proven effective and have become an integral part of implementing SE&I activities. The following paragraphs describe, in no particular order, some of the most important techniques in planning and implementing new programs.

Importance of SE&I Early in a Program. In the early stages of complex programs, comprehensive SE&I support helps determine the architecture to be used to delegate 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 organizations 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 interrelations 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 organization has members who represent 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, 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.

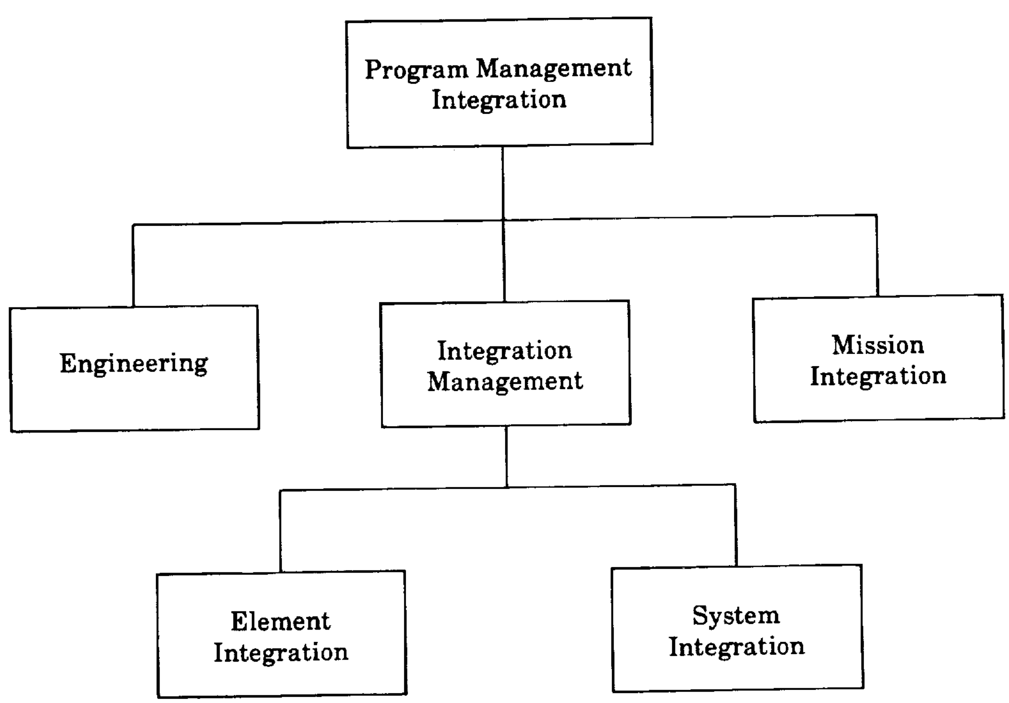

Figure 5 Space Station Freedom Technical Review Structure (1990)

Each organization is responsible for developing the integration plan in its area of responsibility, monitoring the execution of the tasks, identifying problem areas, and either resolving them or submitting them to the overall program management structure for resolution. 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 area of expertise. As rapport develops between members, many potential problems and issues are identified and resolved without being referred to 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 any issue for deliberation and resolution. All of the panels and working groups support each review 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 the working groups. Since the reviews cover all of the panels and working groups, they provide an excellent way of assessing and recommending to management the interdisciplinary priorities of the program.

Chairpeople of the panels and working groups are the most qualified individuals available in a particular discipline. 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 credible. The panels and working groups also call in outside expertise when needed, but such outside inputs are filtered by the panels and working groups before making a recommendation to the reviews or other management organizations.

Internal vs. Matrix SE&I Staffing. As already noted, SE&I has been staffed and accomplished in different ways in different NASA manned programs. In the early manned space programs, the personnel required to accomplish the SE&I activity were assigned directly to the program and project offices. 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 Centers' functional organizations in a matrix fashion. Although each method has its advantages and disadvantages, the matrix approach generally has more advantages in that manpower can be increased or decreased as needed by pulling support from the matrix organizations without reassigning the people involved. The primary disadvantage is that the leader of a particular area does not report functionally to the program or project office, which means that the line of direction is not as strong. The importance of this negative factor, however, 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 individual's personal qualifications. This led to a marked decrease in the stature of the ad hoc structure, which then 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 among the organizations involved.

2

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, which form the basis for planning, executing and evaluating the SE&I activities.

As used in the Space Shuttle program, 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 for the near-term 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; 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 in the next paragraph.

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, the logic network and the schedule could be easily correlated. The schedules allowed cost and manpower estimates to be prepared for each organization and provided an excellent means of determining status and managing activities in real time.

Associated with the 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 content of the EMS changes character over the life of the program and accordingly, requires various technical capabilities over time. Early in the program, the design activities 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 in an analytic sense 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 to perform 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; after selecting the most desirable scenario, it forms the nucleus of the overall SE&I logic. In the Space Shuttle program, the scenario chosen was (1) develop the necessary models and simulations; (2) determine the structural modal characteristics; (3) determine the loads on each of the system elements; and (4) perform 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 defining all of the required activities, a document was prepared to identify the models to be used, and the mission events to be analyzed and to define the configuration to be used. The sequence described above formed an analysis cycle of a specific configuration subjected to specific operational requirements. In the Shuttle program, it was termed an integrated vehicle baseline characterization cycle (IVBC). As previously described in the SE&I scenario, several characterization cycles are needed during the program: as the program matures, the cycles have additional synthesis detail, more definitive configuration information, and better operational information.

At the completion of each of the characterizations 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 before 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, preliminary design review, critical designreview, 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. The engineering master schedule gives a graphic representation of whether the integration progress is 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 indicate the maturity of the element participation in the system-level SE&I process.

Design Reference Missions. Most of the manned space programs had to be capable of performing a relatively large number of diverse missions, and the specifications are written to allow 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 systems 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 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. Although most of the verification is delegated to projects, SE&I is responsible for identifying the overall verification requirements and specific system-level verification tests and simulations, which frequently require specialized facilities and significant amounts of system hardware and software. Since these system-level verification tests are frequently complex and expensive, planning for them needs to start very early in the program. The system-level verification network is developed as an integral part of the program SE&I logic networks and is 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 promote the maximum synergism possible between system verification and operational training.

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

DCR Process. One of the most significant activities of SE&I its role in the certification of the system design prior to the start of the flight operations and then 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 becomes the final major system characterization cycle, using a synthesis of the as-built vehicle hardware and software capabilities and results of tests and analyses. DCR results also form the basis for the system operational data books that are used to plan and conduct 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 is determined and responsibility for developing hardware and software is delegated, 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 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 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 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 additional organizational element 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 architecture that divides the program into project offices, to enable simple interfaces between projects and delegation that is all-encompassing. All of the deliverable hardware assigned to a given project should be the responsibility of that project to design and manufacture. In all 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 Apollo, 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 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 the instrumentation was a significant management problem throughout the entire time that the development flight instrument was used. In the Space Station Freedom program, considering the many hardware and software items that must be passed between work packages, it will be difficult 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 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 overstressed. 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 often 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 reestablish 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 most important, have been discussed previously 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 all organizational elements take a common approach to the implementation of SE&I. This is difficult to accomplish using the normal program office organizations because they cannot directly address inter-organizational communications and have difficulty 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 inter-organizational 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 organization, the issue can be referred to the proper program management office for decision.

Standard Organization 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 organization structure: five offices reported to the program manager and the same five offices reported 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, 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. As previously described, it is best to have a well-defined core of activity that, when completed, will characterize the capability of the system 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 in a consistent manner, and create 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. Manpower can be brought in from the organizations only when it is actually needed, and the technical composition can be changed over time to satisfy programmatic needs. The quantity of personnel can be augmented to meet program needs, i.e., during major program reviews; the personnel involved can be assured of a career path in their parent organization; and the individuals involved can continually replenish their expertise by participating in the R&D activities of their parent organization.

This mode of operation has been quite successful and has demonstrated several additional advantages, 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. In particular, 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 fashions, allows 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 Shuttle program, the SE&I support contractor was also the prime contractor for the 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 in 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) Technical experts 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-level and program-level activities.

The management of SE&I in NASA manned space programs has developed over the last 30 years to satisfactorily integrate relatively complex programs. 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 a start of a program has an overriding effect on the effort required to accomplish the SE&I activity.