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SYSTEMS ENGINEERING AND INTEGRATION PROCESSES INVOLVED WITH MANNED MISSION OPERATIONS

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The quality of the systems engineering and integration (SE&I) process determines the viability, effectiveness and the survivability of major NASA flight programs. In mission operations, SE&I is the process by which the technical, operational, economic and political aspects of programs are integrated to support the program objectives and requirements consistent with sound engineering, design and operations management principles.

Major flight programs involve operational, cost, and political elements and priorities, international prerogatives, and often poorly focused utilization requirements, in addition to traditional technical trades, technology utilization, and interface definition and control. This combination demands an effective SE&I process that spans and involves all these elements.

SE&I, therefore, is a distributed process that involves the structuring and integrated management of a program within and between the program, project and technical levels, with a life cycle consistent with the program phase. SE&I must anticipate program needs by providing clear technical assessments, trades and alternatives aimed at satisfying the program objectives and requirements.

This paper will describe the key principles and processes used within mission operations, emphasizing the pre-mission preparation activities most useful for describing the principles of an effective SE&I process.

EARLY DEVELOPMENT OF MISSION OPERATIONS

The development of mission operations capabilities for manned space flight involved a rapid evolution from the traditional method of aircraft flight test operations used during the early Mercury program to the mature and structured process used for Apollo. The flight experience of the Mercury program revealed the need for a deeper knowledge of spacecraft systems by flight operations teams. It further indicated a need for systems documentation tailored to the operator's real-time task. By the completion of Mercury, a systems handbook had been developed as an "on-console," real-time document for flight systems data. Direct communication was established between the operating team and the manufacturer so that any additional systems data needed during the course of the mission could be obtained. This communication also provided a means for getting engineering judgment on operational trades, whenever time permitted. The flight rules became the focus of operational policies.

The Gemini program required the development of the trajectory capabilities needed for rendezvous and docking, as well as a guided reentry capability. These requirements established the linkage between trajectory; guidance, navigation and control (GNC) systems; and propulsive consumables. The Gemini extravehicular activity (EVA) increased awareness of the relationship between crew, the task and the working environment.

During Apollo, science became the final mission component supported by the operations teams. The Apollo operations team worked in an integrated fashion on all issues involving flight systems, flight design, science and manned operations.

It was during the Skylab program that the first formal and broad-scale application of the mission operations (SE&I) process emerged to support the early flight system hardware and software design. During the Skylab design reviews, many of the review item discrepancies (RIDs) revealed the need for much closer relations between systems design and operational utilization.

The multiple Skylab systems elements, combined with the broad spectrum of scientific objectives and the complexity of manned and unmanned flight, required an early and effective relationship between flight systems designer, scientist-user and mission operations. A Johnson Space Center (JSC) operations team and a Marshall Space Flight Center (MSFC) engineering team joined to conduct a series of systems operations compatibility assessment reviews (SOCARs). During these and all subsequent reviews, the Skylab systems and software handbooks produced by mission operations were used as the baseline reference documentation for the SOCAR. These documents were also used by the JSC and MSFC teams for the flight phase of the program. Skylab real-time operations demonstrated the effectiveness of this relationship between the JSC and MSFC teams.

The mission operations team supported the design and development phase of the Space Shuttle program at the program and project levels and helped develop operational workarounds for flight systems and software deficiencies that could not be corrected before the flight test phase of the program.

MISSION OPERATIONS STRUCTURE

The Mission Operations Directorate (MOD) at the Johnson Space Center is highly integrated and structured around the principal skills needed for mission preparation, planning, training, reconfiguration, facility development, facility operations and real-time flight operations.

Each mission operations element consists of a single functional discipline, e.g., mission design, flight systems, reconfiguration, training, etc. Usually each organizational element is structured to provide dedicated support to either the Shuttle or Space Station. This is believed to be the best way for assuring accountability in individuals and management, avoiding conflicting priorities and providing leadership focus. The only exception is a Flight Design and Dynamics Division (FDDD), which provides integrated flight design for the Shuttle and all programs using Shuttle services.

Each division is responsible for integration within its work area and provides mission operations representation to the project–level boards. Program-level boards are generally supported through the Flight Director Office, by the Operations Division and by the FDDD. Integration between programs is accomplished by the MOD assistant directors for the Shuttle and for the Space Station.

In addition to the internal integration process, each division generally has a horizontal integration responsibility that identifies, collects and documents the capabilities and constraints imposed by other elements. This integration process frequently incorporates participants external to mission operations (for example, participants from the program and the project), as well as the flight system contractor and the payload user. In most cases, this is accomplished by mission operations directed panels that are chartered by the program.

INTRODUCTION TO MISSION OPERATIONS SE&I

This paper will discuss three mission operations functions that are illustrative of the key principles of operations SE&I and of the processes and products involved.

- The flight systems process was selected to illustrate the role of the systems product line in developing the depth and cross-disciplinary skills needed for SE&I and providing the foundation for dialogue between participating elements.
- FDDD was selected to illustrate the need for a structured process to assure that SE&I provides complete and accurate

results that consistently support program needs.

- The flight director's role in mission operations was selected to illustrate the complexity of the risk/gain tradeoffs involved in the development of the flight techniques and flight rules process as well as the absolute importance of the leadership role in developing the technical, operational, and political trades.

Flight Systems Division SE&I

The early Mercury program employed a mixture of operations and engineering personnel to support the real-time operations. Later, flight experience established the need for a full-time systems operations team. The need for an integrated compilation of flight system data usable by the crew and ground team for real-time operations led to early versions of the systems handbooks that are the foundation for today's handbooks. Rudimentary integrated schematics were used for Gemini, but with the Apollo program came more complex inflight computing capability. Consequently, the schematics were expanded to define the computer interfaces and used significantly more of the vehicle design and performance data base within the schematic notes.

As mentioned earlier, the schematics were used for the first time to support the Skylab critical design reviews and the SOCAR. During these reviews, program and project management recognized that the systems operations teams and the systems handbooks were an SE&I asset. The modularity of the Skylab elements, along with the integrated nature of the systems, established the pre-mission role for the systems handbooks to support the flight system design review process as an integrated activity. The usefulness of the handbooks in addressing integrated systems issues was thus formally established. For the Apollo Soyuz Test Program (ASTP), and the Shuttle and Spacelab programs, the preliminary version of the mission operations schematics were completed prior to the flight system critical design review (CDR) and were used as the foundation for the mission operations assessments.

The Systems Handbook Today

Mission operations schematics are developed by the controllers to a common set of internal drafting standards and conventions and use the design engineering drawings, vendor schematics and software source code. For the Shuttle, operations personnel were required to develop Houston Aerospace Language/Shuttle software language skills as a job requirement. Permanent, prime contractor, in-house and in-plant support assures the flow of the raw design data and provides the communications conduit between the systems operations personnel and the prime contractor design engineers so they can address questions as they arise. After the STS-51L accident, all handbook schematics were expanded to provide direct traceability to design drawings by title, drawing number, revision and date.

The systems controllers who develop the schematics derive significant training from using design data and translating this data into an operationally useful format. The schematic development and the integration of data from supporting systems and subsystems provides independent validation of the system design intent. In particular, it identifies issues where the integrated design may have compromised the program intent. The drawing configuration control process requires verification by section and branch chiefs and final approval by the division chief. Formal reviews are conducted before major handbook releases. As a result, the operator and the supervisory chain derive a training benefit from the systems handbook process.

The systems handbooks are used by crews, flight directors, training instructors and mission operations payload support personnel. They are a formal portion of training documentation and are carried in the Shuttle flight data file. The schematics support airborne system troubleshooting and provide a common base for the crew and the ground to discuss suspected problems and follow-on actions. They provide the basis for MOD discussion with the contractor engineering team and with the mission support team.

Flight Procedures. The development of the systems handbook provided the foundation for the development of flight procedures. Three basic categories of flight procedures are developed: the operations checklists, the pocket checklists and the malfunction procedures.

The operations checklist procedures allow the crew and ground systems operations to accomplish a planned activity and are normally developed as blocks of integrated systems activities; for example, aligning the inertial measurement unit. Procedures development requires intimate familiarity with the system; its interfaces, controls, and displays; and with the intended task to be accomplished. Operations checklist procedures cross all systems and technical disciplines, and as a result of their development, provide another level of systems integration and design validation. Procedures associated with an Orbital Maneuvering Subsystem burn, for example, involve loading the maneuver targets into the computer, selecting and configuring engines for the burn, activating the correct digital autopilot, selecting displays, and specifying of data to be recorded.

Pocket checklists are emergency procedures based on the operations checklist. The term "pocket" is used because the checklists must be readily available for critical mission phases and are sized to be carried by the crew in the pockets of their flight suits.

The pocket checklist procedures define the steps to be taken when an unplanned event occurs. These procedures address critical failures and are flight-phase unique. They require knowledge of system performance limits, crew capabilities, failure modes, and crew and ground response times. The emergency procedures therefore provide a bridge from operations checklist procedures into options that allow the crew to continue the current flight phase with modification, to reconfigure to recover capabilities, or to utilize an alternate capability. Figure 1 is a typical procedure used during powered flight for a main B undervolt condition.

The final type of flight procedures developed by the controllers are the malfunction procedures (MALS), which are used when time is available to troubleshoot, locate and define the boundaries of problems that occur inflight. To solve the problem, the crew and ground use the full range of instrumentation available and any visual or external cues available. The procedures are developed in a logical format using a series of "if," "and," and "or" statements. Warning notes are provided, as well as permissive steps when ground and crew consultation is required prior to continuing the procedural sequence. These procedures have allowed the correct isolation of the majority of inflight problems for the Shuttle program.

A final category of flight procedures concern payload operations and involve multiple flight elements.

Flight Systems Organizations. Since Gemini, the MOD flight systems organizations have been structured to address a complete space system. Examples include command service module, lunar module and Shuttle. Each section within an organization has responsibility for an assigned system, with its subsystems, software, instrumentation, display, crew controls, command controls, procedures, mechanical, power, cooling, and thermal and consumable interfaces. During the Skylab program, each organization also had to know about inflight maintenance and support logistics.

The systems organizations of the MOD participate in flight systems design via formal membership on the working groups,

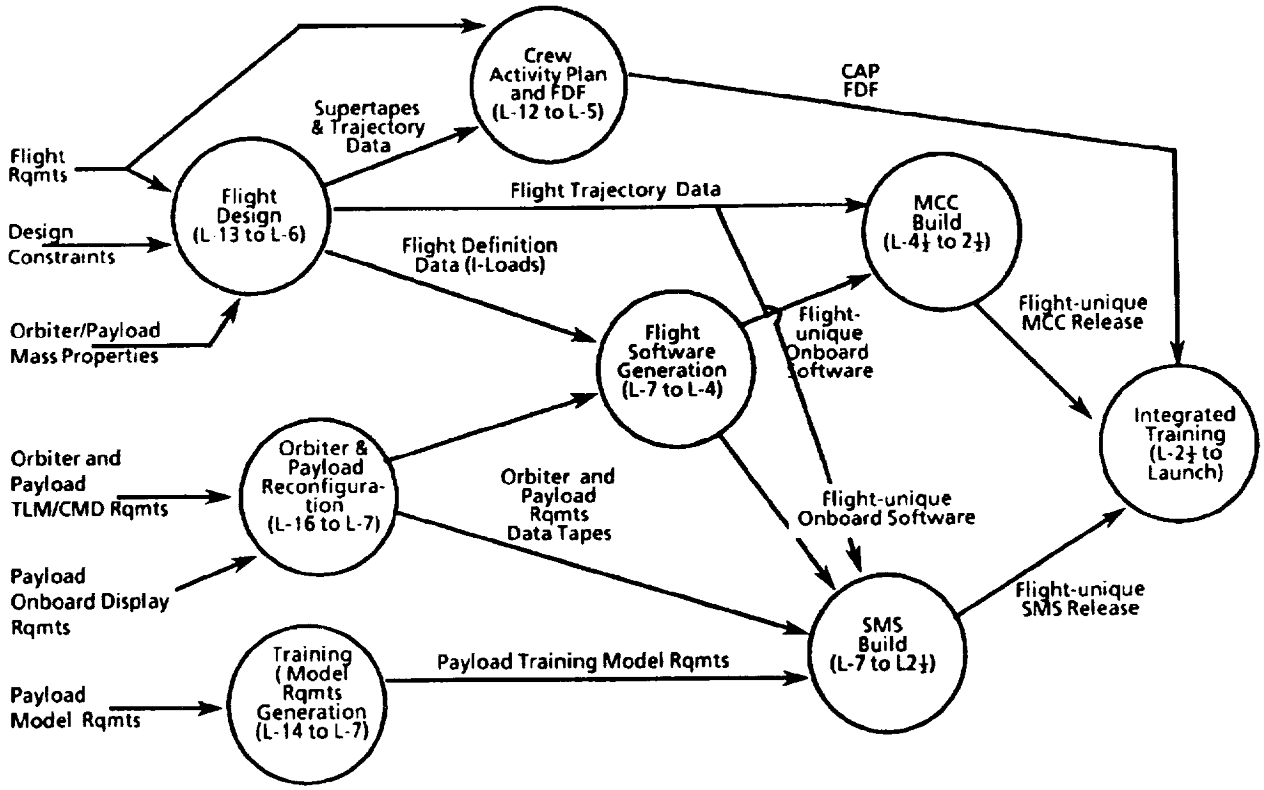

Figure 1 MOD Production Process Overview (L-Time in Months)

panels and boards established by the program office. During the early design phase, they establish the data base for the development of schematics and procedures for the flight controllers. Because of this, direct contractor liaison is maintained within the MOD systems organization and in-plant.

Development of the mission product line by the systems flight controllers increases their skills and knowledge. In addition, the product line focuses the operations assessments of overall flight system architecture and provides the foundation for subsequent steps. Finally, as a recognized product, it is used by several groups in support of their individual responsibilities. Program SE&I products typically must exhibit the same characteristics—they must pass the value-added test.

The systems operations contribution to the early design and eventual operation of the flight system has been essential in assuring safe, effective and functional system capability for space flight. The perspective of the systems operator provides the cross-disciplinary assessment needed to assure effective overall systems engineering and integration. This perspective is the cornerstone of the real-time capability of the manned spaceflight operations team.

Flight Design Division SE&I

The flight design process involves the integration of payload and engineering requirements with mission objectives to form an integrated mission design. The flight design must satisfy both Shuttle system design and payload design constraints while considering the additional constraints imposed in consideration of safe mission conduct and mission success.

The flight design process is a critical node in the Shuttle mission preparation process. In addition to flight design, the process provides initialization data for the ground

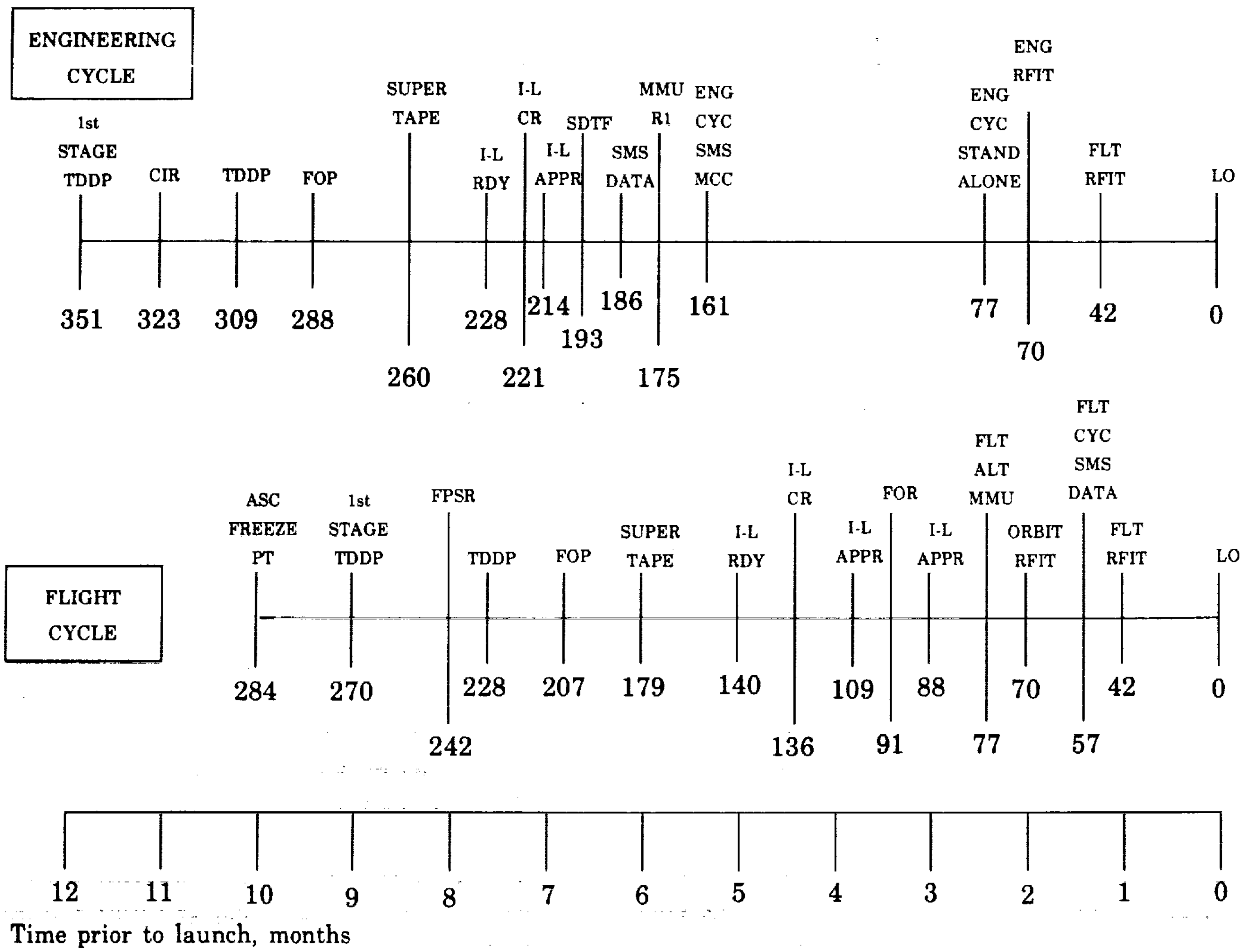

Figure 2 Flight Design Template

facilities, Shuttle primary and backup software, flight and payload planning, and real-time decision support products.

Within the flight design and dynamics discipline there are three mission phase analysis and design work areas—ascent, orbit and descent—and one functional area—real-time operations. The FDD, working in coordination with other mission operations elements, establishes and integrates the propulsive and non-propulsive consumables, abort propellant dump analysis, and manipulator requirements and analysis into the overall flight design. The overall integration of activities supporting a mission is provided by a flight design manager.

The flight design process acquires a vast amount of input data from a wide variety of sources. The input data for the early phase of the program is typical specification data, but during the operational phase of the program it becomes highly flight specific and frequently component specific. A good example would be constraints for engine throttling related to a specific Space Shuttle Main Engine turbo pump.

Flight Design Cycles. The flight design process has three principal cycles designed to satisfy the requirements and lead times of the many users. The conceptual flight profile cycle provides the program office with data for making commitments to the payload customers and assessing the overall suitability of the operations flight design approach.

The engineering cycle supports the initialization of the engineering and test facilities as well as the initial shuttle mission simulator (SMS) training load. The flight cycle supports MCC and SMS initialization for final training and operations, Kennedy Space Center (KSC) Launch Processing System checkout and launch support, Goddard Space Flight Center network support, and range safety. The flight design cycles are under review to determine if a single cycle could be used to satisfy all user requirements. This latter objective requires significant standardization within the program, improved and timely provision of payload specific data and significant training standardization.

Flight Design Documentation. The flight design process is the last of the mission operations processes to be documented as a structured flow from the conceptual phase through the delivery of the launch-loads used for flight. The full documentation of these processes is now contained in 22 volumes of flight design handbooks. Documentation was undertaken to serve four distinct objectives: (1) document the corporate memory of this process before it is lost; (2) establish an error- and omission-free process, necessary because of the critical nature and use of the flight design products; (3) support the design of an integrated computing system as an aid to support the flight design process; and (4) assure consistent design and rationale between similar missions.

The two years after the STS-51L accident were used to safe the flight design system, document the process and initiate a multiyear plan for code conversion, consolidation, documentation and configuration control of all applications software. Process flow charts were developed for every activity involved in the flight design analysis and production activity.

The flight design handbooks developed during recent years have documented the flight design SE&I process and, to a great extent, represent the structure and relationships that must exist to incorporate integrated trajectory design into any space program. These documents are invaluable examples of the structure and approach needed for further space exploration activity. They also provide a good textbook for personnel involved in SE&I management to describe the relation between trajectory, systems, software and objective data. In addition, they define input/output requirements, integration nodes, audit points and interfaces to external elements for data acquisition and transfer.

An Illustration of the Flight Design Process. The integration of the constraints imposed by the flight system, environment, payload and operations in the determination of the launch window will be used to illustrate one aspect of the flight design process.

The launch window is the time period that the Shuttle should launch to achieve precise program requirements. This activity is described in the flight design handbook via three processes that satisfy Shuttle and payload requirements. These processes are further combined and iterated to develop the integrated launch window. This initial step of the process provides input data for subsequent planning involving deorbit opportunities, sequence of events, pointing, thermal assessments and so forth.

The constraints imposed in launch window determination represent the broad range of considerations faced by the flight designer in this task. Where practicable, priorities are established to assist the flight designer. The actual development of the launch window analyses is governed by a 27-page procedure within the flight design handbook.

Flight design is an essential element for space flight. The documentation of this process captured what was in the minds of the talented and imaginative individuals working in this field, and provided the definitive text for future flight design work for space exploration.

For the Space Station Freedom program, MOD has developed process flow charts for all functions that describe the input/output activities within mission operations and between mission operations and the Level II program elements, MSFC, KSC, GSFC and international partners. These flow charts described interfaces, product exchanges and work templates. They were used to define the roles and mission boundaries needed for sustained and effective relationships between participants. Documentation of the SE&I process is absolutely essential to clear and effective role and responsibility definition, and is a primary step in minimizing jurisdictional battles between SE&I elements.

Flight Directors SE&I

The mission operations SE&I process uses the Flight Director Office to provide the top level, multidisciplinary integration, risk/gain assessment and validation of the integrated mission preparation.

Flight directors are selected from the ranks of MOD personnel. Selection is based on leadership, technical abilities, stability and judgment as established by their performance during flight operations. They are already intimately familiar with the operating disciplines, interfaces, flight and ground systems capabilities, crew capabilities and the mission risk/gain process. The challenge for the flight directors is acquiring and maintaining the clear perspective needed for multidisciplinary technical, operational and political trades and leading the many diverse elements to operationally correct risk/gain decisions.

The lead flight director is central to the process for the assigned missions.

Pre-CDR Support. Support to a program from the Flight Director Office is initiated between the preliminary design reviews (PDRs) and CDRs. This phase is characterized by major tradeoffs between program requirements, flight system design, crew and ground and customer roles, schedule and cost. During this period the flight director, supported by all mission operations elements, refines the operating concepts and leads the operational trades involving autonomy, fault tolerance, crew and ground functions, and flight design and payload supportability. As flight system design becomes more focused during this period, the program costs and the real world design trades converge and program tradeoffs must be implemented. As a result, the mission operations integration process is initiated to provide the program and project managers with a clear understanding of available options. The options are generally provided by in the form of operations compatibility studies, similar to the SOCARs described previously, or in the form of an integrated mission design assessment.

CDR Support. The CDR support to the program from the mission operations team is significantly different because of the availability of the mission operations flight systems handbooks and the increased knowledge of the team. The operations team has acquired significant experience in working with the program and project as a member of the change control board (CCB) and through the CCB processes. The CDR represents a milestone for reassessing the design and is frequently the first time that the maturity of the software begins to approach the maturity of the hardware.

The principal contribution from mission operations during this time is in the detailed operational suitability assessments. These assessments concern the mission suitability of the flight system design and involve program requirements, hardware and software design, mission design, and crew and ground capabilities. Through these assessments the preliminary risk/gain trades and fault down options are established, operating philosophies are defined and mission options ascertained. Within mission operations, the CDR is not a discrete process. It is considered one of the many milestones of a process characterized by an increasing involvement by operations personnel in the change boards and control mechanisms established by the program. The involvement extends to the flight preparation period, which has two distinct processes and products representative of the flight director's role in the mission operations SE&I. These processes involve flight techniques and flight rules.

Flight Techniques. The initial flight techniques process was developed, and since Apollo, has been chartered by the Level II program. The process was established to address the growing complexity of the interaction between flight software, flight system and flight objectives. This process provided the technical focus for the operations, engineering and contractor teams to address the use of the as-built flight system, the software, and the crew and ground capabilities in accomplishing flight objectives. During Apollo, the ground system, flight procedures and flight software were the only elements that could be readily changed within cost and schedule considerations. The flight techniques process, assisted by Draper Laboratories and the operational vehicle and software developers, established virtually all of the navigation capabilities for Apollo. They developed the technique for the Apollo 12 pinpoint landing and were a principal contributor to the Apollo 13 return.

The product line of the techniques process is initially the series of detailed meeting minutes, which provide the basis for flight procedures and the rationale for the majority of the flight rules and mission design constraints. The flight techniques process provides the integration of the knowledge base available on the flight system to drive flight designs, procedures and flight rules.

Flight Rules. Flight rules are the fundamental risk/gain policy document for mission conduct. The "flight rules outline preplanned decisions to minimize the amount of real-time rationalization required when non-nominal situations occur from the start of the terminal countdown through crew egress."

The most complex, difficult and critical of the integration processes provided by the Flight Director Office is flight rules development. Flight rules used today trace their beginnings to aircraft flight tests. Rudimentary guidelines were provided for the flight test pilots relative to test conditions, and go-no-go criteria were provided for test continuation or termination. Similarly, during Mercury the rules for selected systems failures were also a simple set of go-no-go criteria involving powered flight abort and mission continuation or termination. Rules also addressed the control center, network and flight instrumentation requirements. Today's flight rules involve sophisticated risk/gain trades across redundant systems, multiple mission phases, engineering and payload objectives, and crew and controller capabilities. They also reflect and tradeoff the payload objectives, crew adaptation and flight system survivability in defining mission duration for off-normal conditions. Additionally, they clearly define the responsibilities of key personnel implementing flight operations.

While the rules are infinitely more complex, the principle of the rules remains the same; that is, "to establish the risk versus gain trades" before the mission, utilizing the full range of operational, program and engineering judgment available in the premission environment.

To assure complete visibility to all tradeoffs involved in the flight rules, rule rationale, techniques data and Systems Operations Data Book (SODB), references are contained in the published rules. The SODB and its variants were developed during

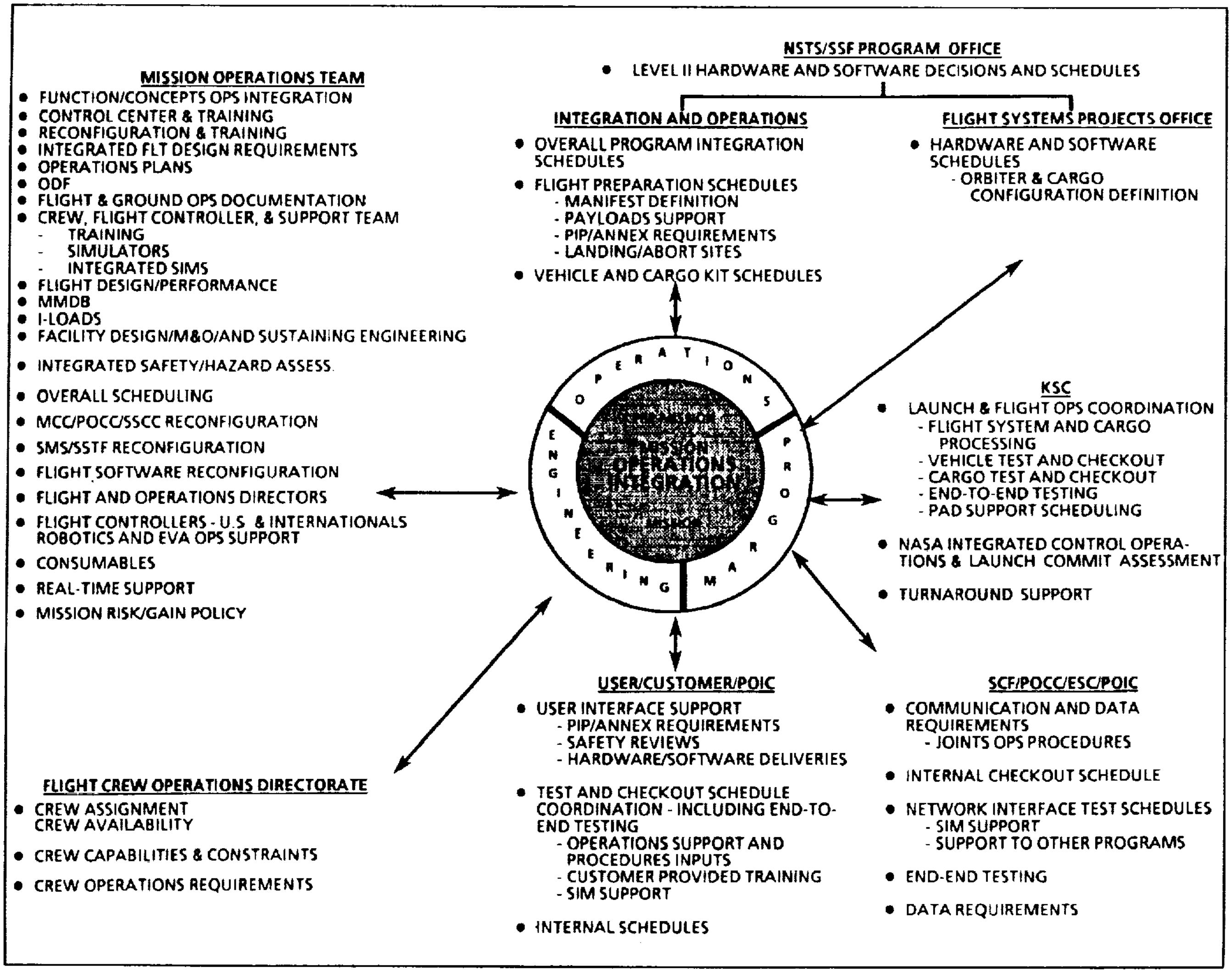

Figure 3 Mission Operations Integration

Gemini by mission operators with support by the prime contractor for the purpose of documenting the performance capabilities and limitations of the flight system. Since Apollo, the SODB has been maintained by the prime contractor, with mission operations as the primary user.

The leadership function provided by the flight director, using the flight techniques and flight rules process, provides the focus for the integration of flight-specific work within mission operations.

The rules and rationale section in the all-flights document is almost 900 pages. The flight-specific annex published for each mission is about 70 pages. It is provided to address the flight-unique objective and payload risk/gain trades for each specific mission, flight objective and payload element.

Flight directors, like program and project managers, depend on a matrix structure of organizations to accomplish their responsibilities. The flight directors are consistently successful because their roles are well defined, and because the integration techniques are facilitated by the MOD organization structure as well as by clearly defined product line and support processes. These characteristics must exist to successfully cope with the complex issues imposed by all mission elements.

Principal Requirements of an Effective SE&I Process

The mission operations elements, processes, and products are oriented to the singular objective of safe and successful manned flight operations. The spacecraft on the drawing board, like the ship in a harbor, is a safe ship, but that is not what spacecraft and ships are for. The mission operations job is to take the spacecraft from the harbor of the drawing board into space, accomplish a mission and then safely return the spacecraft to Earth.

In recognition of this responsibility, the mission operations processes are structured to assure effective policy, objective, system and operations integration. Within this framework, complex risk/gain trades are conducted and validated at all levels, culminating in a completely independent and dynamic assessment and stress test during the integrated training process.

The mission operations process can illustrate the principles necessary to a successful SE&I. It is believed that these principles are useful to other SE&I elements that have the responsibility for NASA flight programs at the project and program level.

1. *SE&I must have necessary roles and missions that are clearly defined by the program and implemented by the project and technical organizations.*

SE&I is necessary because the integration processes needed to address the technical, operational, political and economic aspects of major programs are complex.

The value-added principle is the basic test that should be used in determining role and mission assignments.

SE&I by its nature will be controversial and participating elements may stonewall the process. When this occurs, the program, project or technical manager must quickly and personally address the issue, establish a program position and demand the support required.

2. *SE&I must utilize the existing capabilities of organizations.*

SE&I is the "integration" of the technical, operational, economic and political aspects needed to support a major program. The broad range of work, skills required and complexity of issues virtually precludes the development of a single SE&I organization for a major program. SE&I responsibility must be distributed to be successful.

3. *SE&I elements must recognize and accept that major and complex programs will involve technical, operational, political and economic needs.*

Major programs must address and support the needs of the various constituencies involved in establishing the program and must consider all of the economic issues involved in program development and operations. This recognition is essential if NASA and its contractors are to develop a more flexible and responsive approach to program management.

4. *SE&I must have a process-based structure and a defined product line and life cycle.*

The complexity of SE&I requires a structured process to assure all interfaces are addressed, proper responsibilities assigned, and SE&I is effectively mechanized. SE&I requires a solid grasp of all the elements to be brought together, where the elements logically come from, where they fit in the sequence, what the end product is and what the alternatives are.

SE&I can be accomplished by a few gifted people for a limited time, but without structured processes, SE&I will become inefficient, outputs will not meet schedule commitments, "more integration resources will be needed, and the downward spiral will begin." SE&I is not provided by massive application of resources. It comes about by structured processes that clearly establish the roles and responsibilities of the supporting elements and use them effectively.

The SE&I process definition is also used to establish the product line of participating elements and define input/output requirements. This product line must be phased to the life cycle of the program.

5. *SE&I leadership must exist within all elements of the SE&I process structure and must be clearly recognized and accepted by the assigned individuals and their organizations.*

Accepting an SE&I leadership role is to recognize and accept conflict, particularly in the project and technical organizations. Organizations assigned an SE&I role must recognize and accept the technical, operational, political and economic implications of the SE&I role. SE&I must address the needs of the program, which must supersede the needs of individuals and organizations.

SE&I within NASA's flight programs is a constantly evolving and complex process involving many conflicting requirements that must be brought together to support program needs throughout the program's life cycle. An SE&I process that is effectively structured with distributed responsibilities will support program needs and recognize many of the prerogatives of the existing NASA elements. Each complex program, however, will have some elements that do not fit neatly into the existing NASA infrastructure because of economic, political or other considerations. SE&I will always be controversial, in structure and in implementation.