AEROSPACE SAFETY ADVISORY PANEL

AEROSPACE
SAFETY
ADVISORY
PANEL

Annual Report March 1992

NASA
National Aeronautics and
Space Administration

Aerospace Safety Advisory Panel

Annual Report

March 1992

Aerospace Safety Advisory Panel
Code Q-1
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Washington, DC 20546

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NASA

National Aeronautics and
Space Administration

Washington, D.C.
20546

Reply to Attn of: Q-1

March 1992

Honorable Richard H. Truly
Administrator
NASA Headquarters
Washington, D.C. 20546

Dear Admiral Truly:

The Aerospace Safety Advisory Panel (ASAP) is again pleased to submit its Annual Report. This report covers the period from February 1991 through January 1992 and provides you with findings, recommendations, and supporting material. We ask you to respond only to Section II, "Findings and Recommendations."

During the past year, we have been gratified by the continued prudent approach NASA has shown with respect to Space Shuttle operations. We also are encouraged by the improvements we have seen, particularly in the area of Shuttle processing. Although more work needs to be done in this area, you certainly appear to be on the right track. We also view the revised Space Station Freedom Program as a welcome improvement and a realistic course to follow.

In spite of these gains, however, we are distressed by the actions taken with respect to the Space Shuttle Main Engine (SSME). In particular, we disagree with the decision to cancel the development of the hydrogen alternate turbopump and large throat main combustion chamber. It is the Panel's consensus that improvements such as these are indispensable to the safe continuation of the Space Shuttle Program for the next 20 to 30 years and would contribute more to safety and reliability than any other identified propulsion improvement. In fact, we consider a comprehensive and continuing program of safety and reliability improvements in all areas of Space Shuttle hardware and software to be an essential component of maintaining successful operations. As a safety advisory panel, we cannot support the elimination of important safety and reliability improvements and urge you to reconsider the advanced turbopump and large throat main combustion chamber projects.

Very truly yours,

Norman R. Parmet

Norman R. Parmet
Chairman
Aerospace Safety Advisory Panel

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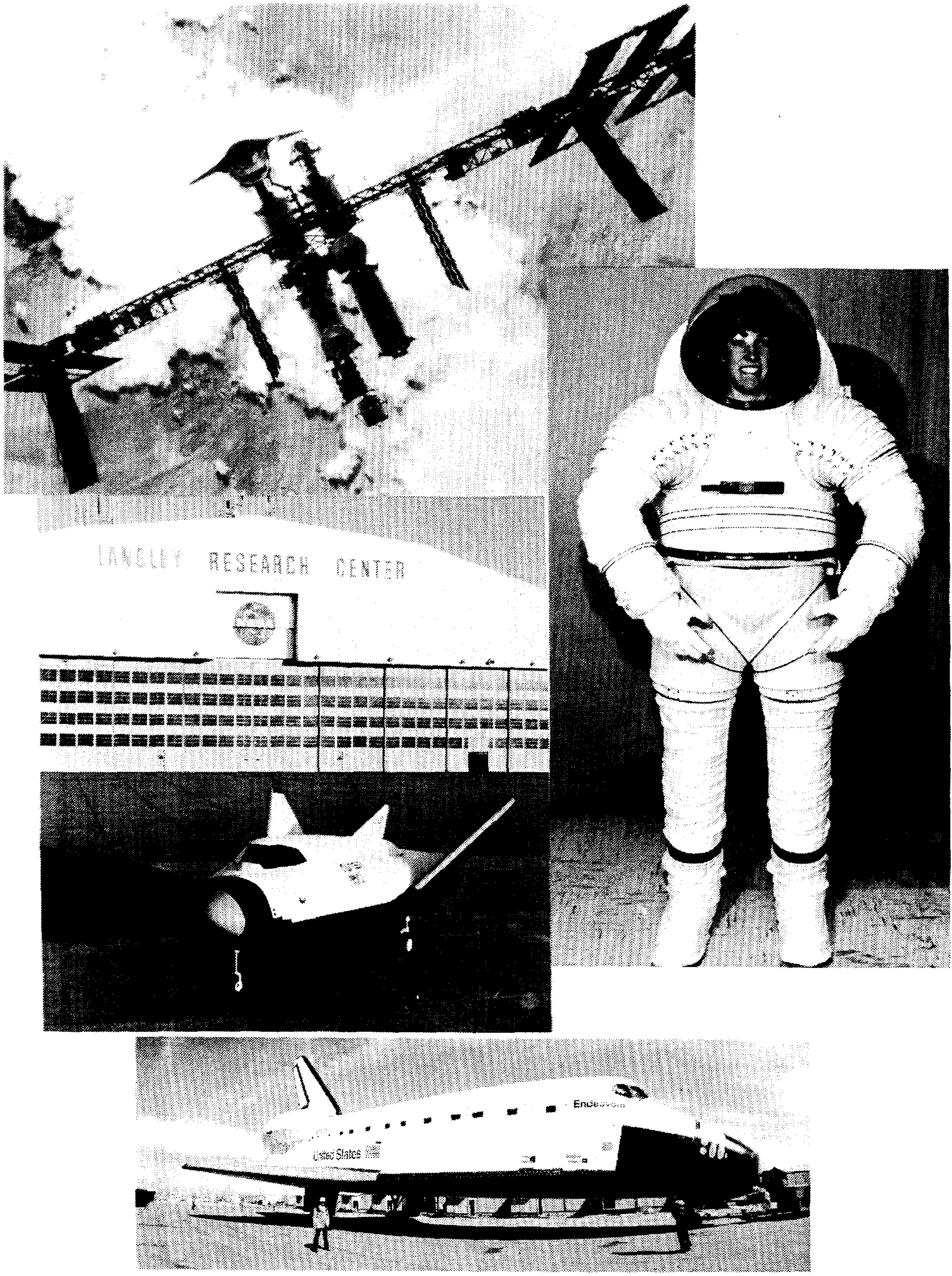


I. INTRODUCTION

I

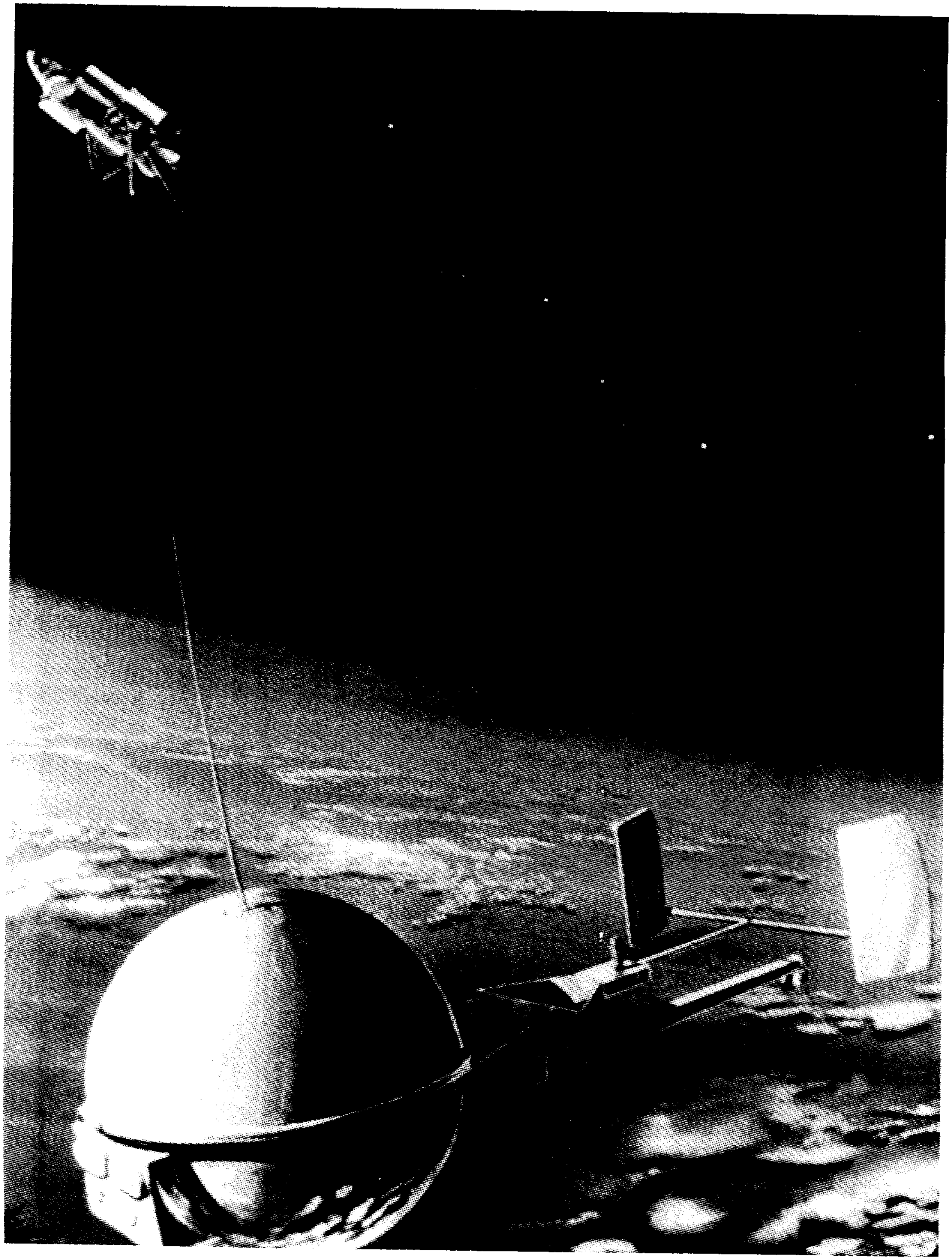
INTRODUCTION

In 1991, NASA continued successful Space Shuttle flights and restructured the Space Station Freedom Program (SSFP) with a downsized design. This design involved significantly lower technological and operational risks than the earlier versions. The Aerospace Safety Advisory Panel (ASAP) monitored these activities as well as NASA's aeronautical programs at NASA installations and contractor facilities. Specific topics that were examined in-depth by the Panel included Space Station organization, Space Shuttle structures, Space Shuttle processing, design and manufacturing plans for the Advanced Solid Rocket Motor (ASRM), Space Shuttle landing performance and the need for an operational autoland capability, Space Shuttle logistics, loads and overhaul plans, and aeronautical flight research programs.

The results of the Panel's activities are presented, as in previous years, in a set of findings and recommendations, which are in Section II of this report. Section III is composed of "Information in Support of Findings and Recommendations." Appendices in Section IV provide a listing of Panel members, the NASA response to the findings and recommendations contained in last year's report, and a chronology of the Panel's activities during the reporting period.

This report highlights both improvements in NASA's safety and reliability activities and specific areas where additional gains might be realized. One area of particular concern involves the curtailment or elimination of Space Shuttle safety and reliability enhancements; it is addressed by several findings and recommendations. The Panel considers this essential to the continued successful operation of the Space Shuttle. Therefore, it is recommended herein that a comprehensive and continuing program of safety and reliability improvements in all areas of Space Shuttle hardware/software be considered an inherent component of ongoing Space Shuttle operations.

During 1991, Joseph F. Sutter retired from the Panel after serving as its Chairman and, most recently, as a consultant to it. Paul M. Johnstone and John A. Gorham joined the Panel as consultants.



II. FINDINGS AND RECOMMENDATIONS

II

FINDINGS AND RECOMMENDATIONS

A. SPACE STATION FREEDOM PROGRAM

Finding #1: During the past 1½ years, Space Station Freedom (SSF) has undergone a reconfiguration involving many technical changes and program deferrals. These changes were highlighted in the Aerospace Safety Advisory Panel's (ASAP's) March 1991 report. Some of the changes affect risk and safety while others influence serviceability and usefulness. Nevertheless, the SSF design that has emerged is more realistic and capable of supporting a stable development program.

Recommendation #1: Safety and risk considerations should remain of paramount importance in the development of the reconfigured Space Station.

Finding #2: The ASAP March 1991 Annual Report characterized the Space Station Freedom Program (SSFP) as plagued with technical and managerial difficulties and lacking an effective systems engineering and integration organization. Significant developments have occurred in the ensuing year. In particular, there has been a clarification of system engineering and systems integration responsibilities among NASA Headquarters and the Centers. Also, key managerial assignments have been delegated to appropriate Centers. The new arrangement benefits the program by drawing on the substantial technical expertise of the Centers' staff members not specifically assigned to the SSFP.

Recommendation #2: The changes introduced in the systems engineering and integration management areas should be monitored to ensure that the new arrangement is effective and that maximum use is made of each Center's particular capabilities.

Finding #3: NASA's current policy is not to leave a crew on the Space Station without an attached Space Shuttle or other assured return capability. At present, there is no program to develop a dedicated assured return vehicle. However, using an Orbiter as an assured return vehicle on long-duration missions reduces the number of Space Shuttles available for other purposes and raises potential safety and reliability issues.

Recommendation #3: NASA should continue studies to explore various options for assuring a safe return capability from SSF leading to the selection of a preferred option in a timely manner.

Finding #4: Use of preintegrated truss (PIT) sections for SSF greatly simplifies on-orbit assembly. However, the capture latch, guide pins, and motorized bolts used to couple the assemblies may not always be in proper alignment. This could lead to damaging the guide pins or bolts thereby precluding mating.

Recommendation #4: The PIT development program should consider actual hardware tests to verify the assembly process to be used in orbit. These tests should encompass the full range of misalignments, tolerances, and impacts that might reasonably be expected to occur when the truss is assembled with the actual equipment and procedures to be used.

Finding #5: Software for the Data Management System (DMS) represents one of the major challenges to meeting the intensive delta design review (DDR) schedule.

Recommendation #5: The DMS software development process should be monitored closely to ensure it is compatible with the existing DDR schedules.

B. SPACE SHUTTLE PROGRAM

ORBITER

Finding #6: The results of flight tests indicate that the turbulent flow over the body flap creates a spectrum of hinge moments greater than that used in the original structural fatigue analysis. It also has been determined that an additional load path exists from the flap to the supporting structure. Further, the flap actuators were found to be more flexible than originally assumed. Additional tests are to be conducted to evaluate hinge moments and actuator flexibility.

Recommendation #6: NASA should evaluate, as rapidly as possible, the results of the new tests and loads analyses to reestablish the allowable number of flights for the body flap.

Finding #7: NASA has developed a Shuttle Modal Inspection System (SMIS) for detecting changes in stiffness in structural/mechanical systems due to factors such as wear or cracking. The SMIS has shown good results when used on the Orbiter body flap and elevon systems (including actuators and supporting structures). However, it is not a complete replacement for more conventional nondestructive inspection (NDI) methods. These conventional methods are capable of detecting cracks in primary structures with a "critical crack length" too small to cause a detectable change in stiffness and hence be measurable by SMIS.

Recommendation #7: The SMIS procedure should be used only to augment more conventional NDI methods.

Finding #8: Thermal protection system tiles are inspected for damage after every flight by specially trained and highly experienced inspectors using tactile techniques. These inspectors determine if the tiles are loose and help to identify problems in step and gap. The current procedure is largely qualitative and highly dependent on the skill of the individual inspectors.

Recommendation #8: A program to select and train new inspectors should be instituted to ensure the availability of an adequate cadre of qualified inspectors throughout the life of the Orbiters. In addition, further effort should be applied to the development of a quantitative inspection technique.

Finding #9: The Space Shuttle Program requires both turnaround and periodic major Orbiter overhaul functions.

Recommendation #9: Overhaul and major modification efforts should be organizationally and functionally separated from routine turnaround operations because of the different types of planning and management skills and experience required.

Finding #10: The Space Shuttle design presently includes an automatic approach guidance system that requires crew participation and does not control all landing functions through touchdown and rollout to wheel stop. The present system never has been flight tested to touchdown, but a detailed test objective for such a test is in preparation. The availability of a certified automatic landing system would provide risk reduction benefits in situations such as weather problems after de-orbit and Orbiter windshield damage.

Recommendation #10: Future mission plans suggest the potential for significant risk reduction if the present Space Shuttle automatic landing capabilities are fully developed and certified for operational use. System development should include consideration of hardware, software, and human factors issues.

Finding #11: NASA continued its software independent verification and validation (IV&V) activities during the year. This independent review has demonstrated its value by finding failure modes that previously were unknown. The Safety and Mission Quality organization has taken on greater responsibilities for software safety.

Recommendation #11: NASA should continue to support a software IV&V oversight activity. The present process should be reviewed to ascertain whether it can be streamlined. The IV&V oversight activity should include the development of detailed procedures for test generation. NASA should not attempt to duplicate, through IV&V or otherwise, the actual performance of all verification and validation tests.

Finding #12: The new Space Shuttle general purpose computer (GPC) apparently has performed well. The Single Event Upsets (SEUs) were no more numerous than expected. Based upon NASA's model of SEUs, the accuracy of the predictions is excellent, and supports NASA's estimate that the probability of an SEU-induced failure is negligibly small. Nevertheless, there still is concern about the eventual saturation of usable memory on the GPC.

Recommendation #12: NASA should initiate a small study on alternatives for future GPC upgrades and/or replacements. This should involve other NASA organizations that have been studying computer evolution.

Finding #13: The replacement of some requested software upgrades with crew procedures is a matter of serious concern particularly when the functions addressed could be handled with greater reliability and safety by software. The crew already has to cope with a very large number of procedures.

Recommendation #13: NASA should conduct a thorough review of all crew procedures that might be performed by the computer system to determine whether they are better done manually by the crew or by the software. Human factors specialists and astronauts should participate.

SPACE SHUTTLE MAIN ENGINES (SSME)

Finding #14: There are currently a sufficient number of flightworthy engines to provide each Orbiter with a flight set as well as provide an adequate number of spares.

Recommendation #14: Maintain this position.

Finding #15: The SSME component reliability and safety improvement program, designed to enhance or sustain the current component operating margins, has made progress towards achieving its objectives. The high-pressure fuel turbopump (HPFTP) has completed its certification. Changes to the two-duct powerhead have eliminated injector erosion, but more work is needed to reduce main combustion chamber (MCC) wall damage. The process for producing the single-tube heat exchanger has been developed, and heat exchangers are being installed for testing. The high-pressure oxygen turbopump (HPOTP) changes were less successful in meeting service-life objectives, but an operational workaround to reduce turnaround time for the HPOTP has been implemented.

Recommendation #15: Continue the development of these reliability and safety improvements. Complete their certification as expeditiously as possible.

Finding #16: The development of the large throat main combustion chamber (LTMCC) and Advanced Fabrication Processes for the SSME have been discontinued. Both of these efforts eventually would have led to significantly enhanced safety and reliability of the SSME.

Recommendation #16: Restore these important safety-related programs.

Finding #17: The Alternate Turbopump Program has made major progress toward achieving its objectives despite design problems uncovered during design verification systems (DVS) and component development tests. Engine-level tests have begun for both turbopumps. The value of heavily instrumented test items run on the E-8 component test stand has been demonstrated clearly, as evidenced by the rapid identification of problem sources and the development of design changes to overcome them. NASA has opted to delete the work on the alternate HPFTP and to continue only the development on the alternate HPOTP with the intent to use it, when certified, in conjunction with the current HPFTP. While such a configuration is feasible, such usage will not achieve the increase of operating margins in the engine system to the levels desired and advocated by program and propulsion specialists.

Recommendation #17: Restore the alternate HPFTP development.

SOLID ROCKET MOTORS

Finding #18: NASA previously has investigated the possibility of developing a new, low-temperature elastomeric O-ring material to eliminate the need for the field joint heater assembly on the Redesigned Solid Rocket Motor (RSRM). None was found that was compatible with the grease used during assembly. The material (GCT Viton) being developed for the Advanced Solid Rocket Motor (ASRM) O-rings has proper elasticity down to 33°F.

Recommendation #18: NASA should evaluate the ASRM O-ring material (GCT Viton) for use on the RSRM to eliminate the field joint heaters and their installation.

Finding #19: The full-scale ASRM propellant manufacturing facility may not be directly scaleable from the continuous mix pilot plant. Particular problem areas relate to the particle size of the propellant and the screw pump section of the rotofeed.

Recommendation #19: Scale-up of the ASRM propellant manufacturing plant should be scrutinized closely by NASA to ensure that safety and schedule are not compromised.

Finding #20: An ambitious automated process is planned for the ASRM propellant mixing and casting. This process will be largely computer-operated with human operators serving primarily as initiators and monitors. This will place significant demands on the design of the operator interface of the system to ensure an effective and safe allocation of tasks and responsibilities between humans and computers.

Recommendation #20: The ASRM program should develop task and functional analyses of the human operator's role in the solid rocket manufacturing process and the operator interface with the computer system with emphasis on safety aspects.

Finding #21: Development of the ASRM case and its manufacturing processes includes a number of new methods and materials. For example, a new steel case material with associated plasma-arc welding and repair techniques and automated internal stripwinding of the insulation are part of the design.

Recommendation #21: Due to the extensive use of new materials and processes in ASRM case manufacturing, NASA should monitor the associated development test program carefully to ensure that safety is not compromised.

Finding #22: NASA has decided not to improve the current aft skirt design to meet the original design specification of a factor of safety of 1.4. NASA now believes that a 1.28 factor of safety is adequate because the loads are well-defined.

Recommendation #22: Due to the lower factor of safety on the current RSRM skirts and the planned use of the same skirt on future ASRMs, NASA should task its safety organization to monitor the loads/strains measured during launches to establish a truly credible data base for the statistical justification of the lower factor of safety.

Finding #23: Logistics development for the ASRM is being pursued. All related major contractors and NASA groups are actively participating. Planning documents for support equipment, training, and transporting the motor elements are being prepared.

Recommendation #23: Continue the early and thorough consideration of ASRM logistics issues.

LAUNCH AND LANDING

Finding #24: Several landing anomalies were experienced during the past year, including an extremely short landing on STS-37. Careful examination of the causes of these anomalies led to significant operational improvements.

Recommendation #24: A continuing analysis of landing performance should be undertaken to include hardware, software, personnel functions, and information transfer. Continued improvement in all areas related to landing safety, including use of wind data and automatic guidance, should be sought as part of the movement to shift more landings to the Kennedy Space Center (KSC).

Finding #25: In spite of significant advances over the past year, there is still a need to improve the effectiveness of launch processing at KSC. It is rare when a vehicle is taken to the pad and launched without delays. Subsystem problems sometimes either require rolling the vehicle back to the Vehicle Assembly Building (VAB) or they cause delays at the pad.

Recommendation #25: Continue efforts to improve the effectiveness of launch processing operations. Each occurrence of a problem at the pad should be reviewed to determine why it was not caught in the VAB or Orbiter Processing Facility.

Finding #26: Morale among launch processing personnel at KSC improved over the past year. This most likely is the result of a heightened sense of individual responsibility, improved systems training, and a better supervisory/management approach.

Recommendation #26: Continue and expand the approaches that have been successful over the past year.

Finding #27: Operations and maintenance instructions (OMIs) have shown improvement. However, recent over-pressurization of a solid rocket booster (SRB) hydraulic tank has been attributed to an improperly written OMI. It also has been noted that an apparent excess of signatures still is needed in the paperwork generation and revision process.

Recommendation #27: Effort should be continued to improve the quality of OMIs. This should include the generation, review, and revision of the instructions. Efforts also should be made to reduce unnecessary signature requirements and consolidate paperwork systems.

Finding #28: The use of task teams at KSC appears to be working well.

Recommendation #28: The task team approach should be expanded as planned. In addition, coordination among task teams should be improved.

Finding #29: Procedures for tracking, analyzing, and providing corrective action for hardware problems arising at KSC are complex and lengthy involving numerous entities. There is no overall coordination effort to ensure that appropriate corrective action is taken.

Recommendation #29: The Space Shuttle Program should establish a coordinating function that is responsible for ensuring that proper and timely action is taken by responsible organizations in correcting problems that occur during launch preparation.

Finding #30: The Shuttle Processing Data Management System II (SPDMS II) has not yet provided many of its anticipated benefits. This may be because prospective users have not been fully involved in its design. Various temporary subsystems have emerged and are being used. However, these may be difficult to integrate into the final design.

Recommendation #30: Designers of the SPDMS II system should directly involve users in the system's design and implementation. In particular, care should be exercised to ensure that the various subsystems now being used successfully are included in the final design.

LOGISTICS AND SUPPORT

Finding #31: The Orbiter logistics and support program appears to be exhibiting a steady trend of improvement. The component overhaul and repair facility has been enhanced, and personnel skills have been upgraded. This has improved the control of such issues as cannibalization, serviceable component spares levels, and replenishment of spares stocks. However, support of Orbiter OV-105 (Endeavour) has caused extra effort in the latter months of the year and undoubtedly will continue to do so in 1992.

Recommendation #31: This excellent program should be continued with particular attention on the possible impacts of servicing OV-105.

Finding #32: Coordination among NASA Centers and contractors on logistics and support is excellent. This is due in large part to the activities of the Integrated Logistics Panel (ILP), which meets at various locations at approximately 4-month intervals.

Recommendation #32: NASA should continue to support the excellent work being performed by the ILP.

Finding #33: Transfer of critical management skills and authority to the NASA Shuttle Logistics Depot (NSLD) and to KSC under the Logistics Management Responsibility Transfer (LMRT) Program is continuing. However, in some instances, funding limitations are slowing the process. Memoranda of Agreement (MOA) documents that establish details of transfer arrangements between such Centers as the Johnson Space Center (JSC), Marshall Space Flight Center (MSFC), and KSC are being revised or finalized.

Recommendation #33: It is important that the centralization of authority and equipment at KSC continues as planned under the LMRT concept.

Finding #34: NSLD is consolidating its activities at Cocoa Beach and is having a positive effect upon the critical issue of repair turn-around time (RTAT) for line replaceable units (LRUs). It provides protection against threats of unavailability of repaired or overhauled units in many cases in which the original manufacturers are no longer providing support. RTAT data support the importance of the proximity of the NSLD facilities to KSC.

Recommendation #34: The NSLD is essential to the efficient support of the Space Shuttle fleet and should continue to be supported at its current level.

Finding #35: Cannibalization (or the removal of working components from an Orbiter to meet shortages in another vehicle) has been the subject of much management attention. With a few persistent exceptions such as auxiliary power units (APUs), cannibalization rates now have been reduced to a commendably low level.

Recommendation #35: Maintain rigid controls on cannibalization. This will be particularly important to accommodate the absorption of OV-105 into the operating fleet next year.

Finding #36: The reduction of component RTAT has been subjected to as much management scrutiny as cannibalization and has, perhaps, an even greater economic and support effect upon Orbiter capability.

Recommendation #36: There can be no relaxation of the vigilance entailed in the pursuit of this cost-sensitive problem. Therefore, continue to keep the tightest control over the RTAT problem.

Finding #37: The problem of stock inventory held at or below minimum established levels is becoming critical. This is largely due to introduction of OV-105 and to major modification programs to other Orbiters.

Recommendation #37: Establish stocking recovery programs as soon as possible.

Finding #38: The problem of providing replacements or substitutes for parts or components that are now out of production will inevitably worsen with each passing year. In many cases, original equipment manufacturers (OEMs) are unwilling or unable to regenerate small batch production.

Recommendation #38: It is essential to try to anticipate potential shortages before they impact the program. Although this problem currently is being addressed by NASA, increased management pressure is needed to avoid a potential launch rate problem in the future.

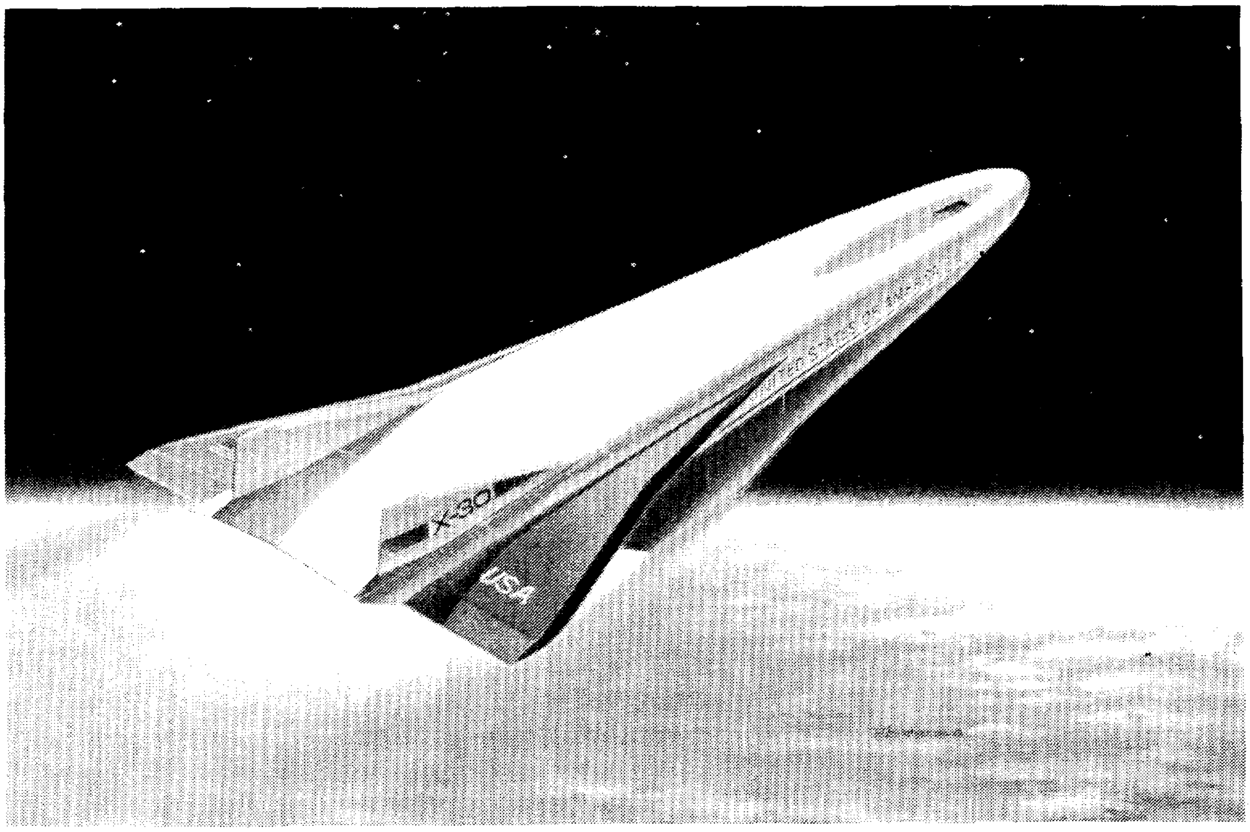
C. AERONAUTICS

Finding #39: The Panel was pleased to note the promulgation on August 12, 1991, of NASA Management Instruction (NMI) 7900.2 on aircraft operations management. This NMI and a companion delineation of aviation safety requirements in the basic safety manual are needed steps in the establishment of a total safety management organization and Agency-wide philosophy of aviation safety for administrative aviation.

Recommendation #39: Incorporate aviation safety requirements in the basic safety manual as soon as possible to ensure that NASA personnel have a common reference for administrative aviation safety requirements. Completion of a Headquarters organization to coordinate flight policies throughout NASA is needed.

Finding #40: Management of NASA's aeronautical flight research continues to place strong emphasis on flight safety. Procedures for review and approval of the flight programs [from project conception through Flight Readiness Reviews (FRRs)] are adequate to ensure full awareness of the major safety issues involved in each project.

Recommendation #40: NASA's aeronautical flight research should continue to be given strong support at appropriate levels to maintain a safe program for preserving the nation's dominance in the aeronautical sciences.



D. OTHER

__Finding #41:__ Crew members working on the Space Shuttle for extended periods have experienced difficulties achieving sufficient sleep. This problem is magnified when two shift operations are conducted. These problems are similar to those experienced by aircraft flight crews in long-haul operations.

__Recommendation #41:__ NASA should support a program of research and countermeasure development on crew rest cycles and circadian rhythm shifting to support both Space Shuttle and Space Station operations. This program could be modeled productively after the ongoing NASA aircrew research.

__Finding #42:__ Despite acknowledged examples of contributions to aviation safety analyses through human factors research, NASA has not marshalled its resources in this field to study similar problems in spaceflight orbital and ground operations. Efforts in this arena have been stymied by a lack of appreciation of its potential value and the absence of clear guidelines regarding programmatic responsibilities.

__Recommendation #42:__ In view of the anticipated increase in manned spaceflight activity during the present decade involving joint Space Shuttle and Space Station activities, NASA's human factors resources should be marshalled and coordinated effectively to address the problems of risk assessment and accident avoidance.

__Finding #43:__ NASA has a hierarchy of reporting systems for mishaps and incidents that defines investigation procedures/responsibilities and provides for developing lessons learned. These reporting systems function quite well for relatively serious accidents, incidents, mishaps, and near-misses. NASA does not have a system analogous to the Federal Aviation Agency's (FAA's) Aviation Safety Reporting System (ASRS) for collecting self-reports of human errors that do not lead to an otherwise reportable event.

__Recommendation #43:__ NASA should examine ways to encourage self-reports of human errors and to analyze and learn from data and trends in these reports. Inclusion of coverage of the need for human-error reporting in task team training with an associated method for analyzing the reports could prove to be an excellent method for collecting this information.

__Finding #44:__ The Tethered Satellite System (TSS) program was plagued by two quality control problems during the year. One problem was a failure of the bonding between the rotor of the vernier motor and the cork clutch material. The other problem was associated with an error in identifying heat treating requirements for 15-5 stainless steel. Installed components using this steel that was not heat treated should require a waiver before clearance to fly is granted. Failure of 15-5 steel pins in the concentric damper negator motor or tower tabs could potentially impact safety.

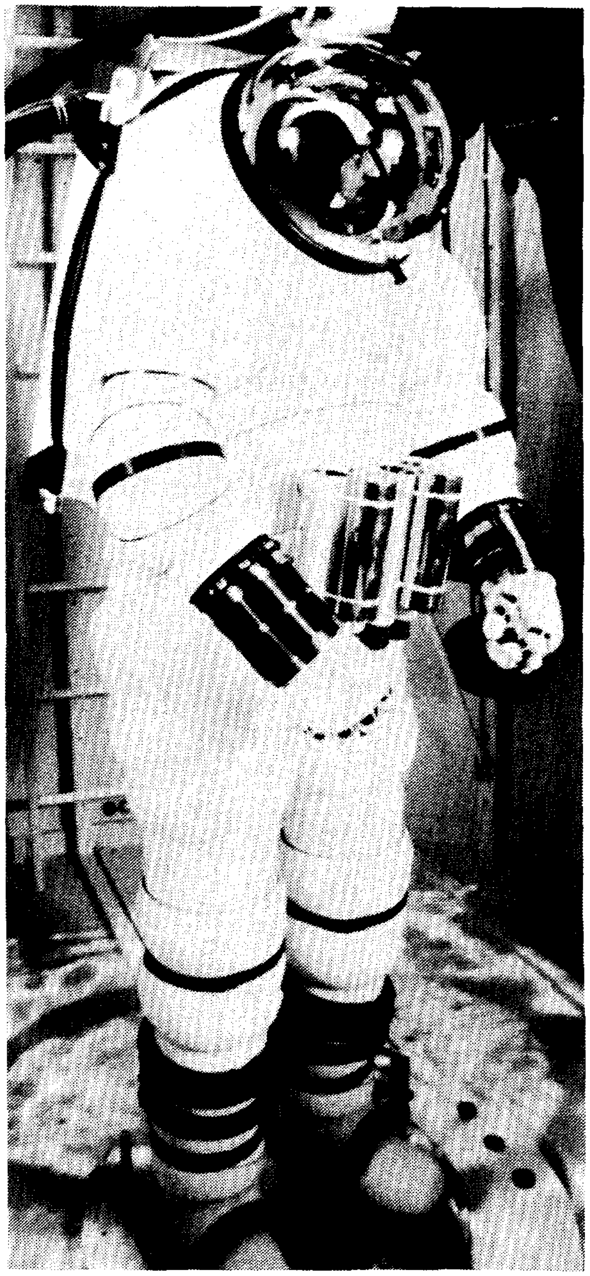
__Recommendation #44:__ A complete review of the TSS quality assurance program should be conducted before flight in addition to the already initiated examination of the suitability of the suspect parts.

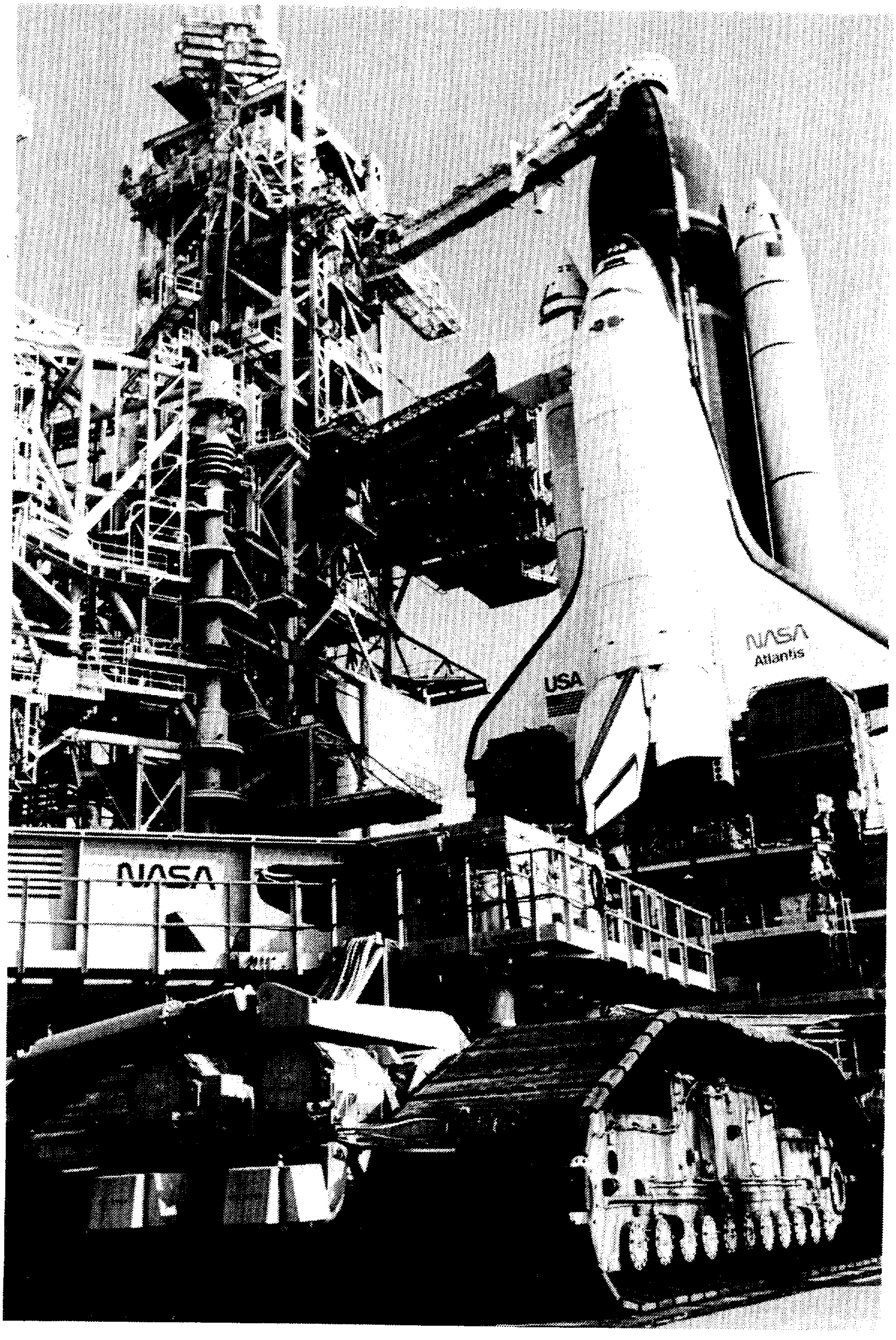
__Finding #45:__ Existing plans for Space Shuttle missions such as the Hubble Space Telescope (HST) repair, and the assembly and maintenance of the downsized SSF, highlight potential benefits from the use of an improved spacesuit and extravehicular mobility unit (EMU) to replace the existing suit and portable life support system (PLSS). Limitations inherent in the design of the present system could pose operational for safety problems on these and future missions. The AX-5 and Mark 3 research and development programs have provided an excellent basis for implementing a new, improved design for extravehicular activity (EVA) equipment. Compatibility of the new suit designs with the existing PLSS potentially provides a cost-effective upgrade path.

__Recommendation #45:__ NASA should reconsider the specification and development of a new suit and EMU based on the information developed in the AX-5 and Mark 3 programs. NASA should acknowledge the need for a new suit and EMU as soon as possible and establish its development and implementation schedule consistent with budget availability. Use of a new suit with the existing PLSS specifically should be examined as an interim safety improvement step.

__Finding #46:__ Determinants of the risk of bends during EVA activities have not been fully researched. Existing prebreathing protocols are based on ground-based pressure chamber tests and scuba diving tables. A significant safety uncertainty could be removed if the specific effects of micro-gravity EVA conditions on nitrogen bubble formation were determined and documented.

__Recommendation #46:__ NASA should support the research necessary to characterize more fully the bends risk associated with micro-gravity EVA activities using its extensive expertise at the research centers and the data collection opportunities available during on-ground simulations and Space Shuttle flights.





III. INFORMATION IN SUPPORT OF FINDINGS AND RECOMMENDATIONS

III

INFORMATION IN SUPPORT OF FINDINGS AND RECOMMENDATIONS

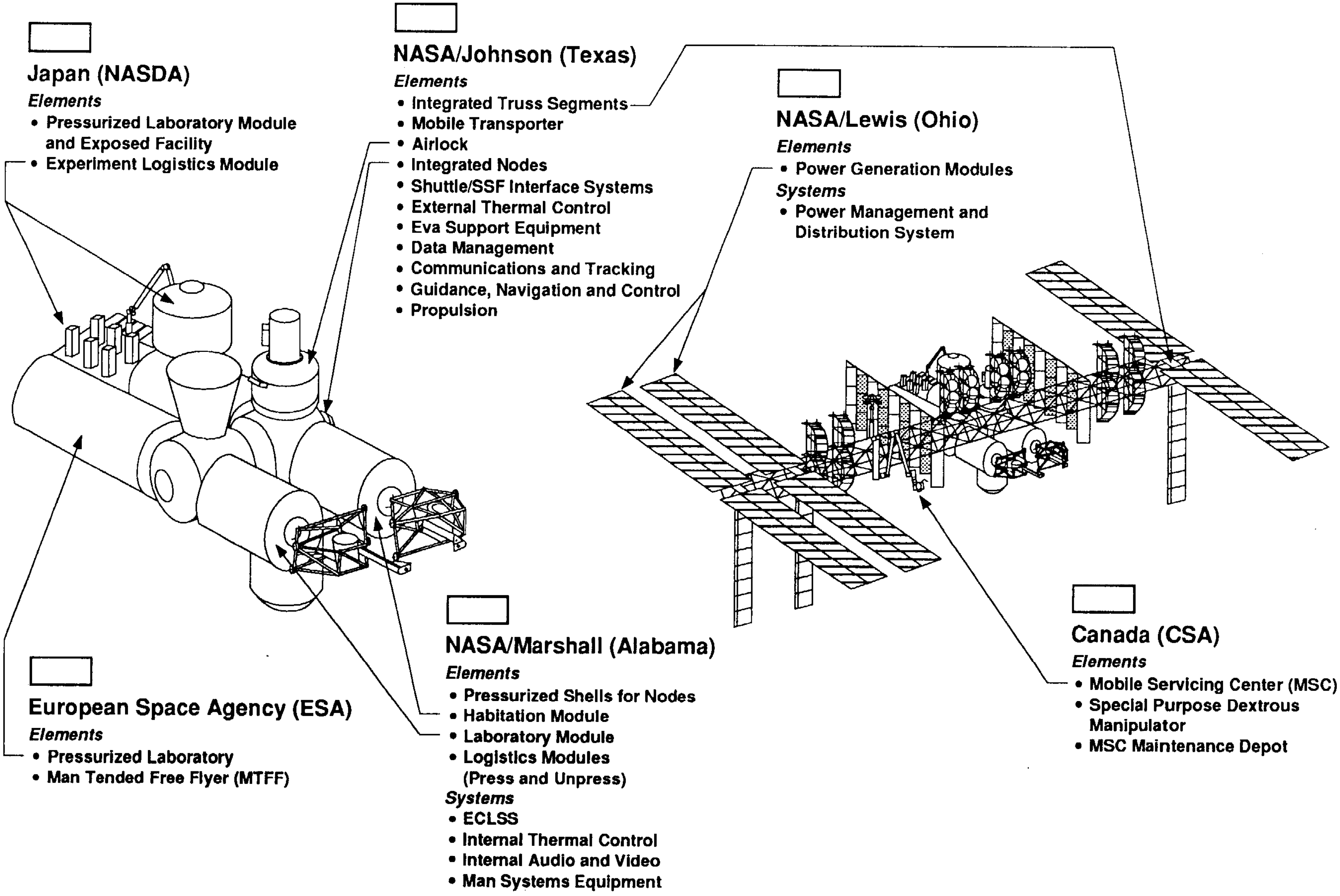
A. SPACE STATION FREEDOM PROGRAM

Ref: Findings #1 through #3

Space Station Freedom (SSF) has undergone a major restructuring. Difficult issues in program content and operations have been realistically confronted. Nevertheless, SSF remains a very complex program involving three NASA development Centers, three international partners, a significant ground integration, and launch responsibility for the Kennedy Space Center (KSC) and numerous development and support contractors. Figure 1 depicts the overall program plan and organizational responsibilities. An outline of the administration of program policy and direction is shown in Figure 2.

Geographically dispersed locations and fragmented levels of responsibility have contributed to management complexity, especially in the systems engineering and integration area. Management has attempted to mitigate this situation by combining the systems engineering and systems integration responsibilities into a single office at Reston, Virginia (Level II) and delegating specific implementation authority to the field centers as outlined in Figure 3. The field managers, in administering their responsibilities as Level II staff, have at their disposal the technical and administrative resources of their Centers as well as staff members specifically assigned to that office. At the same time, they are close to the Level III activity at the Centers where the development responsibility resides. The activity at the Marshall Space Flight Center (MSFC) shown in Figure 4 is an illustration of this arrangement.

The Elements Integration Office Manager at MSFC (Level II) reports programmatically to the Manager, System Engineering and Integration Office (Level II) located in Reston, Virginia, and attends Level II meetings and briefings with managers from other Centers. The manager's relationship with the Space Station Projects Office (SSPO) at MSFC (Level III) remains a typical Level II/III interface. The advantage of the arrangement is in the personnel allocations. The Elements Integration Office Manager has a staff of 13 people supported by Grumman, the Space Station Engineering and Integration Contractor (SSEIC), which has approximately 80 staff members assigned to the MSFC Element Integration Office. In addition, as a consequence of being located at MSFC, the manager also can enlist a full range of specialists from the Science and Engineering Directorate as needed. Similar arrangements exist at other Centers.



Japan (NASDA)

Elements

- Pressurized Laboratory Module and Exposed Facility
- Experiment Logistics Module

NASA/Johnson (Texas)

Elements

- Integrated Truss Segments
- Mobile Transporter
- Airlock
- Integrated Nodes
- Shuttle/SSF Interface Systems
- External Thermal Control
- Eva Support Equipment
- Data Management
- Communications and Tracking
- Guidance, Navigation and Control
- Propulsion

NASA/Lewis (Ohio)

Elements

- Power Generation Modules

Systems

- Power Management and Distribution System

European Space Agency (ESA)

Elements

- Pressurized Laboratory
- Man Tended Free Flyer (MTFF)

NASA/Marshall (Alabama)

Elements

- Pressurized Shells for Nodes
- Habitation Module
- Laboratory Module
- Logistics Modules (Press and Unpress)

Systems

- ECLSS
- Internal Thermal Control
- Internal Audio and Video
- Man Systems Equipment

Canada (CSA)

Elements

- Mobile Servicing Center (MSC)
- Special Purpose Dextrous Manipulator
- MSC Maintenance Depot

Figure 1. Space Station Freedom Program Plan

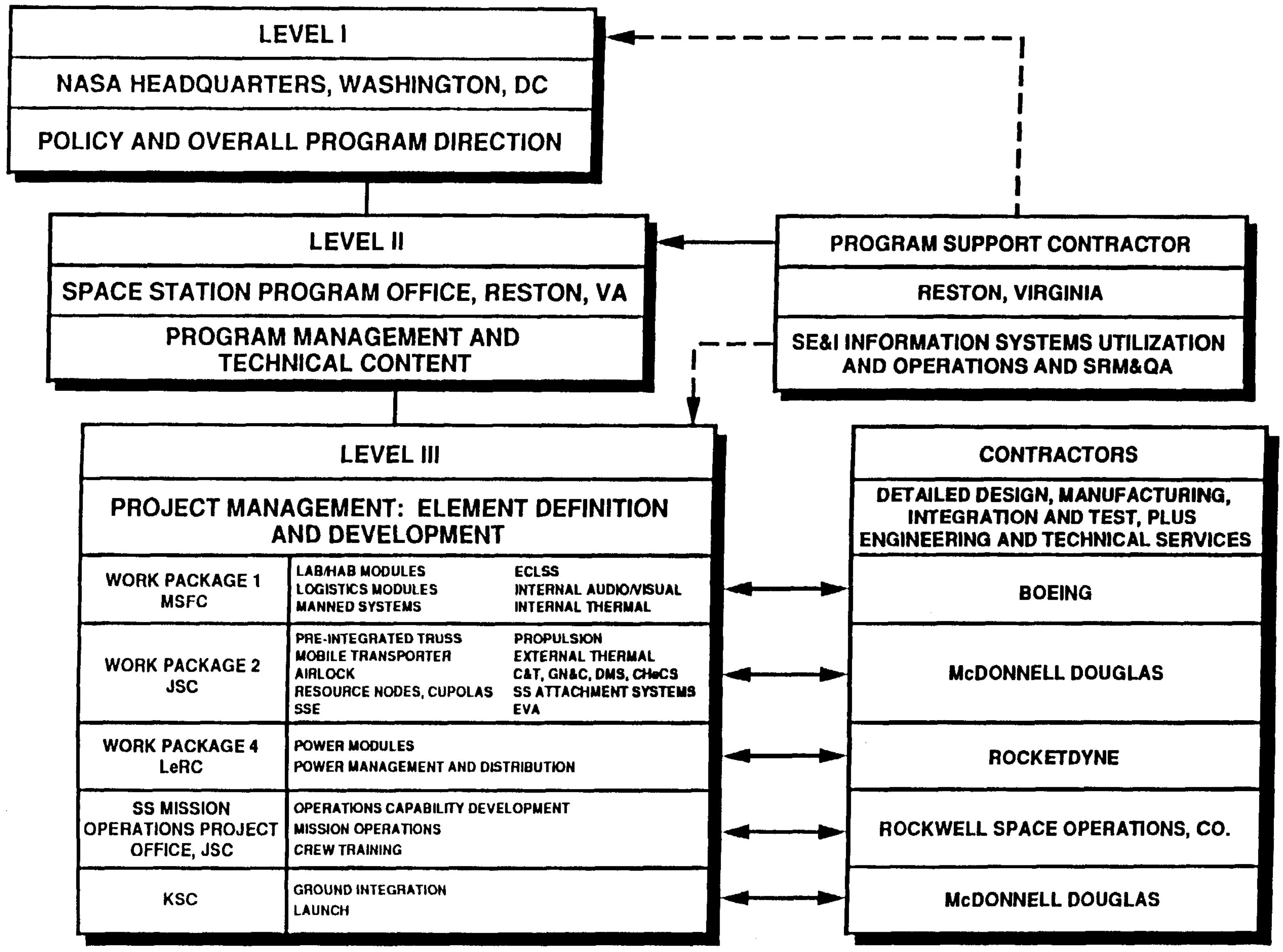


Figure 2. Space Station Freedom Program Organization

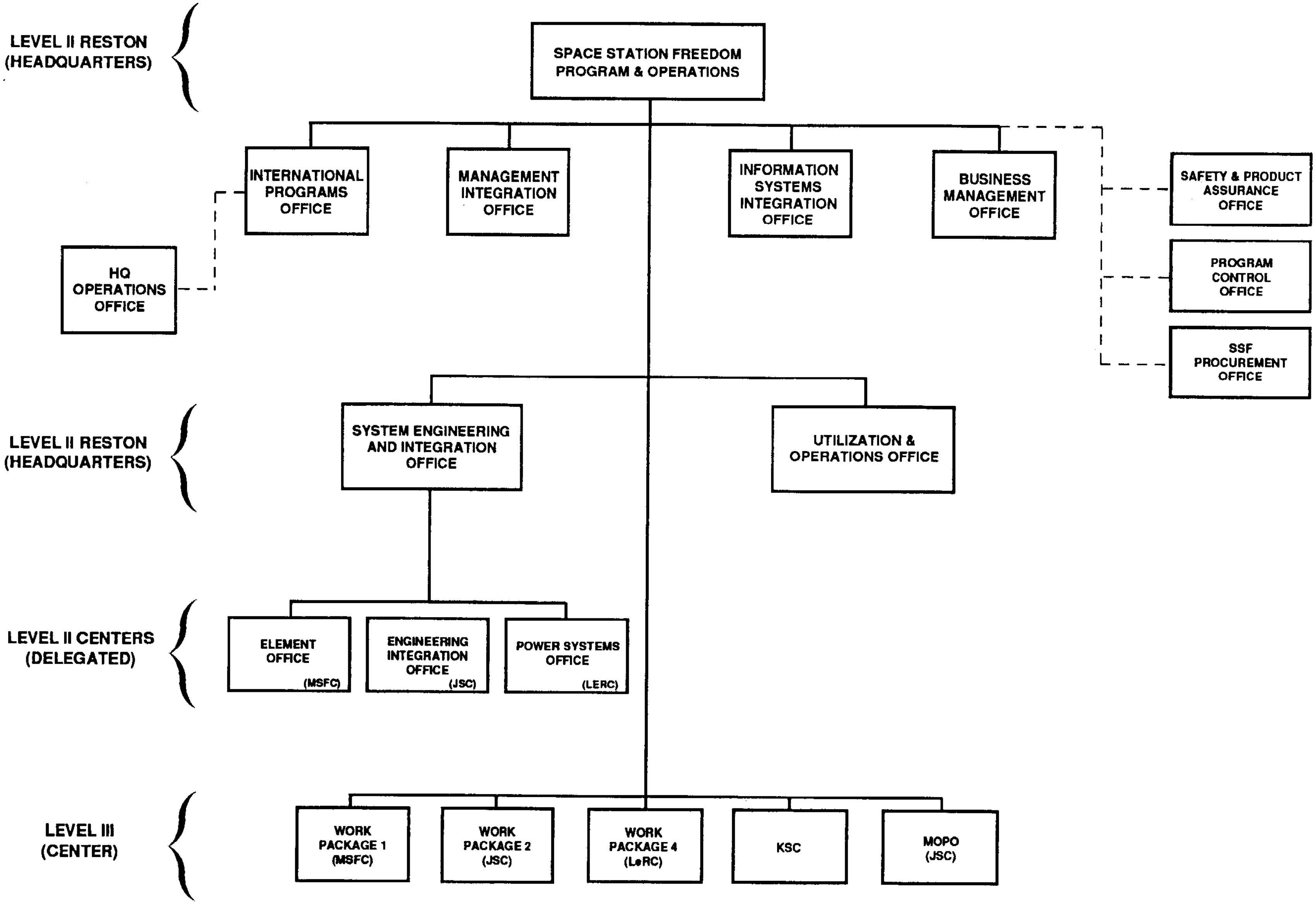
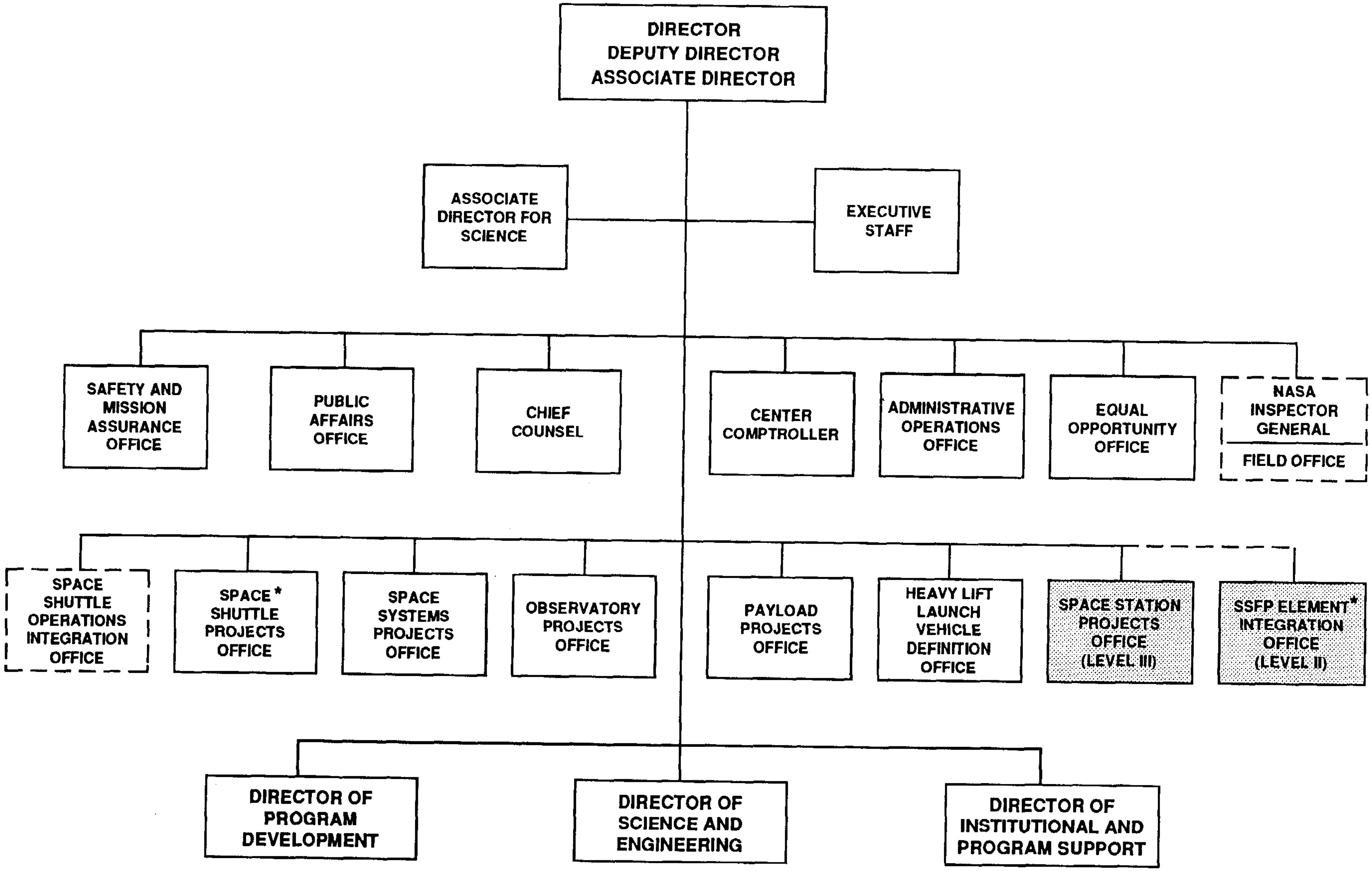


Figure 3. Space Station Freedom Program and Operations



* MANAGERS ARE LEVEL II EMPLOYEES WHO REPORT TO RESPECTIVE PROGRAM OFFICES, NASA HEADQUARTERS

▨ LEVEL III – II INTERFACE

Figure 4. MSFC Organization

Changes also have been effected in Level II activity at Reston. The new management structure is in place and has established clear responsibility among the various organizations and program levels. Grumman, SSEIC to NASA Level II at Reston, is now undertaking a realistic integration role in addition to the supporting function it has been serving. Communications between NASA and SSEIC have improved greatly. For instance, SSEIC personnel now attend the SSF meetings of key NASA integration managers from which they previously were excluded.

The SSF design changes have had some impacts on safety and risk. For example, use of a preintegrated truss (PIT) structure (see below) greatly should reduce risks associated with the extensive extravehicular activities (EVAs) required by erection of the previous design. On the other hand, the elimination of two nodes reduces the available egress paths and, hence, likely increases risk. Overall, it appears that the program has struck a reasonable balance between reduced cost and complexity and the acceptance of an appropriate level of risk.

Ultimately, the operational risks associated with SSF will depend to a great extent on the availability and type of emergency assured crew return capability. The issue of providing such a capability from SSF continues to challenge NASA. There are several options under study including the development of a dedicated "lifeboat" and utilizing the Space Shuttle. Other factors that may influence selection of a final design include the possible use of an expendable launch vehicle and associated personnel carrier that could be utilized as a return vehicle. Studies of these various alternatives are only partially complete. Current information appears to be insufficient to select a preferred approach.

Ref: Finding #4

The use of truss segments, which are preintegrated with distributed systems and verified on the ground instead of erected on-orbit, has reduced technical risk and made the Space Station a more viable program. The preintegrated truss members (PIT) must be heavier than the original truss elements per running foot because the entire mass of the PIT is subjected to launch loads.

PIT members are aluminum I-beams bolted together instead of the more flexible graphite composite elements that previously were part of the design. The heavier construction allows Orbit Replaceable Units (ORUs) to be located in their optimum positions for accessibility.

Table 1 compares several features of the restructured and original SSF designs.

One benefit of the restructured design is that EVA time has been reduced considerably so that EVA targets are now feasible. This has been accomplished by reducing the demand for EVAs and increasing the efficiency of those that must be performed. Examples of changes that positively impact EVA in addition to the use of the PIT are:

- Providing tools and equipment for independent and/or parallel EVA operations
- Enhancing the utility of EVA support equipment

TABLE 1
SSF Assembly and Operational Capability

	Preintegrated (After Jan. 91)	**Erectable** (Before Jun. 90)
Truss	315 ft.	479 ft.
Sections/Bays	7 Sect.	29 bays
Assembly Elements	17	122
Lab/Hab Modules	27 ft.	44 ft.
Nodes	2	4
Cupola	1	2
All International Elements	Yes	Yes
Assembly Flights	16	18
Man-Crews	4	8
KW-Power	56.25	75

- Locating ORUs to simplify EVA operations

- Simplifying the Mobile Transporter.

In the assembly of the PIT sections on-orbit, a capture latch provides final alignment by engaging guide pins after the sections are brought into proximity by the Space Shuttle remote manipulator arm. Motorized bolts then make the final latch-up. There is a chance that these sections may not line up correctly; therefore, damage may occur to the guide pins and bolts when the motorized bolts engage. Because the PIT sections will be assembled on the ground, the opportunity exists to test the alignment and mating procedures prior to flight.

The SSF restructuring has eliminated some risks and hazards inherent in the previous design, but has introduced the following new ones:

- The provision of only one airlock instead of two. Loss of node #2, which contains this airlock, would severely hamper EVA activities.

- A totally "open race track" making it impossible to have dual egress paths.

- The reduction of the atmospheric pressure to 10.2 psia, which increases fire risk due to the increased partial pressure of oxygen.

Although the hazards analyses are proceeding well, many potentially serious items still are contained on the critical item lists. These should be reduced or eliminated as the design process progresses.

Ref: Finding #5

The basic architecture and functions of the data management system (DMS) have not changed significantly with the most recent restructuring of the SSF design. Originally, the DMS components exceeded their power allocations. The current DMS design almost meets its weight, power, and volume allocations.

Although the DMS hardware design seems to be proceeding as planned, the software is still a great challenge; it is one of the pacing items of the program. To meet the present delta design review (DDR) schedule, 17 DDRs will have to be accomplished in 1992. This may not be possible unless software development keeps pace.

B. SPACE SHUTTLE PROGRAM

ORBITER

Ref: Finding #6

Photoanalysis of the STS-28 (OV-102, Columbia) flight showed larger body flap deflections than were calculated. The flaps are in a turbulent flow field, which creates a hinge moment spectrum greater than that used in the structural fatigue analysis. The loads are all within the structural limits, but the fatigue analysis shows a reduction of allowable flights from 100 to 77.

After the higher hinge moments were observed, additional ground tests were conducted using recalibrated strain gages on the body flap actuator as well as additional instrumentation on the rotors and stators. Three types of loads were applied. It was discovered that an additional load path existed back through the driving gear to the supporting structure. The original equations assumed only four load paths at the actuators. With a fifth load path, it is necessary to develop a new set of equations. It also was discovered that the actuators were more flexible than originally assumed and that the OV-102 (Columbia) actuators were more flexible than those on OV-103 (Discovery) and OV-104 (Atlantis). This is attributable to increased tooth width on the OV-103 and OV-104 actuators. Additional tests are planned to further evaluate the body flap structure.

Ref: Finding #7

To apply traditional inspection techniques, such as visual and X-ray methods, disassembly frequently is required. Therefore, a Shuttle Modal Inspection System (SMIS) has been developed to augment more conventional structural inspection techniques. Although not a replacement for conventional inspection processes, SMIS is capable of finding some defects without the need to disassemble the system being tested.

SMIS uses changes in structural dynamics characteristics to detect problems such as wear of actuators, honeycomb debond and cracks in primary structure that are large enough to change stiffness. Actual modal tests experienced on OV-102 and OV-103 have proven the benefits of this system to detect structural damage. To apply SMIS, each Orbiter part must be tested to establish baseline modal information to serve as a standard to determine if structural changes have occurred.

Currently, it is planned to use SMIS on a regular basis for data acquisition and analysis of Orbiter body flaps after every fifth flight.

Ref: Finding #8

In the past, tile bonding process controls and bond verification testing were used to ensure the integrity of the thermal protection system and identify substandard bonds. Approximately 20,000 to 27,000 tiles were tested on each individual vehicle. Typically, only 13 to 64 tile bond failures were found. Initial checkout of OV-105 (Endeavour) has shown only 13 failures.

Use of such bond verification testing has been discontinued because it was determined that tactile and visual inspection techniques by specially trained and experienced inspectors provided adequate results. These "Wiggly" tests depend on the sensitivity of the inspector's touch to determine if tiles are loose. The inspectors also examine and measure step and gap dimensions. Such tile inspections are conducted before each flight.

Tile inspection clearly is dependent on the availability of skilled inspectors. New quantitative methods could be devised to reduce the dependency on qualitative human inspections. These likely will take some time to develop. Therefore, new inspectors must be trained well in advance of their need to support the Orbiter flow.

Ref: Finding #9

The Space Shuttle Program has commenced its first major Orbiter overhaul cycle with work on OV-102 (Columbia) at the Rockwell Palmdale facility. Future overhauls and major modifications on the other Orbiters presently are scheduled to take place at KSC. With aircraft systems, line maintenance and overhaul or major modification functions are typically organizationally separated even when they are conducted at the same location. This has worked well with aircraft and is likely a good model for the Space Shuttle Program to follow. Simply, different types of planning, management skills, and experience are required by routine turnaround flow and the more major overhaul and modification operations.

Ref: Finding #10

The Space Shuttle system presently includes an autoland system that provides automated guidance capable of navigating the Orbiter to the selected landing runway. Automated approach guidance requires the availability of a well-calibrated microwave scanning beam landing system. Completion of a successful landing requires the crew to manually deploy the air data probes and landing gear by activating cockpit switches. This is similar to the situation with commercial aircraft. The crew also must be active in the post-touchdown rollout phase to ensure a safe transition to wheel stop because no automatic braking is provided. The present system is viewed by the Space Shuttle Program as an emergency backup to the commander and pilot, but there are no documented decision rules for its use or operational scenarios under which it is mandated. It has not been tested all the way to touchdown during an actual flight. However, a detailed test objective (DTO) is being developed by the Space Shuttle Program to provide for at least one full automatic landing.

The increased duration of Space Shuttle flights as part of the Extended Duration Orbiter Program (EDO) has raised the issue of the need to qualify the existing system during actual flights. It also raises the issue of the possible need to fully automate all landing, rollout, and braking functions so that the Orbiter could be returned safely from orbit without any crew intervention, if necessary.

Before discussing the need for possible enhancements to the present capability, the status of the present subsystem must be reviewed. The existing subsystem is designed to provide guidance information to the Orbiter through all of the descent flight phases:

- Entry guidance (500,000 feet to Mach 2.5)
- Terminal Area Energy Management (TAEM) (Mach 2.5 to 10,000 feet)
- Approach and landing (10,000 feet to touchdown).

Although the crew must deploy the air data probes and landing gear, there is an automatic speed brake deployment and positioning that occurs independent of the guidance system. This is similar to the prevailing autoland systems in commercial airliners.

The Space Shuttle system differs from those in airliners because it defaults to automatic mode when deorbit commences, and remains there unless the crew switches to the control stick steering (CSS) mode (manual flying). The switch to CSS can be accomplished through a pushbutton on the instrument panel or, on an axis-by-axis basis, by moving the control stick. This is known as "Hot Stick" downmoding to CSS.

The TAEM phase is of particular interest because it determines the energy state and runway alignment of the vehicle at a time in the descent when correction for low or high energy states is possible. TAEM usually is flown manually by the crew, although guidance can adequately control the vehicle around the heading alignment cone and on to touchdown. When the crew flies manually, they tend to manage energy somewhat less aggressively than would the programming of the present automatic system. This increases crew comfort and reduces loads on the Orbiter. Effort presently is being devoted to examining a change in the guidance system to emulate more closely the trajectories actually flown by the crews.

The existing automated approach guidance system never has been fully flight tested. The second Space Shuttle flight, STS-2, left the auto mode engaged until the latter part of the TAEM region and demonstrated that the system was capable of returning the vehicle to a flyable energy state from a low energy state. STS-3 left the system in auto until the commander's scheduled takeover at 125 feet. The system was on energy and trajectory at takeover, but the pilot had difficulty getting "into the loop," and an uncomfortable situation developed. The final several thousand feet of a Shuttle's descent involves relatively complex flare maneuvers with which a pilot might be expected to have difficulty when retaking command.

A DTO for remaining totally in the automatic mode to touchdown was scheduled for STS-16 (41F). However, when STS-15 (41D) had an engine-out pad abort, flights were remanifested and the DTO was canceled and never rescheduled. As a result, although there have been numerous simulation runs, computer modeling, and post-flight analyses of guidance commands, there never has been a flight demonstration of the auto guidance capability all the way to touchdown. Therefore, the cognizant contractor would not certify the system because of the absence of a flight test.

Rockwell is undertaking a reverification of automatic entry and autoland as part of their funding for the EDO missions. However, this does not mean that it has been determined that autoland will be needed for EDO or that a decision to use it has been made. Plans are being formulated for an autoland DTO to be executed within the next year. This will begin the process of in-flight verification of the system. Future analyses are planned to determine if additional flight tests will be required to develop an operationally certified system.

The existing automatic approach guidance capability represents a sufficient foundation of hardware and software to support the contemplated DTO. Eventually, a fully certified system may require certain enhancements such as increased redundancy, decision rules for leaving the automatic mode engaged, and automated gear and air data probe deployment.

There are four basic situations under which Space Shuttle flight safety would be enhanced by the use of some degree of automated landing assistance. These are:

- *Crew unavailability.* This is a situation in which the crew cannot perform their piloting functions adequately because of external conditions. For example, a situation of unavailability might occur if the windscreen of the Orbiter became completely obscured or the cockpit filled with smoke or fumes making it impossible for the crew to guide the craft visually.

- *Obvious crew incapacitation.* The crew may become physically or mentally incapacitated in a manner that allows them or ground controllers to detect the incapacitation. Such obvious incapacitation might range from total loss of consciousness to loss of visual accommodation or the ability to move.

- *Subtle crew incapacitation.* The crew may become physically or mentally incapable of flying the Orbiter in such a manner that both they and the ground controllers continue to believe that they, in fact, are in control. Subtle incapacitations have been experienced in many high stress environments. They typically involve phenomena in which the human sensory and/or cognitive mechanisms are misleading. Examples might involve impaired depth perception, spatial orientation, or eye-hand coordination.

- *Capability Limitations.* There are flight situations, particularly abort maneuvers, that stress crew capabilities to the limits. This stress may be particularly acute if a landing is required into a relatively unfamiliar field.

For situations involving capability limitations, computer assistance through an autoland system can augment or replace the human crew. This has the added benefit of permitting the crew to undertake other critical tasks besides the landing guidance and management of the Orbiter. The generally quicker response time of a computerized system as well as its ability to store and recall vast quantities of contingency information make a standby autoland system a valuable resource.

In the event of crew unavailability or incapacitation, the crew may retain some limited functional capability. For example, they may be able to activate switches to deploy air data probes and landing gear. Under these circumstances, an automatic landing system that required minimal crew interventions, such as switch activations, likely would represent adequate support. Alternatively, the crew may be totally incapable of participating in the landing operation due to unconsciousness or the inability to move or function. In this case, a fully autonomous autoland capability would be required to ensure the safe return of the Space Shuttle. This system might need the capability of remote activation to account for situations in which the crew becomes totally incapacitated after downmoding to manual (CSS) steering.

The situation of subtle incapacitation raises additional salient issues. If the crew is unaware that their performance is degraded, it is illogical to expect them to decide to execute an automated approach. This suggests the need for objectively defined operational rules for the use of automated guidance. For example, a rule might require the use of autoland for all missions exceeding a specified length (e.g., 10 days). The system also should include specific decision rules for engaging the automatic mode (or leaving it engaged) during flights not covered by the operational rules. It also would be beneficial to research possible crew performance measures that could be used during flight to assess the need for an automatic landing. Such measures could be examined during actual Space Shuttle landings by collecting data from secondary tasks performed by nonflying members of the crew.

The reluctance of the crews to give up their manual landing opportunities as well as their concern about the "takeover" problems based on the STS-3 experience is understandable. However, it would seem that a takeover at such a low altitude would be highly unusual and might not be sufficiently credible to include in the certification criteria.

The basic flight controls and computers are in use and have been shown to be reliable during Space Shuttle missions. However, additional sensors and inputs may have to be employed for a full feature and safe "nonpilot participating" autolanding. This may call for a safety review of the extended system.

With commercial airplanes, the overall safety level of the total system, airborne and ground, is checked carefully by a comprehensive failure mode and effect analysis (FMEA) to ensure that the whole system will meet a prescribed safety level. This analysis is conducted independent of any consideration of pilot intervention. A significant factor of the FMEA in commercial aircraft probability analysis is the evaluation of fault-free performance. That is, out-of-tolerance performance not due to a detectable fault that could lead to an incident, possibly an accident, must be considered when arriving at the overall predicted safety level.

In commercial aircraft, autopilots used for approach/landing are designed to have various redundancy levels depending upon their operational use. A fail passive or fail-benign system is used for operation down to 100 feet. If a fault occurs, the autopilot will automatically disconnect and warn the pilot, but not disturb the flight path. Airplanes conducting such landings in low visibility using fail passive systems generally are certified for use in approaches to low altitude (e.g., 100 feet or so). This is provided it can be shown that the pilot can take over and conduct a landing or go-around safely. If the automatic pilot is to be used down to touchdown without pilot intervention, such as a go-around or path correction, a fail operational system of some form is required and a very low probability of a failure that could lead to a loss of control must be established before the system can be certified. The probability of a safe go-around can mitigate this value somewhat. Obviously, this is not the case with the Space Shuttle.

Without considering pilot intervention, the Space Shuttle system will need to land with an extremely high probability of being within prescribed parameters of touchdown vertical velocity limits, lateral and longitudinal dispersions, and any other limits peculiar to the Space Shuttle such as body angle. The confirmation of the possibility of a malfunction or fault-free performance outside limits would need to be shown to be extremely improbable. Therefore, a Space Shuttle autoland system would need to provide full fail-operational performance through touchdown and rollout.

Another vital aspect of autoland certification is to ensure that the landing parameters, flare profile, decrab maneuver, transition to rollout, etc., conform to what a reasonable pilot would tolerate. In the early days of commercial autolanding, these profiles were determined by software engineers. Although they achieved the accuracies required, they were unnatural and unacceptable to the pilots, thus causing a potential and possibly dangerous pilot intervention to occur.

Today, the flight profiles flown by commercial autoland systems have been refined to be so natural and consistent that most airline pilots say "the system does a better job than I do." If NASA embarks upon a program to develop natural landing maneuvers by the automatics that are pilot acceptable, it also will have the distinct advantage that pilots will be more likely to use the system, even when it is not mandated. Thus, this will provide valuable operational experience and data and, in the end, a higher safety level.

On the assumption that operation solely by the human pilot as the prime safety element may not be viable under certain operational circumstances, a fully automatic landing system becomes essential to the safe completion of a Space Shuttle mission.

Ref: Findings #11 through #13

During the year, NASA continued its independent review of the verification and validation process related to Space Shuttle software. This independent review has demonstrated its value by finding failure modes that previously were unknown. Increased involvement of the Office of Safety and Mission Quality with software safety also was a positive step.

Software verification and validation can take several forms including:

- Continual oversight and review of the <u>process</u>
- Oversight and review of the generation of the tests used in the process
- Complete verification and validation conducted by a totally independent organization.

Costs and benefits of these approaches vary considerably. The cost of an ongoing, independent review of the verification and validation process and of the test generation is relatively small compared to the total cost of the process. The present ongoing, independent review has demonstrated the value of this activity and should be continued. Although an internal steering committee on embedded verification and validation has been formed, it was not until the independent contractor became involved that a "roadmap" of the process and generation of the tests used was established. The internal steering committee has not succeeded in carrying out the necessary functions on its own.

Now that a complete roadmap for the verification and validation process is available, the Panel believes that the independent contractor should review the process, end to end, and look for ways to simplify it. At present, it involves a great number of machines and people. In addition, the independent contractor should investigate the process by which the tests for the verification and validation process are generated. It is essential that the independent contractor utilize personnel intimately familiar with NASA's software processes. An independent contractor not utilizing such personnel would have great difficulty in adequately carrying out this function.

Independent performance of the tests, however, is another matter. Costs associated with the verification and validation process are very high. One unofficial estimate puts the cost as high as $500,000 for the physical apparatus alone. Further, the process can only be reliably performed by personnel intimately familiar with the software production process. Therefore, great care must be taken in any proposed decision to independently perform the verification and validation function. There must be both an acceptance of the substantial costs involved and a plan to acquire the experienced personnel necessary to carry out the work. ASAP believes that these two factors mitigate against the third listed alternative, independent performance of the verification and validation tests. Simply, the potential gain does not justify the cost.

The new general purpose computer (GPC) hardware seems to be performing well. The single event upsets (SEUs) were no more numerous than expected. Indeed, accuracy of the predictions based upon NASA's model of SEUs was impressive. A cursory analysis concurs with NASA's estimate that the probability of an SEU-induced failure is negligibly small.

There is still a potential problem arising from the eventual saturation of usable memory on the new GPC. While the time horizon of the "new" GPC has been extended somewhat by moving some requested upgrades into procedures and slowing the software change process, the conclusion is the same. Long before the end of its planned lifetime, the "new" GPC will be saturated and a further change will be necessary. It is still the case that any foreseen possibility of further upgrade will require massive reverification and revalidation. With the extension of the time at which this impasse will occur, NASA has the time, if it acts promptly, to plan carefully for this next change and complete it at minimum cost and turmoil. A small planning effort on the next generation computer upgrade should be started as soon as possible. This study should not be constrained to living with the current architecture, and should involve others in NASA who have been studying long-term computer evolution for space applications.

The movement of some requests for software upgrades to crew procedures is a matter of serious concern. The crew already has a very large number of procedures with which to be familiar. Adding to that load, particularly with items that could be handled easily with greater reliability and safety by software, does not seem wise. Procedures such as "do not touch the keyboard for X seconds after the occurrence of event Y" can be handled easily by software. If such procedures are contingencies that are employed infrequently, the chance of error when they are needed rises.

A review of all computer-related procedures to ascertain whether or not there is significant potential for design-induced human errors should be mounted. This review should include crew representatives, experts on human factors, and members of the Safety and Mission Quality organization.

SPACE SHUTTLE MAIN ENGINES (SSME)

Ref: Findings #14 through #17

The in-flight performance of the Space Shuttle Main Engines (SSMEs) has been very consistent and without significant anomalies since the return-to-flight after Challenger. There are now sufficient engines at KSC to provide four shipsets for the Orbiters plus three spare engines. The practice of removing all three engines from the Orbiter after each flight and conducting the post- and pre-flight tests in the "engine room" has proved beneficial and effective. Except for the high-pressure turbopumps, the major components of the engines have demonstrated service lifetimes in excess of the specified 55 equivalent Space Shuttle flights.

The Phase II component improvement program designed to enhance the safety and/or reliability of the current engine components has continued to make progress. The status of the changes to the major components is:

- <u>High-Pressure Fuel Turbopump (HPFTP)</u>: All changes to this turbopump have completed the certification requirements; flight units are being built. The machine has demonstrated the requisite 10,000 second run time (20 flights) and was to have been authorized a service life of a "green run" on the test stand plus nine flights (half certification life). The failure of a high-time HPFTP turbine blade in test engine 0215, most probably the result of a blade material flaw, has resulted in a reduced "certified operating time" of 7,000 seconds (14 flights). This is the equivalent of a service life of a "green run" plus six flights. A new Computer Tomography blade material inspection technique has been implemented, which will allow the restoration of the 10,000 seconds certification. Pumps with such blades are being assembled, and flight use is estimated for the middle of 1992.

- <u>High-Pressure Oxygen Turbopump (HPOTP)</u>: As noted in last year's report, the SSME project decided to abandon its attempt to certify the HPOTP for 10,000 seconds of service life and instead opted to certify the turbopump so that the pump-end bearings can be used for three flights and the turbine-end bearings used for six flights before replacement. To accomplish this, changes to the inducer/inlet, bearing cage coating, ion implantation of the bearing balls, and a material change to the jet ring to increase its fatigue-life were incorporated and certified. Improved on-engine inspection tools for the turbine-end bearing have been developed and are in service. In-flight strain-gage measurements of the vibration signature of the pump-end bearings to detect early signs of bearing wear are also a part of this configuration. Experience to date with these measurements has been satisfactory. A number of HPOTPs have been flown three times.

- <u>Single-tube Heat Exchanger</u>: The fabrication process for producing the 41-foot long single tube for the heat exchanger has been developed and 10 tubes have been completed. Two tubes have been coiled, and mockups and test specimens are being built. This represents a major hurdle in this program. One coil is in the process of being welded into a powerhead and is to be tested in mid-1992. Certification is scheduled for completion in FY 1993.

- <u>Phase II+ Powerhead</u>: The Phase II+ Powerhead (also known as the two-duct powerhead) was tested last year. As noted in last year's report, both injector erosion and chamber wall blanching were experienced. On the positive side, lateral pressure gradients and velocity profile nonuniformities were reduced substantially. Since then, the flow shields on the injector posts were modified, and tests on a second powerhead were conducted. Injector erosion was eliminated, but main combustion chamber (MCC) blanching and wall damage still were experienced. This has been attributed to a high flow resistance coolant circuit in the specific chamber used. Two units have been built to continue development; one with the current design combustion chamber and one with the large throat combustion chamber. Tests have been conducted with the large throat main combustion chamber (LTMCC) unit with very satisfactory results (the absence of blanching in these tests is the result of improved cooling design in the chamber).

As noted in last year's report, the LTMCC was tested on engine 0208. In some 3,700 seconds of testing, including 26 starts, the predicted benefits were verified. In addition to reductions in the chamber pressure, turbine temperatures, and speeds, the hot gas wall temperature in the chamber was reduced about 100°F. This will have a significant effect on the rate of combustion chamber blanching and cracking. Analysis indicates that using the LTMCC would increase the margin-of-safety of selected engine components by 12 to 30 percent. The testing noted above with the Phase II+ Powerhead has increased the accumulated run time of the LTMCC to 5,000 seconds. Unfortunately, the LTMCC development was tied to the Advanced Fabrication Project whose results were to be incorporated no earlier than mid-1997. Were this not the case, the benefits of the LTMCC could have been realized much sooner, as the LTMCC does not depend on improved fabrication processes to achieve increased margins. Because of NASA budget constraints, funding for both of these efforts was eliminated for FY 1992. To the detriment of the program, all activity on these efforts will come to a halt before mid-1992.

The design verification system (DVS) testing (both laboratory and rig tests) of the components of the Pratt and Whitney (P&W) Alternate Turbopump Program (ATP) is substantially complete including demonstrations of component life. Some data still are being analyzed, but results to date look good. Significantly, the bearing materials and coatings have been selected and proven. An acoustic emission probe installed for the bearing rig tests shows promise of serving as an in-flight health monitoring instrument. Spin tests of shafts, disks, and impellers have verified the burst margins of these parts. Note that these test specimens were heavily strain-gaged so that data could be obtained to verify the structural analysis models of these critical components. A few DVS tests await the build of final configurations.

- <u>HPFTP</u>: Testing of the HPFTP on the P&W E-8 test stand and of unit 4 on an engine at Stennis Space Center (SSC) revealed a number of problems with the design. Among them were thermal cracks in the first turbine vane inner shroud, tip seal displacement on the third pump impeller, main pump discharge housing vane cracking, and turbine inlet housing strut and slot cracking. Fixes for these have been devised and are in work. Some have been incorporated into unit 5, which has been run at SSC for reasonably long times at 100-percent rated power level (RPL) and has reached 109-percent for a brief time. The plan is to have all fixes incorporated by unit 7.

- <u>HPOTP</u>: This turbopump encountered more difficulties than its fuel counterpart during development testing. Among them is a synchronous vibration problem at high power levels when pumping LO_2. Many changes to the mechanical design and assembly details have been incorporated in an attempt to solve the rotordynamic problem. This includes increasing the tiebolt load, the pump-end ball bearing deadband, and the damper seal diameter. So far, the changes that have been incorporated have performed well during the E-8 test of unit 05-1, which ran to 104-percent RPL with acceptable vibration characteristics. This unit has been cleared for 100-percent RPL operation on an engine. Heavily instrumented unit 4-1D was used to verify some additional improvements. It ran satisfactorily to 111-percent RPL with LO_2 on E-8. Unfortunately, unit 6 (which incorporated a de-swirler, in addition to other changes) exhibited rotordynamic instability at 109-percent RPL. It is believed that the cause of this phenomenon has been identified. Follow-on units will include additional changes to attempt to eliminate this cause.

Integrated Tests: The tests of the HPFTP on an engine with the current HPOTP have shown that the transient characteristics of this machine generally are compatible with the rest of the engine system during start and shutdown. There are differences, of course, because of different moment of inertia and breakaway torque of the new machine. As a result, some valve sequencing had to be modified to reduce the fuel preburner ignition temperature spike. Some additional tuning will undoubtedly be required. Performance of the HPFTP, as measured on the engine, agrees well with the data obtained in the E-8 tests. Testing of both the P&W HPFTP and HPOTP on an engine is scheduled.

In summary, as in most turbopump development programs, the problems encountered in the ATP lie in the (subtle) mechanical details of the design. Problem causes include details such as clearances, seals, venting of volumes enclosed by cover plates, effects of damping seals and bearing preloads on rotordynamics, and effects of thermal transients during startup. The ability to determine the causes of the problems encountered has been enhanced greatly by the use of component test rigs and, perhaps more importantly, availability of the E-8 turbopump test stand. Coupled with good and extensive instrumentation of the development units, these facilities allow rapid identification of problems and permit rational corrective action.

Operation of the E-8 stand has improved much since last year. It is reported that two out of three test attempts now lead to successful runs - excellent performance for so complex a facility.

Engine-level tests have revealed some system issues but, so far, nothing of major consequence. Schedules are still optimistic. Significant progress has been achieved since last year. Engine tests with both turbopumps installed will be a major milestone in the near future.

In a recent decision resulting from budgetary problems, NASA has decided to cancel work on the P&W HPFTP and to continue only the development of the P&W HPOTP. The plan is to use this new HPOTP in conjunction with the current HPFTP. While such an engine configuration is feasible, it will not achieve the operating margin increases sought for the engine system. NASA has made provisions in its planning to review the status of the P&W HPOTP development in 1994 and reconsider the cessation of HPFTP development at that time.

ADDITIONAL ORBITER COMPONENTS

APU Turbine Wheel Blade Cracks: Blade root and tip cracks have existed since the start of the program. The turbine wheel speed is 72,000 rpm, with a high speed of 81,000 rpm. A design revision was initiated in December 1987; it produced 15 wheels that have accumulated 210 hours with no cracks. By the time this report is published, all APUs will have been equipped with the new turbine wheels. The new design wheels are certified for 20 hours with a 75-hour certification test to be completed in the first quarter of 1992.

APU Gas Generator Valve Module Seat: The shutoff outlet seat has evidenced cracks. The investigation of the launch scrub of STS-31 showed that the seat was broken and a piece missing. The consequences could be a reduced APU output or possibly a shutdown. As a result, a liquid leak check of the valve prior to flight is required as well as a valve replacement every 18 months.

Orbiter Drag Chute: The plan is to use the chute on every landing because it enhances directional stability. Structural requirements were validated by analysis. The drag chute system was tested successfully at the component and system level. There still are a few tests remaining. All nominal condition tests with the B-52 have been completed. Tests to expand the envelope still have to be conducted.

SOLID ROCKET MOTORS

Ref: Findings #18 through #21

Work performed on the Advanced Solid Rocket Motor (ASRM) to date generally has been well-conceived and of high quality. The schedule does not have much contingency time. Although techniques can be made to work adequately, it might take considerably longer than planned because there is a lot to integrate.

There are concerns about scale-up of the pilot propellant mix and casting facility. Many parameters and processes have not been fully determined. However, Aerojet has produced a substantial amount of similar solid propellant using continuous production processes so the basic techniques are familiar. The continuous solid propellant production facilities involve a variety of mixing and transport facilities. Safety concerns arising from propellant remaining in the transfer lines have been addressed. The propellant requires a period of 40 to 50 hours to gel, and can be expelled from the transfer lines for a significant time after it enters. Hazard analyses revealed no credible hazard that could prevent evacuating the lines for as long as 15 hours. The propellant is normally in the transfer tube for only about 30 minutes.

Safety devices are installed on the propellant flow line to limit the spread of fire in case of an accident. The flow line transporting the uncured propellant has several fire breaks to prevent propagation of a fire along the tube. The basic safety device is an explosive-fired guillotine valve that interrupts the flow, with a water spray on the propellant to lower the temperature below the ignition point. In addition, there is a collar in the flow line upstream of the guillotine and on the casting pit side of a fire wall that can be blown to allow the propellant to flow out on the floor and prevent pressure buildup. A matter that must be considered is cleanup after an accident involving a dump of uncured propellant on the floor. The continuous mix pilot plant at Aerojet provides a way of proving a new propellant and upgrading the equipment before establishing a full-scale facility at Yellow Creek. The major differences between the pilot plant and the full-scale facility are equipment size and process control software. The pilot plant production rate is 1,000 to 1,400 pounds/hour with the full-scale facility producing 20,000 to 26,000 pounds/hour. The ultimate particle size of the propellant is dependent on parameters such as geometry of piping, length of lines, and fluid working pressures that may not be directly scaleable. There are many challenges such as metering of propellant solids, pre-mix of iron oxide and aluminum, and real-time process control. Upscaling the rotofeed deaerator and pump equipment probably presents the greatest challenge.

The propellant manufacturing process includes several methods to ensure the quality of the product. There is a 30-minute delay loop in the propellant lines that permits extracting and analyzing a sample before the material reaches the casting pit. In addition, small test articles are cast with each batch. Propellant samples are tested after casting to ensure burning properties are to specification.

A new method for assessing propellant quality is under development. This Fourier Transform Infrared/Factor Analysis (FTIR/FA) produces "fingerprints" of the propellant being produced. If the development proves successful, it could be used on-line to eliminate most of the laboratory testing during production.

Obviously, successful development of the insulation strip winding process will be a marked improvement in cost and time to the present hand lay-up method used in the Redesigned Solid Rocket Motor (RSRM) installation. The extruder equipment that produces the insulation material in the process development is identical to that specified for the Yellow Creek facility. Initial tests of the stripwinding were conducted on bare metal that had been neither cleaned nor treated with adhesive. These tests were successful in that the insulation did stick to the inside of the casing.

It is necessary to develop a data base for strip winding before producing the 48-inch insulation test articles. A 48-inch long section of a 150-inch diameter case will be developed for the field joint test article. However, the boom travel will have to reach 400 inches for the full-scale motor. Finally, the entire process will be verified in the development and qualification motor tests.

The case will be turned on end for the liner spraying operation. A robot arm will traverse a vertical beam and spray the liner on top of the white insulation.

Much of the work to date has been directed toward determining the proper chemical composition of the liner. Current plans include a visual inspection of the liner after spraying facilitated by the addition of black pigment to the spray.

The HP9-4-30 steel for the case was selected to be forgeable, machineable, and resistant to stress corrosion cracking and to general corrosion with proper coating. The steel case will be inspected using magnetic particle inspection along with alternative non-destructive inspection (NDI) methods. The consistency of the case properties is dependent on proper process control and development testing. A thorough program of testing to characterize this material is needed to support the finalization of the case design and manufacturing plans. This must include development and characterization of the manufacturing processes such as plasma arc welding and weld repair procedures for the large diameter steel casing.

A key item in the propellant mixing and casting program is the development of the software for the overall process control. Although contracts for development of the software are underway, little attention has been paid to the design of the user interface. It would appear that the system design would benefit from a more complete analysis of the interface and the participation of an expert in human-computer interfaces. As a basis for making decisions, a complete task and functional analysis should be performed.

Ref: Finding #22

NASA is committed to using the current aft skirt configuration on all RSRMs and ASRMs. Data received by the Panel justifies the NASA decision. This data consists of maximum strains recorded at all eight hold-down posts during 18 firings of the Space Shuttle (1 flight readiness firing and 17 actual launches).

Using the data received and a tensile strain of 5,143 micro-inches as the strain measured at 100-percent Design Limit Load (DLL) on the static test specimen, the confidence level in the estimated probability that certain load levels will or will not be exceeded can be calculated:

- The probability that DLL will be exceeded is 5 percent, with a confidence level of 95 percent.
- The probability that 1.28 x DLL will not be exceeded is 99.9 percent, with a confidence level of 99 percent.

Although there is a fair likelihood that the DLL will be exceeded, it is quite unlikely that a failing load will be experienced. In the above prediction, static test failure strength was not corrected to account for variability of weld strength. This variable deserves more consideration. It could be argued that in the large volume of weld material exposed to maximum stresses in the test article, there existed at least one of the maximum flaws that could escape NDI detection. Therefore, failures were initiated at near A-type strength values. The fact that two test articles failed at nearly identical values of load lends some credence to this argument.

Calculated ASRM lift-off loads are within aft skirt certification limits. The