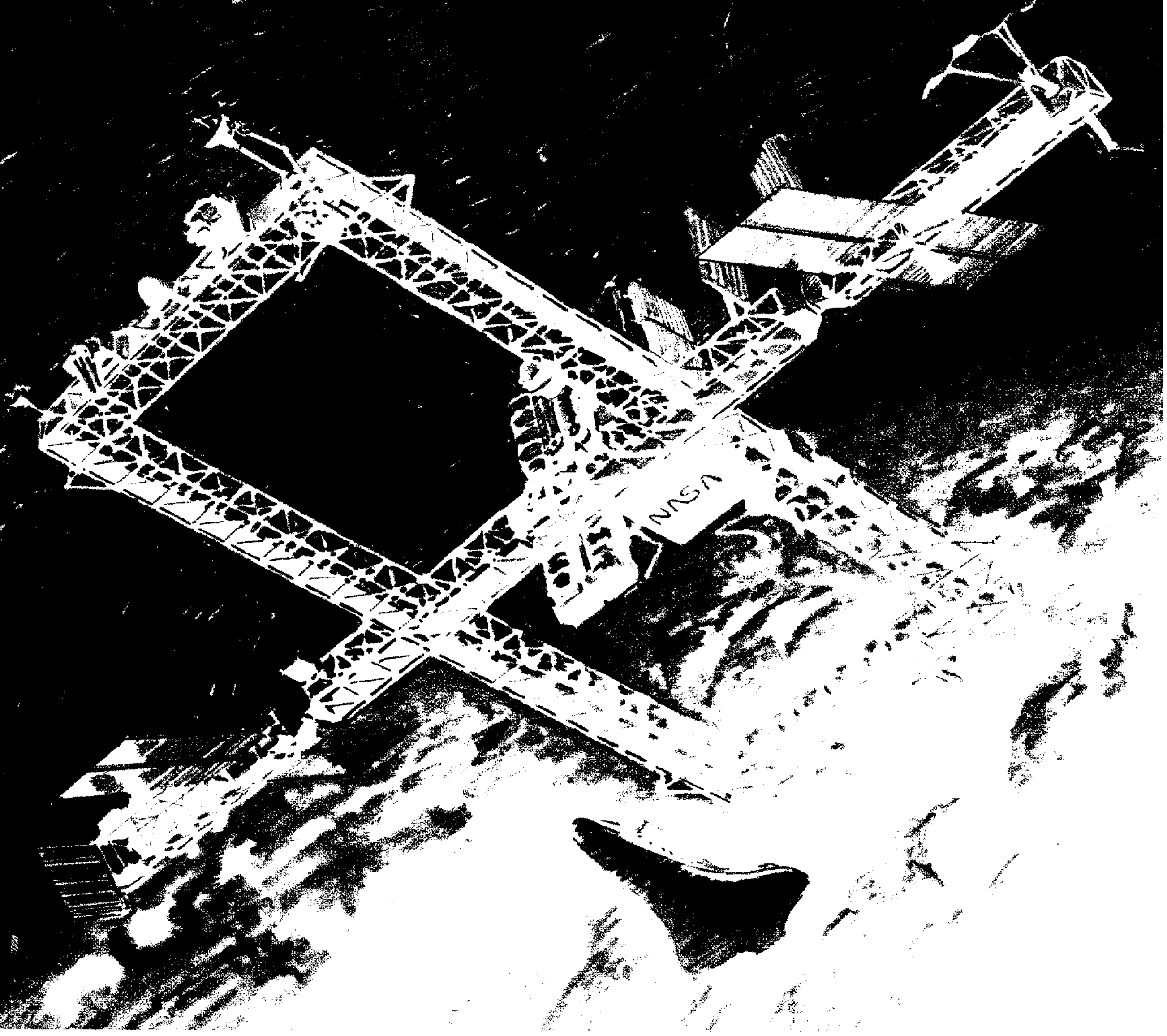
National Aeronautics and
Space Administration

Aerospace Safety Advisory Panel

Annual Report FOR 1986



AEROSPACE SAFETY ADVISORY PANEL

ANNUAL REPORT

COVERING CALENDAR YEAR 1986

Issued February 1987

TABLE OF CONTENTS

EXECUTIVE SUMMARY

The Challenger accident set in motion a great number of activities directed toward Space Shuttle recovery, the results of which will affect NASA and its contractors for the foreseeable future. The Aerospace Safety Advisory Panel's factfinding and reporting activities were also in support of returning the Space Shuttle to safe flight status in a timely manner.

Given the breadth of Panel findings and recommendations resulting from this year's factfinding work, this report is structured to provide a compact and useable Executive Summary focusing on the most significant areas of interest followed by stand-alone sections covering Space Shuttle management, Shuttle hardware/software systems, Shuttle operations, NASA Safety/Reliability/Quality Assurance, Space Station Program, and aeronautical activities. The majority of the Panel's efforts were directed toward understanding and providing constructive criticism in support of Shuttle Program recovery efforts.

Panel members and consultants were involved in more than 50 individual and group factfinding sessions, congressional hearings, "one-on-one" meetings with NASA senior managers, and were participants in three National Research Council (NRC) independent oversight groups examining the solid rocket motor redesign, flight rate and manifests, and critical items and hazard analyses. Panel information, oral and written, was supplied to the Presidential Commission on the Space Shuttle Challenger Accident and the House Committee on Science and Technology Investigation of the Challenger Accident.

NASA's response to the Panel's last annual report (issued January 1986) is quite detailed. Due to the changes which NASA experienced in 1986, multiple response letters were provided between September 1986 and February 1987 covering first the aeronautical programs, then the Space Station, and last the Space

Shuttle Program. These appear in the Appendices portion of this report along with a status ("open" or "closed") for each specific point covered.

A report summarizing specific and generic lessons learned as a result of the Panel's factfinding activities was issued in November, "Lessons Learned--An Experience Data Base for Space Design, Test and Flight Operations." Copies went to NASA and contractor organizations.

Space Shuttle Management

1. The Panel finds the recent reorganization of Space Shuttle management to be a positive step in recapturing or rebuilding a spirit of mutual respect and trust at all levels. The Panel recommends that: a priority objective of the new management team must be to enforce NASA's management instructions and to define clearly the responsibilities and authority of the NASA centers; a willingness of all NASA centers to pull together, to subordinate parochial interests, and to help each other is absolutely crucial if the Space Shuttle program is to succeed.

2. The Panel finds that NASA and the Congress need to appreciate that the Space Shuttle is a system which remains primarily developmental with some operational characteristics. It is recommended that NASA needs to emphasize the developmental characteristic or it is likely to miss key elements of the Space Transportation System management challenge.

3. The Panel notes that transfer of part of the Space Transportation System (e.g., Orbiter) logistics responsibility from Johnson Space Center (JSC) to Kennedy Space Center (KSC) must be supported with adequate budgets and appropriate authority to: build a sufficient inventory of spare parts, upgrade the Line Replaceable Units (LRU), and develop an effective program to reduce LRU turnaround time.

4. The Panel recommends that those elements of sustaining engineering that are directly related to launch processing should be the responsibility of the launch operations center (KSC) and those elements of sustaining engineering that require detailed knowledge of the design and development history of airborne hardware should remain with the design centers, as NASA now contemplates.

5. The Panel recommends that NASA should achieve consolidation and upgrading of Space Transportation System data/information systems, particularly those related to configuration management and launch procedures.

6. The Panel finds that although top Shuttle Processing Contractor (SPC) and NASA managers are communicating reasonably well, there is a continuing need to communicate even more directly with workers involved in launch processing to assure that there is a clear sense of mission and direction, and to benefit from employee initiatives and suggestions during these crucial months prior to first reflight.

7. The Panel reiterates that NASA and the Shuttle Processing Contractors need to prevent a recurrence of the condition that developed in 1985 where human resources at KSC were excessively stretched due to launch processing workload and schedule pressures (for example, overtime policy).

8. The Panel recommends that NASA top management should address the growing problem of recruiting and retaining talented engineers and managers due to inadequate Federal salaries. This is not just a Space Shuttle problem.

9. The Panel, in an independent review, concurs with the National Research Council (NRC) Panel conclusions on Space Shuttle Flight Rates and Utilization, that is, an upper limit of 8-10 flights per year with a three Orbiter fleet and 11-13 with a

four Orbiter fleet. Further, the Panel recommends that the Space Shuttle be used only where manned missions are deemed mandatory, and expendable launch vehicles should be used for all other missions.

10. NASA and the Congress should no longer expect that "heroic" performance by its workers and its contractors can compensate for funding shortfalls. The sort of heroism that is needed today is the courage to promise no more than can reasonably be expected given the dollars and people available.

Space Shuttle Systems

1. The Panel finds the redesign of the solid rocket booster (SRB) joints is a marked improvement over the original joint design but there may be problems with mating, demating, and reuse. The approach selected entails more risk than one using new forgings that might permit a more sophisticated design but which would delay first Shuttle flight. Since the proof of adequacy of the design depends strongly on satisfactory results from a thorough certification test program, the Panel recommends a truly complete definition of the certification program and that the elements of the certification program must relate to the specific design requirements.

2. The Panel agrees with the decision to test the solid rocket motors in the horizontal position. In line with this a second horizontal-firing test stand is being constructed that will have the capability to apply simulated flight external dynamic loads. Since there is no way to assure that the tests encompass all possible loading conditions and assembly differences, the Panel recommends that the SRBs and the test stand itself be heavily instrumented to assure that flight-type structural and performance data is obtained as part of the certification program.

3. The Panel urges NASA to provide funds to (1) check Orbiter 102 for loads resulting from the latest loads/stress analysis (designated ASKA 6.0), (2) check the other orbiters for ascent and descent loads, (3) update orbiter load indicators and redlines, and (4) prepare appropriate loads/stress summary reports.

4. The Panel urges NASA to have Orbiter 102 undergo a loads test program to calibrate the strain gauges installed so that flight data from these strain gauges may be used with confidence to obtain wing loads in flight.

5. NASA conducted an extensive reexamination of the Space Shuttle Main Engine (SSME) during 1986 to identify any safety issues that might have been overlooked and then to establish and validate an engine configuration for use in the upcoming Shuttle missions. The Panel finds that the changes being made as a rule do not indicate that there will be any significant improvement in "margin to failure." The Panel recommends that the Phase II engines operate at power levels below 104-percent rated thrust, and if possible at no more than 100-percent rated thrust until these engines have accumulated sufficient flight operating time.

6. The Panel recommends that the Space Shuttle Main Engine two-duct Hot Gas Manifold and the large throat combustion chamber be tested and certified as soon as possible.

7. The Panel recommends that NASA and the SSME contractor continue the development of improved methods for actually demonstrating critical operating failure mode margins and the more rigorous risk assessment analytical procedures. It is recommended that, as part of such procedure, the term "failure" be defined as a violation of any of the governing design criteria for a component rather than as an event such as a structural failure or burn-through.

8. <u>Shuttle Orbiter Computers</u>:

a. The Panel findings regarding the use of upgraded computer systems in late 1988 in either the 4/1 (4 new computers plus 1 old computer) or the 5/0 (5 new computers) configuration include the following factors:

(1) The degree of additional safety provided by dissimilar hardware (there already is dissimilar software);

(2) Human factor contributions to risk--part of the safety provided by computer redundancy is achieved through astronaut training and in flight operations and maintenance procedures performed by the astronauts. This risk difference may well be greater than that in item a above.

(3) The impact of the flight schedule on the scope of software testing, or stated conversely, the impact of required software testing (which is larger for the 5/0 configuration) on the flight schedule; and

(4) The additional costs associated with the 5/0 configuration.

b. The Panel recommends that:

(1) In order to provide greater confidence in the new General Purpose Computer (GPC), it is recommended that the new GPC be flown on several flights as the backup computer before being used as the primary system.

(2) NASA should conduct a study of the human factors aspect of risk associated with in-flight operation and maintenance procedures, particularly changes in procedures and configurations resulting from response to

some failure. Included in this should be a preliminary design of the 4/1 procedures and training and an assessment of their impact.

9. The Orbiter landing gear system (including brakes and nosewheel steering) has been a subject of concern to the Panel as noted in its reports since 1981. NASA's response to Recommendation VI of the Presidential Commission's report appears to meet the intent of the Panel's earlier recommendations. The Panel intends to monitor these areas to assure NASA completes its stated action plan.

Space Shuttle Operations

1. The Panel reviews of NASA and contractor launch processing operations included "one-on-one" interviews with technicians and quality control personnel doing the "hands-on" work. These have shown that recent efforts are steadily improving the effectiveness of both NASA and contractor activities at KSC.

2. Space Transportation System logistics have improved but there remain some concerns:

a. The completion of the procurement of necessary spares.

b. Design improvements to Line Replaceable Units (LRUs).

c. Procedures to control hardware cannibalization between vehicles.

d. Establishment of required repair sites for Line Replaceable Units to improve turnaround time.

e. The many activities in support of returning to flight ("recovery"), e.g., hazards reviews, which may require modifications which affect logistics requirements.

3. The Panel recommends that the recommended "Maintenance Safeguards" program being prepared by NASA in response to the Presidential Commission report be documented quickly and its impact evaluated as soon as possible.

<u>Safety, Reliability, Quality Assurance</u>

1. The Panel finds that three fundamental weaknesses appear evident. First, there has been a lack of in-line responsibility and authority in the Headquarters organization for establishing policy for the safety engineering function throughout NASA. Second, the elements of the safety functions that have been accomplished at various locations did not include responsibility for defining and controlling the validation and certification programs. Third, there is a conscious lack of quantitative approaches to determine failure-mode probabilities for the purposes of defining acceptable margins, and the relative likelihood of resulting system interactive hazards.

2. The Panel recommends that:

a. Within the newly established Safety, Reliability, Maintainability and Quality Assurance (SRM&QA) organization, NASA should develop the operating policy for all NASA SRM&QA and have the authority to ensure implementation. At each Center there should be a NASA Safety Engineering function reporting to the Center Director. This function should be matrixed into the various programs/projects and should be responsible for implementation of safety policies established by the Headquarters organization.

b. NASA continue to independently review all payload components with regard to their individual inherent safety, and should analyze the safety implications of the potential interactions of payloads in the event of a malfunction of any individual one.

Space Station Program

1. The Panel endorses the initiative to simplify the Space Station design and reduce the extent of manned assembly in orbit using extra-vehicular space suits.

2. The Panel suggests that expendable launch vehicles of greater performance than the Shuttle be included in the launch stable inasmuch as such vehicles may emerge from other national programs.

3. The Panel recognizes that "Safe Haven" and "Life Boat" options are under study in the continuing efforts to define the Space Station. The Panel suggests that both concepts may be required to satisfy ultimate safety requirements for Space Station operations.

4. The Panel is concerned that the computer systems being considered for the Space Station may not be taking into consideration evolutionary changes that will inevitably evolve in the industry in the next two decades. The Panel recommends that the system be designed to allow for the replacement of components as new technology develops. A 32-bit architecture and industry standard bus should be mandatory.

5. The Panel reiterates an old theme: Lessons learned from prior programs must be applied and that such documented material is readily available, e.g., Saturn-Apollo, Skylab, Centaur, Space Shuttle.

NASA Aeronautics

1. The Panel recommends that NASA ensure that the level of the Headquarters Flight Operations Management office and those at the Centers have proper recognition and ready access to their top management.

2. The Panel recommends that the Shuttle Flight Simulators (aircraft) program be completed in a timely fashion so that astronaut training will not be hampered.

3. X-Wing/Rotor Systems Research Aircraft (RSRA) incorporates a number of complex analyses, simulator and test efforts. The Panel recommends the Flight Readiness Review be conducted after completing these efforts and that the correlation between them be carefully examined. Included in this are the following:

   a. The raising of the vertical center of gravity of the vehicle by some 18 inches as compared with the standard RSRA vehicle. This is having a pronounced effect on structuring of the flight test program.

   b. Aircraft structural divergency prediction from the tunnel tests.

   c. Refinement of the flutter and divergence analyses.

   d. Results from the powered model tests correlation with predicted downwash interference predicted by analysis.

   e. The definition of the telemetry requirements with emphasis on software requirements for automatic monitoring.

4. The X-29 project with so many new technologies involved is an example of a meticulously conducted flight program taking safety into account throughout.

I. INTRODUCTION

A. Scope and Structure

The Challenger accident, January 28, 1986, set in motion a great number of activities, the results of which will impact NASA and its contractors operations for the foreseeable future. The Aerospace Safety Advisory Panel's factfinding and reporting activities were also directed toward supporting the return of the Space Shuttle to a safe flight status. This year's annual report mirrors this in several ways:

- Our efforts this past year have resulted in the report devoting itself mainly to the Space Shuttle Program, then to the Space Station Program and to Aeronautics.

- Three major subjects make up the Space Shuttle section: management, systems and operations, safety/reliability/quality assurance.

- NASA has responded to our January 1986 annual report in greater detail than before with circumstances dictating three separate letters from the NASA Administrator: first, covering aeronautics and aircraft operations; second, covering pressure suits, Space Station and space debris; and third, covering the Space Transportation System. These are found in the Appendices.

B. Role of the Aerospace Safety Advisory Panel (The "Panel")

The Aerospace Safety Advisory Panel was established in the aftermath of the Apollo Command and Service Module spacecraft fire January 27, 1967, at Kennedy Space Center. Shortly thereafter the Congress enacted legislation which established the Panel as a senior advisory committee to NASA and to the Congress.

The breadth and depth of the Panel's activities have been defined, refined and redefined since its inception. The Panel's charter is to conduct reviews of NASA and its contractors management and programmatic activities with regard to the safe conduct of their operations, and to advise the NASA Administrator and senior management, and the Congress of Panel findings and recommendations for their consideration and for their guidance.

C. Overview of Panel Activites During CY 1986

The Panel has three parallel streams of effort:

- o Factfinding activities conducted by Panel personnel covering significant facets of the Space Transportation System, Space Station, and Aeronautics.

- o Special tasks in direct support of the Administrator, for instance, support of those actions being taken by NASA to implement the Presidential Commission recommendations, NASA's response to the Congressional report of the House Committee on Science and Technology.

- o Independent oversight groups such as the National Research Council "Panel on Technical Evaluation of NASA's Proposed Redesign of Space Shuttle Solid Rocket Boosters." Aerospace Safety Advisory Panel member, Melvin Stone, participates as our representative and independent observer. The NRC "Post-Challenger Assessment of Space Shuttle Flight Rates and Utilization" had Panel member Norman R. Parmet as a member of this group which issued its report in October 1986. The NASA Administrator requested NRC to form a panel "Space Shuttle Criticality Review and Hazard Analysis Audit" to respond to another Presidential Commission recommendation. Aerospace Safety Advisory Panel members Norman R. Parmet and Gerard W. Elverum, Jr. are full time members.

The Aerospace Safety Advisory Panel factfinding sessions during Calendar Year 1986 numbered 49, and in addition, numerous ones were associated with the above NRC panels. There were a number of sessions before both the U.S. House and Senate.

In a departure from the Panel's normal factfinding, while at KSC in August and December 1986, a six-man team personally interviewed 48 technicians and quality control personnel doing "hands-on" work for the Shuttle Processing Contractors. The results of this are noted in appropriate sections of this annual report.

II. SPACE SHUTTLE MANAGEMENT

A. Background

In recent annual reports, the Panel has expressed concerns and made recommendations relating to management and organization of the Space Shuttle program. In the 1984 annual report, for example, the Panel discussed the heavy launch processing burden associated with each mission. We cautioned NASA management to avoid advertising the Shuttle as being "operational" in the airline sense "when it clearly isn't." We observed that, in the Panel's opinion, such routine operations would not likely be achieved for 5 to 10 years and NASA should focus on improving the Shuttle's reliability, maintainability, safety, and the allowable flight envelope.

Last year we noted some progress in the Shuttle Processing Contractor's (SPC) handling of the burden of preparing the Shuttle for individual missions. But we also pointed out that problems associated with unplanned vehicle modifications, unexpected anomalies, shortage of spare parts, a generally underfunded logistics program, shortage of qualified technicians, heavy paperwork burden, lack of hardware reliability, and internal planning and communication problems would necessarily limit the flight rate for the foreseeable future. We expressed the view that NASA's goal of 18 to 24 flights per year was not within reach at present and that 12 to 15 per year was the most NASA could hope to achieve. The Panel believed that an "operational" Space Shuttle program was still many years in the future.

Many of these same concerns were raised by the Presidential Commission in the aftermath of the Challenger accident and a number of recommendations dealing with organization and management problems were made. Since then, NASA has made resolution of these problems a high priority. The Administrator appointed General Sam Phillips and his team to review NASA's entire organizational structure. Astronaut Robert Crippen led a study of how to improve the Space Shuttle's program management and internal communications. In November 1986 NASA announced an interim office of space flight management structure. This was finalized with an organizational structure with key personnel assignments announced in February 1987.

The Panel's current observations necessarily take into account these continuing efforts by NASA to respond constructively to the Rogers Commission and to build an organization that can sustain the Space Transportation System with safety and reliability into the next century.

B. Organization

In the past the Panel has urged formation of an entity within NASA charged with full responsibility and authority for Space Shuttle operations. We have urged a stronger leadership role by NASA Headquarters in directing and bringing together the work of the NASA centers. Panel members have commented on what appeared to be a lack of discipline in following internal management instructions and a failure by top management to insist that established procedures be followed. As a result, communication breakdowns and confusion over priorities in the overall Space Shuttle program have occurred. In the opinion of Panel members, NASA's characteristic dedication to excellence as a key ingredient in achieving effective management was being subordinated in some cases to concerns over institutional roles and priorities, i.e., "turf." The extent of organizational change required to fix these breakdowns has been a topic of discussion within the Panel. Since the Challenger accident, we have thought a great deal about these problems and have further refined our views.

The Panel emphasizes that in any management structure responsibility and authority must be clearly identified and delegated. During recent years, NASA has not done this adequately and performance has suffered.

Business management systems are generally self-policed or controlled by the net profit figure. This is a sensitive, effective control system for costs but it is not particularly effective or even desirable for other matters such as maximizing system safety. As a result, we conclude that monetary/financial controls are not appropriate for NASA to use as the principal management control system for the Shuttle. In addition, such financial-based controls do not work well in a bureaucratic system such as the Federal Government. Yearly budgets are politically impacted and must be observed, but this constrains the rate at which the work can be accomplished and can limit the scope of a project.

During the years after Apollo, NASA matured into a more traditional bureaucracy with the attendant problems of self-interest and status quo, and the character and motivation of its managers changed in subtle ways. The program was still important, but more and more attention was paid to the means. Turf battles ensued and communications suffered. Management instructions were not followed in a disciplined manner. In view of this reality, we conclude that you cannot solve this problem simply by changing NASA's Shuttle organization. A key ingredient of success at this time must be a return to the program orientation that was responsible for the earlier successes within the NASA management structure.

The task is no less important and not all that different from the earlier task, and in some ways is more crucial because until the Shuttle can be operated effectively, NASA cannot develop its Space Station. We advisedly say "effective," not "routine" operation. It will be a very long time, if ever, before the Shuttle operation is routine.

Findings and Recommendations:

a. The Panel finds the recent reorganization of Space Shuttle management by creating a Space Transportation Systems (STS) Director, reporting to the Associate Administrator for Space Flight, operating out of Headquarters, and supported by a Deputy Director for STS program matters and a Deputy Director for STS operations is a positive step. The Panel recommends that a priority objective of the new management team must be to determine the correctness of NASA's management instructions, to enforce such instructions, and to define clearly the responsibilities and authority of the NASA Centers--principally JSC, MSFC, and KSC--associated with the STS program. A focus on program success, rather than Center dominance, must be achieved. A willingness of all NASA Centers to pull together, to subordinate parochial interests, and to help each other is absolutely crucial if the Space Shuttle program is to succeed.

b. The Panel finds the problem of worker morale, especially at KSC, is of special concern. This is a classic problem of organizational and inspirational leadership that cannot be solved simply by changing institutional structures. The Panel recommends that NASA's top management, including the Administrator, Associate Administrator for Space Flight, the STS Director, and the Center Directors, take the lead in recapturing or rebuilding a spirit of mutual respect and trust at all levels.

c. The Panel notes that recapturing NASA's self-confidence in managing the Shuttle program is crucial to success and requires NASA's leadership to keep in perspective the activities of the many advisory groups, task forces, and panels that have been created in the aftermath of the Challenger accident. NASA has the ultimate responsibility and authority to manage the National Space Transportation System after giving appropriate consideration to the findings and recommendations of oversight groups. The individuals involved in these review panels, as well as Members of Congress, should recognize that excessive reliance by NASA management on external and internal review groups runs the real risk of destroying NASA's initiative and self-confidence, key elements of success in any human endeavor.

C. Research and Development vs. Operational Status

In 1984, the Panel noted in its annual report that ". . . continuing use of the term 'operational' simply compounds the unique management challenge of guiding the STS through this period of 'developmental evolution.'" The Panel stressed the importance of upgrading the safety and reliability of many of the Space Shuttle's critical systems (e.g., SSME, orbiter structure, avionics, and brakes) and of recognizing that this continuing process of change and improvement would require the discipline and caution of a developmental, as opposed to "operational," program. In the aftermath of the Challenger accident, and taking into account the extensive redesigns and investigations underway, the developmental character of the STS is now clearly accepted by NASA and its contractors. It is still the Panel's view that the Space Shuttle is not likely to achieve operational status in the airline sense.

At the same time, however, NASA must guard against an exaggerated response to this renewed focus on Space Shuttle development. There are activities associated with launch processing, in particular, where achievement of more routine and predictable operations would enhance safety and reliability. For example, a proliferation of data systems still exists with roughly two dozen containing Shuttle data. This complicates development of centralized management information around which a more coherent operation--communication, scheduling, goals, performance, motivation, human resources--can be developed by the Shuttle Processing Contractor.

Findings and Recommendations:

a. NASA needs to recognize that the Space Shuttle is a system with both developmental and operational characteristics. To emphasize either characteristic at the expense of the other is likely to miss key elements of the space shuttle management challenge.

b. Transfer of a part of the Space Transportation System (Orbiter) logistics responsibility from JSC to KSC must be supported with adequate budgets to build a sufficient inventory of spare parts and an upgrading of Line Replaceable Units (LRUs), linked to a capability for timely refurbishment, to eliminate cannibalization of parts from other orbiters and to support orderly launch processing operations.

c. Based on the Panel's reviews of the launch processing activities at KSC, particularly flight critical items, the Panel recommends that those elements of sustaining engineering that are directly related to launch processing should be the responsibility of the launch operations center (KSC). These include the evaluation of launch base test data, generation and maintenance of test and launch procedures, logistics engineering, quick-look launch phase flight data analyses, design changes to GSE and launch facilities, and troubleshooting of hardware. Elements of sustaining engineering that require detailed knowledge of the design and development history of airborne hardware should remain with the design centers and their contractors as NASA now contemplates.

d. NASA, in collaboration with the Shuttle Processing Contractor, should make a concerted push to achieve greater consolidation and upgrading of STS information systems, particularly those related to configuration management and launch procedures. For example, the Problem Reporting and Corrective Action System (PRACA) is not programmed to identify big problems and trends in a timely manner. An improvement in management information will contribute directly to more reliable and predictable launch processing.

D. Human Resources

As with most undertakings, the quality of NASA's human resources in managing the Space Shuttle program will be the single most important factor in determining its ultimate success or failure. Specifically, in view of the opportunity for and potential consequences of human error in Space Shuttle processing, management of employees at KSC by the Shuttle Processing Contractor (SPC) and NASA is of particular concern to the Panel. It would appear that these human resources were stretched excessively prior to the Challenger accident.

It has been reported to the Panel that in August 1985--with SPC employment at 6,100--the overtime rate at KSC was running 10 to 15 percent, with much higher rates in certain critical areas, such as the Orbiter Processing Facility, Pad, Launch Control Center, and Facility Operations and Management. To accommodate the acknowledged schedule pressures, the SPC and NASA were forced to rely on extreme efforts by many key workers, regardless of personal considerations. Workers have told the Panel of considerable internal pressures to work heavy overtime schedules. The Panel has found no evidence of a "safety valve" to balance pressures on the KSC workforce with pressures to maintain a launch schedule. Once the flight rate picks up, the Panel is concerned that reliance on the human endurance of SPC and NASA personnel at KSC may again become excessive.

NASA shares the problem of inadequate salary levels with many other Federal agencies. A program of the technical and management challenges of the Space Shuttle requires the best talent in the Nation if safe and efficient operations are to be achieved. Increasingly, the best often will not work for the salaries that the Federal Government can offer. This fact was clearly confirmed by the recent recommendations of the

Quadrennial Commission on Federal Pay that sought to reduce the 40-percent erosion in top management salaries that has occurred since 1969. Increases as high as 80 percent were proposed by the Quadrennial Commission. The President, however, proposed much smaller increases in the 2-4 percent range that will do little, if anything, to close the salary gap. At this writing it is not known what action, if any, Congress will take in response to the President's recommendations.

As a consequence of this apparent failure to solve the salary problem, NASA, along with many other Federal agencies, will continue to lose key senior managers and will find it difficult to recruit and retain senior personnel from among "the best." This steady erosion of management and engineering talent will make it increasingly difficult for NASA to operate the Space Shuttle in a safe and efficient manner.

Findings and Recommendations:

a. The Panel finds that recent layoffs by the Shuttle Processing Contractor of a large number of workers at KSC to accommodate the STS standdown have lost skilled employees who will be needed in 1987 as preparations intensify for a resumption of Space Shuttle launches. The Panel recommends that the Shuttle Processing Contractor should identify these losses and begin now locating, recruiting, training and retraining the necessary persons with the skills to support all aspects of these preparations, including modifications to the Orbiter and other STS systems that will be identified by ongoing NASA reviews.

b. The Panel finds that uncertainty among Shuttle Processing Contractor workers at KSC as to job security has undermined morale and other management efforts to improve communication and worker participation in launch processing decisions. It is recommended that top Shuttle Processing Contractor and NASA management should personally act to eliminate this uncertainty by dispelling rumors when they arise and leveling with workers as to their future job prospects.

c. The Shuttle Processing Contractor is expanding training opportunities for workers but often this training is not focused on meeting the needs of individual workers. Training opportunities need to be linked more explicitly to expanding worker skills to permit longer term career progression.

d. The Panel finds there still appears to be some difficulties in communication between top Shuttle Processing Contractor and NASA managers with floor supervisors and workers. The paperwork burden remains heavy. Instructions regarding specific processing operations are often inaccurate or incomplete, leading to inefficient scheduling and potentially to safety problems. It is recommended that top managers need to communicate more directly with workers involved in launch processing to provide a clear sense of mission and direction, as well as to benefit from employee initiatives and suggestions.

e. NASA and the Shuttle Processing Contractor need to create a system/procedure that will prevent a recurrence of the condition that developed in 1985 where human resources at KSC were excessively stretched due to schedule pressures.

f. NASA top management should document the growing problem of recruiting and retaining talented engineers and managers due to inadequate Federal salaries. The Panel stands ready to review these data and make appropriate recommendations to the Office of Management and Budget and the Congress.

E. Schedule vs. Budget

Panel members have believed for some time that the Space Shuttle program has been underfunded and that these shortfalls, in turn, contributed to a Space Transportation System that was incapable of meeting the launch schedule NASA projected prior to the Challenger accident. The present review of Failure Modes and Effects Analysis (FMEAs) and Critical Items List (CILs) will likely generate a number of modifications to the Space Transportation System that will have to be accomplished prior to resuming a flight schedule. It is essential that budgetary concerns not unduly limit the designs and modifications that are needed from a safety and reliability perspective. If funds are not available to accomplish this work due to budgetary ceilings or other fiscal limits, the only acceptable alternative is to stretch out the schedule.

Findings and Recommendations:

a. The Panel, in an independent review, concurs with the National Research Council Panel conclusions on Space Shuttle Flight Rates and Utilization, i.e., an upper limit of 8-10 flights per year with a three orbiter fleet and 11-13 with a four orbiter fleet. These projections are based on a number of optimistic assumptions that involve adequate funding resources and the absence of any new major development problems. If these assumptions are not borne out, the flight rates must be reduced.

b. NASA should no longer expect that "heroic" performance by its workers and its contractors can compensate for funding shortfalls. What is needed today is the courage to promise no more than can reasonably be expected given the dollars and people available.

III. SPACE SHUTTLE SYSTEMS

The Panel has continued its process of reviewing all elements of the Space Shuttle systems and operations. Since the Challenger accident, all these systems have been the subject of reviews by both internal NASA and external groups. The objective of this process is to enhance the safety of flight by discovering weaknesses in design or operation that may have lingered or not been discovered and to devise and implement appropriate corrective action. The Panel is participating in these efforts in a variety of ways. These include having individual members serve on several of the oversight committees of the NRC such as the Solid Rocket Booster Redesign panel and by factfinding meetings with the contractor organizations and NASA Centers responsible for elements of the Space Shuttle.

In the following sections the results of these activities are described and recommendations are provided.

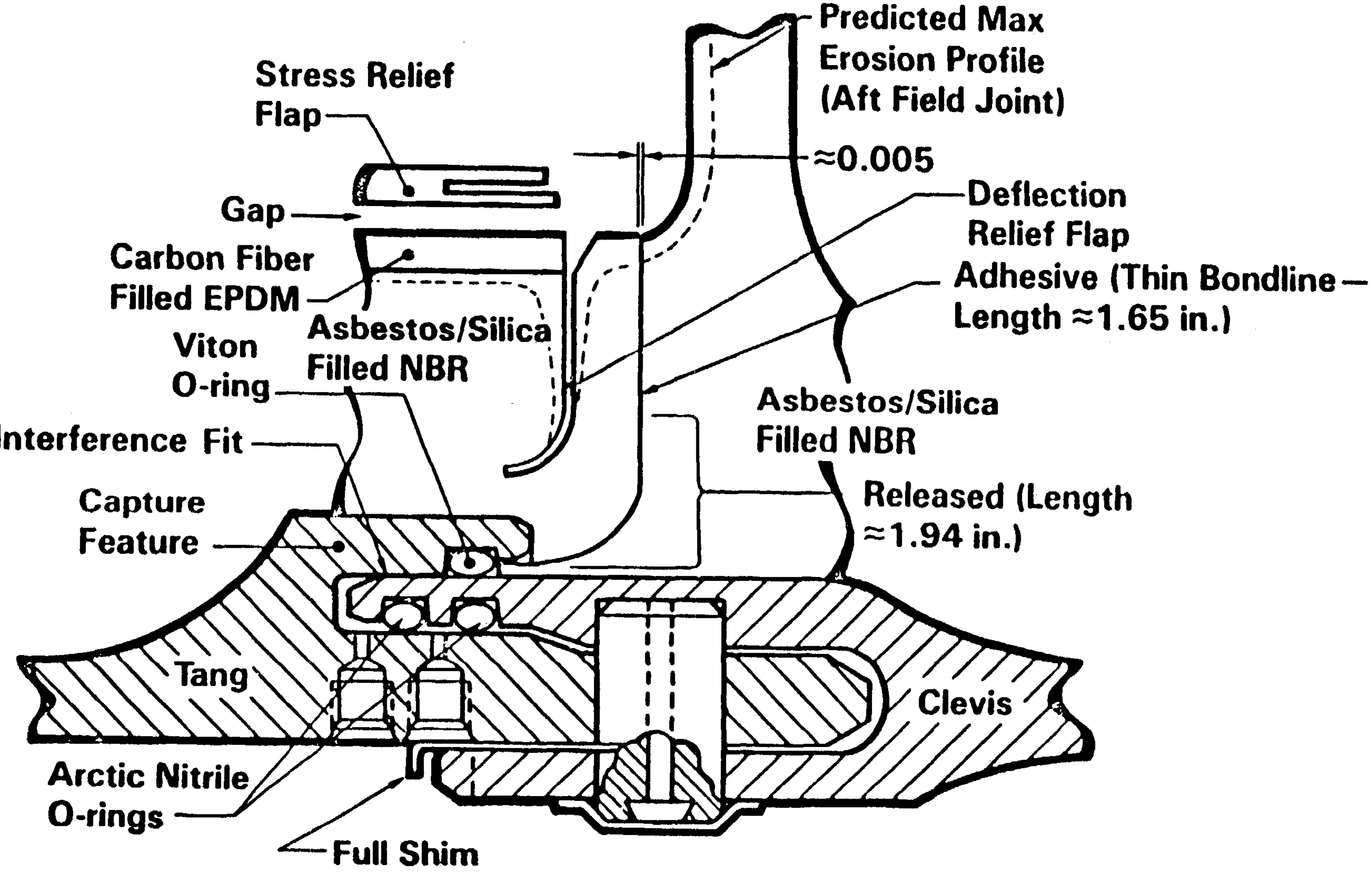
A. Solid Rocket Booster (SRB)

A representative of the Panel is participating in the meetings of the National Research Council (NRC) Panel on SRB Redesign. The following observations are made, based on the information provided at these meetings and additional information brought to the attention of the Aerospace Safety Advisory Panel.

Field Joints: NASA has decided to proceed with a redesign effort for the field joints that make use of 72 existing steel case forgings. This approach entails more risk of not achieving design objectives than would a more sophisticated approach that would offer the possibility of a higher margin of safety. Such an alternate design would, however, require new forgings and would cause a delay of 3 to 5 years in the resumption of Shuttle flights. Such a prolonged delay could result in a loss of national support for the space program. Also, the delay could

CASE FIELD JOINT

Field Joint Baseline Design



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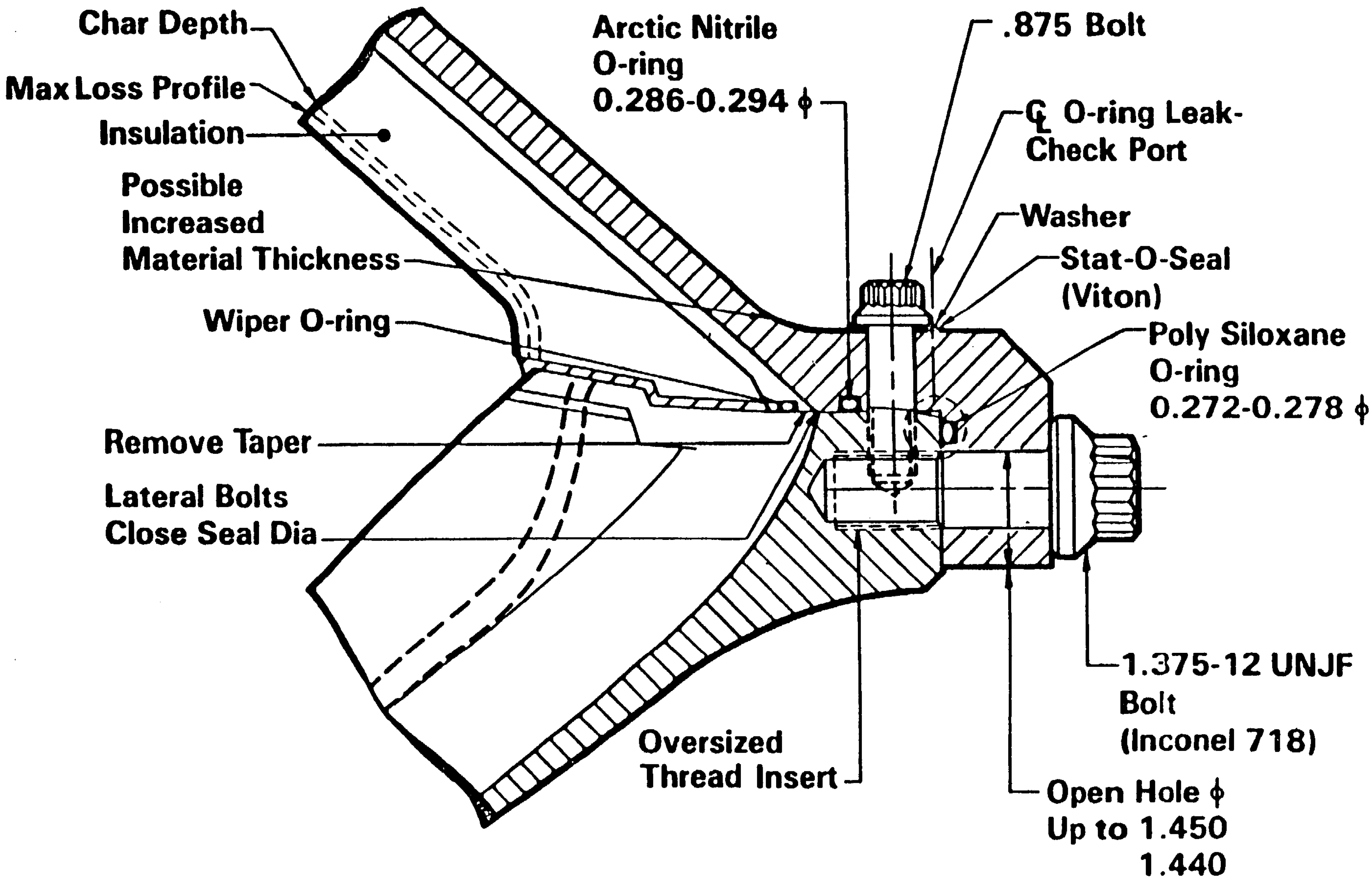
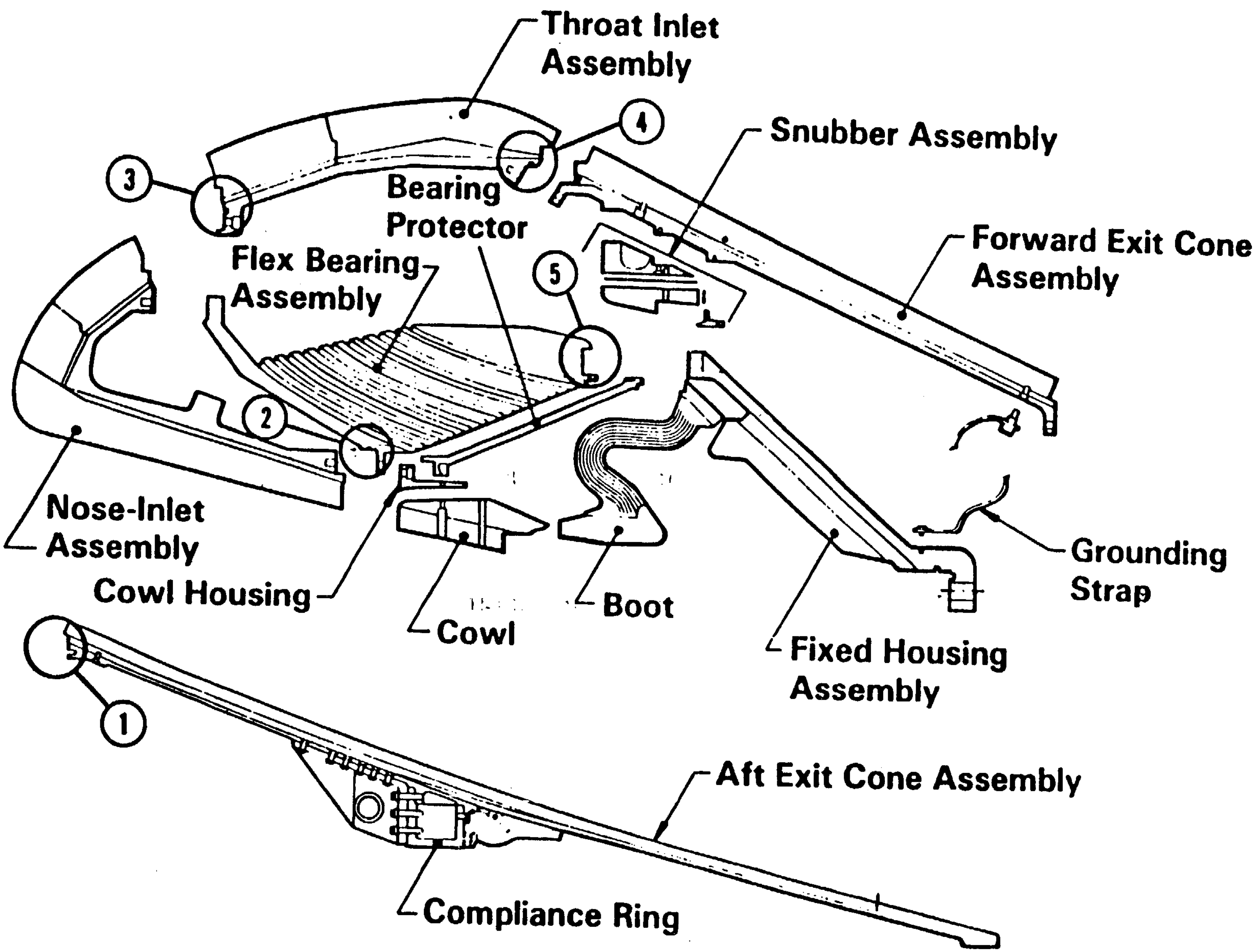
SRM NOZZLE RECOVERY REDESIGN

Case-to-Nozzle Baseline Joint Configuration



SRM NOZZLE RECOVERY REDESIGN



place the United States further behind foreign competition in manned space flight.

Case to Case Joint: The baseline field joint redesign chosen includes an interference-fit capture feature to minimize gap opening that results from joint rotation; three "O"-ring seals with two intervening test ports; improved unvented (bonded) insulation joint configuration to prevent hot gases from reaching the seals; larger seal gland widths to allow axial movement; and a joint heater to control temperature at the seals. Seal materials with improved resiliency and grease compatibility may eliminate the need for joint heaters.

In the baseline design, the unvented insulation at the segment juncture is bonded together. This sealed insulation may be subject to local vent holes which can make it difficult to test under the "worst-case-leak" condition. In addition, it would be difficult to disassemble the segments without damage to the insulation at the joints. The alternate "vented" labyrinth design for this interface between segment insulation has been eliminated due to problems surfaced during thermal calculations. Additional unvented designs with various bonded insulation joints are being pursued.

These configurations will be tested in sub-scale and full-scale hot-firing tests.

Tests have been successfully performed on removable composite ring overwraps with aluminum wedges and tensioning bolts on the existing steel cases adjacent to the field joints. This concept is being fully evaluated as to its effectiveness in reducing field joint rotation in the Engineering Test Motor (ETM) static test using four existing steel case segments.

In addition to the designs just described, NASA is pursuing other field joint redesigns (block II) that may enhance the safety of the SRB for the long term.

Nozzle-to-Case Joint: The redesign of this joint incorporates 100 radial bolts, each with a "Stat-O-Seal" under its head. The bolts are intended to reduce the relative motion between the housing and the aft dome. The new design also includes a third (wiper) seal and a second test port as well as circumferential flow baffles in the insulation.

The addition of the bolts adds multiple potential leak paths and residual stresses in the fixed housing that can reduce the reliability of the joint. The wiper seal bears on insulation rather than on metal. This could limit the pressure that can be employed during leak testing of the assembly.

There are a number of unresolved design questions at this time. Among them are the possibility of hot gas jet impingement or circumferential flow of such gas that could result from an insulation debond, and the ability to disassemble the nozzle from the case without damage to the insulation. Two alternate designs are being considered. One incorporates a metal thermaloc U-seal which maintains contact with the nozzle fixed housing and case aft dome during pressurization. The other concept is to insulate over the case-to-nozzle joint making it a factory joint. This design requires a new "field type" joint in the aft segment case and a redesign of the aft propellant grain. Other contractors have proposed a design wherein joint rotation acts to close the joint against the seal but, unfortunately, this approach probably requires a new forging with attendant schedule impact.

Nozzle System: The existing nozzle seals have performed adequately to date. The new design requirement for redundant and verifiable seals has, however, resulted in a complete redesign of all these seals. All such nozzle internal joints (there are five) are being revised to contain two seals with an intervening seal test port. All of these joints act to close the joint under operating load conditions except for the "number 5" joint which acts to close the inboard seal and open the outboard seal in operation.

In addition to internal nozzle joint seal design changes, the ply lay-up angles of the ablator material on the several rings of the nozzle structure are being changed to reduce, if not eliminate, the pocketing erosion that has been experienced in the past. The cure cycle for the graphite composite material employed may have to be changed in order to limit erosion and charring.

The changes being made are many and complex and to validate their suitability requires full-scale, full-duration, hot-firing tests. The number of such tests required to establish confidence in the reliability of these changes will be large and is yet to be established.

Thus, the categorical application of the requirement that all seals be redundant and verifiable to all SRB joints may affect cost, schedule, and inspection procedures and may also reduce inherent reliability.

Igniter System: The thickness of the igniter aft dome case will be increased to eliminate a negative margin of safety. This redesign is the only change that has been deemed mandatory for first reflight by NASA.

In the past, the igniter joint has exhibited primary seal erosion and blow-by during the full-scale hot-firings. Test should be made to identify the joint leak paths so corrective action can be taken.

Verification of Insulation Bondline Integrity: Major improvements in inspection techniques and procedures are required in order to be able to verify the integrity of the insulation bondline with confidence. The use of new non-destructive evaluation techniques (NDE) to detect a defective bond between insulation and case before propellant casting and prior to final stacking of the segments must be pursued aggressively.

General: The Panel is of the opinion that the redesigned joint is an improvement over the original and can result in a safe structure. Mating, demating, and re-use of the baseline configuration may prove to be a problem, however. Proof of the suitability of the redesign depends critically on achieving satisfactory results from a thorough, carefully planned, conducted, and instrumented test program. At present there is not sufficient definition of the development and certification test programs to permit comment as to their adequacy.

Achieving higher safety margins than that possible with the current baseline configuration would likely require something like the "Langley" design (or its equivalent) for the field joints and the "Hercules" design (or its equivalent) for the nozzle-to-case joint wherein the segment joints tend to close as the motor builds up internal pressure.

Horizontal vs. Vertical Firing Tests: In its report, the Presidential Commission on the Challenger Accident recommended that SRB motor firings to certify the redesign duplicate expected flight conditions as closely as possible and that conducting such firings with the SRB in a vertical attitude be given thorough consideration. The testing planned to verify the corrective action taken to remedy the problem encountered by the Titan 34D solid motor will be conducted in a vertical firing attitude using existing Titan test facilities.

NASA has given thorough consideration to the pros and cons of horizontal and vertical firing attitudes. The Panel concurs with NASA that peak loads that simulate extreme conditions on the joints can be applied to the SRB during horizontal attitude test firings. It is extremely difficult, if not impossible, to simulate such loads during vertical attitude test firings. Other parts of the SRB are not sensitive to firing attitude or are unchanged and have demonstrated their flightworthiness during the 24 successful Shuttle flights. Opting for vertical testing of the SRB would entail large added costs and an additional months of schedule time.

The Transient Pressure Test Article (TPTA) provides the means to test the insulation joint seals and the capture feature over a broad range of temperatures, dynamic conditions, and ignition times, repeatedly.

The addition of a second horizontal firing test stand to the program not only adds test capacity, it includes equipment that enables the simulation of flight-type external dynamic loads. This will enhance the validity of the test program results.

It is the opinion of many experts in solid rocket motor design that the number of tests in the preliminary test program is minimal for the scope of the redesign. The Panel notes that it recognizes that there is no way to guarantee that any number of tests can ensure that all possible operating and loading conditions and assembly differences can be encompassed by a finite test program.

Findings and Recommendations

1. SRB Joint Redesigns

The Panel finds that NASA is proceeding with a redesign of the SRB joints that use existing steel cases and forgings. The redesign is a marked improvement over the original joint design but may have a problem with mating, demating, and re-use. The approach selected entails more risk of not being able to achieve design objectives than would one using new forgings that might permit a more sophisticated design but which would delay the first Shuttle flight for 3 to 5 years. Proof of adequacy of the redesign depends strongly on satisfactory results from a thorough test program. The Panel agrees that the baseline case field joint and nozzle-to-case joint redesigns (and their parallel and alternate designs) along with a thorough and rigorous qualification test program can result in a safe structure.

The Panel recommends that a more complete definition of the certification test program be required in order to determine its adequacy. The Panel also recommends that a concerted effort be made to include additional full-scale hot-firing tests in the final test program plan so as to reduce the possibility of undiscovered weaknesses. Further that during the first year of resumed Shuttle flights, the SRBs be heavily instrumented to obtain both structural and performance data and that these data be considered as part of the certification program.

To attain a SRB design with a higher margin of safety for the long-term use with the Shuttle, it is suggested that NASA proceed with the development of the "Langley" design (or its equivalent) for the case field joint and the "Hercules" design (or its equivalent) for the nozzle-to-case joint in an aggressive effort.

2. SRB Test Firing Attitude

The Panel agrees that to check the redesigned SRB joints, peak test loads that simulate extreme conditions can be applied to the SRB when it is in the horizontal attitude. It is extremely difficult to simulate such loading with the SRB in the vertical attitude.

A second horizontal-firing test stand is being added to the program. This added test stand will have the capability for the application of external dynamic loads. It will, of course, also permit an increased rate of testing.

The Panel recommends and agrees with the decision to conduct the hot-firing tests of the SRB in the horizontal attitude. The Panel notes that, despite the array of sub-scale, large diameter, and full-scale tests contemplated, there is no way to ensure that the tests encompass all possible loading conditions and assembly differences. The Panel strongly urges, therefore, that during the first year of resumed STS flights, the SRBs be heavily instrumented to obtain structural and performance data and that these data be considered to be part of the certification program.

B. Orbiter Structural Loads

The current loads/stress analysis cycle (designated ASKA 6.0) will provide analyses of the structure of Orbiters OV-103 and OV-104 and this will be finished by February 1988. There are not sufficient funds in the program budget to provide such an analysis for Orbiter OV-102. This would leave this vehicle with a different basis for the definition of structural capability than the others in the fleet. In addition, funds are not available to provide separate ascent and descent load information or for the updating of pertinent load indicators (strain gauge and redlines) or for the preparation of summary strength and loads/stress reports. The technical community agrees that these tasks should be accomplished.

Because the Space Shuttle will be used at least until the beginning of the next century, there will undoubtedly be a need from time to time to refurbish the vehicles, expand the operating flight envelope, and answer questions regarding the structural adequacy of the vehicles under new conditions. Without the data base provided by the analyses and reports noted above, evaluations like those mentioned cannot be made in a timely manner.

Findings and Recommendations - Orbiter Structural Loads

The Panel finds that no funds have been provided to check Orbiter 102 for the loads/stress analysis (ASKA 6.0) or to check all vehicles for separate ascent and descent loads, update load indicators and redlines, and for the preparations of summary loads/stress and strength reports.

The Panel recommends that NASA provide funding to accomplish these tasks as the information developed is required for decision-making and should be readily available. These tasks should be performed as soon as the loads/stress analyses (ASKA 6.0) are completed.

C. Experimental Verification of Orbiter Flight Loads

For the Space Transportation System flight in early 1986, Orbiter 102 was instrumented with approximately 250 pressure transducers on both upper and lower wing surfaces as well as with a number of strain gauges on the wing structure. This instrumentation was provided to obtain experimental data under flight conditions that would permit the verification of the structural load/stress analyses. It was determined that the pressure transducers read incorrectly (low) because of the roughness of the surface in the vicinity of the islands in the insulating tiles containing the instruments. The pressure transducers are, therefore, not suitable for use in determining wing loads in flight in their present installation. Wind tunnel testing and experimentation with installation techniques are required to determine whether techniques can be devised that will permit pressure data to be used for reliable determination of wing loads in flight.

Until it becomes possible to use pressure data with confidence, verification of analytical loads must rely on data from strain gauges. It is estimated that data derived from at least four flights will be required to correlate strain gauge derived information with the ASKA 6.0 loads/stress analyses. In order to do this with a sufficiently high confidence, Orbiter-102 should undergo a loads calibration test program while the fleet is grounded so that the strain gauges can be accurately calibrated, the instrumentation system "wrung out", and answers to questions regarding the number of gauges employed answered.

Findings and Recommendations - Experimental Verification of Orbiter Flight Loads

The Panel found that data from the pressure gauges installed on vehicle Orbiter-102 cannot be relied upon for predicting wing loads accurately, and therefore data from the installed strain gauges will have to be used to verify the ASKA 6.0 loads/stress analyses. The strain gauges installed on the vehicle have never been calibrated as installed.

The Panel recommends that Orbiter-102 undergo a loads test program to calibrate the strain gauges installed so that flight data from these strain gauges may be used with confidence to obtain wing loads in flight. This testing should be accomplished during the present hiatus in STS flights.

D. Space Shuttle Main Engine (SSME)

As reported in prior years, a multiphase program has been underway to improve the operating margins and/or the time between replacement for many of the critical engine components. This program had focused its resources primarily on what was designated as the Phase II part of the program. The work consisted of specific improvements in various turbo-machinery components and their incorporation into two Phase II engines to be "certified" for operation at 109 percent of rated thrust. One of these engines had completed its certification testing in 1985 and the second engine was in test before the STS 51-L accident.

Following its review of 51-L, the Presidential Commission recommended that NASA reassess its critical items and hazard analyses to ensure that all Criticality 1 items were properly identified and that actions were taken to minimize their risk. This review was initiated throughout NASA and its contractors in March 1986. The NASA strategy for safely returning the Shuttle to flight status included the following:

- All waivers on Criticality 1 and 1R items be revalidated and submitted for new approvals.

- All items for which an acceptable revalidation and waiver could not be justified using more stringent guidelines for adequacy of the retention rationale were to be redesigned and certified for flight.

In response to this NASA direction, a major program was undertaken on the SSME. This program encompassed a number of different areas of effort which, when completed, would provide a basis for defining a modified engine configuration having better margins of safety and an improved validation test program. In addition, a more sophisticated risk assessment methodology would provide criteria for operational constraints which would govern use of modified engines in the return-to-flight program. These constraints might encompass power limitations of only 100 percent of rated power on the first few flights as it might not be possible to provide engines of full margin configuration until a year or two after first flight.

This program was reviewed in considerable detail by propulsion specialist members of the Panel in May, June, October, and November of 1986. The primary elements of the program are listed below.

Element 1: Establishment of a modified engine configuration based on the Phase II certification program and conversion of

Phase I to Phase II engines prior to their next flight use. The new engine configuration must incorporate a number of additional changes to the current Phase II configuration that are necessary to resolve many issues currently identified.

Element 2: A thorough re-do of the Failure Modes and Effect Analysis (FMEAs) and Hazard Analyses and Criticality categorizations of identified failure modes for the Phase II engines. This re-do was carried out by Rocketdyne (the engine contractor) and, separately, by an independent contractor, the Martin-Marietta Company.

Element 3: A thorough review of the Interface Control Documents between the engine and the Orbiter and external tank.

Element 4: A review of all discrepancy reports on the "fleet leader" engines and turbo-machinery and the re-establishment of the engine redline rationale and the launch-commit criteria.

Element 5: A revalidation of the KSC Operating and Maintenance Instructions based on the Phase II engine design and operating constraints, the changes arising from the 51-L reviews, incorporation of all pertinent "unwritten" limits in prior use, and the elimination of prior exceptions and waivers by making the required changes.

Element 6: A review of the Flight Readiness Review and Countdown Decision Making processes with recommendations for improvement to be provided to NASA.

Summary and Assessment of the Program

The engine configuration to be incorporated in the next series of Shuttle flights will be based on the Phase II engines which were being certified for 109-percent of rated thrust. These Phase II engines will incorporate new turbopump component designs developed during the Phase II improvement program carried out in 1984 to 1986. During the course of the Phase II effort, several additional engine hardware issues surfaced that also required resolution. The resulting design modifications will also be incorporated. In addition to such hardware issues that arose from the ongoing engine test program, the 51-L accident led to considerable rethinking of such issues as redlines, instrumentation, and operational constraints. Also, the results of the re-do of FMEA/CIL and hazard analyses in this program identified a number of areas wherein the effect of a given failure mode might be reduced or eliminated by changes in hardware, redlines, software, or inspection procedures. Therefore, the new engine configuration must account for all of these issues in a way that will result in high confidence that Shuttle flights can be resumed safely.

The several issues may be put in the following categories:

1. Those that require changes regardless of the operating flight power level.
2. Those that require additional changes for operation at 104-percent maximum.
3. Those that require additional changes for operation at 109-percent maximum.

In all three categories, acceptable solutions may be either hardware design changes or other techniques such as a new redline, life limit, or inspection procedure. In addition to those changes that are considered mandatory prior to the next flight regardless of thrust level or flight profile, a number of items have been identified that effect additional improvements in margins of safety at given thrust levels or enhanced life cycle limits and, hence, cost effectiveness for LRUs. Some of these changes are under development (albeit very slowly) in the so-called Phase II+ and Precursor programs about which we reported in previous years.

In a session at Rocketdyne in November 1986, the changes required for the next flight were reviewed. As of that date, there were 25 items identified that require resolution and changes to either hardware or operating limits. These items are listed in Table I. Of those listed, the Panel reviewed those marked with an asterisk (*) in considerable depth as they concern the most significant issues to be resolved before the next flight irrespective of the thrust level selected. They can be grouped as follows:

1. High Pressure Turbopump Blade Cracks
2. Bearing Ball Temperatures in the Oxidizer Pumps
3. High Pressure Fuel Turbopump Coolant Liner Buckling

TABLE I

NEXT-FLIGHT CHANGES IN ADDITION TO PHASE II

1. 1st Stage High Pressure Fuel Turbopump (HPFTP) Turbine Lobe Cracks*
2. 2nd Stage HPFTP Turbine Face Cracks*
3. HPFTP Coolant Liner Maximum Pressure*
4. HPFTP 1st Stage Impeller Hub Cracks
5. 1st Stage High Pressure Oxygen Turbopump (HPOTP) Turbine Shank Cracks*
6. HPOTP Bearing Ball Temperature*
7. Low Pressure Oxygen Turbopump (LPOTP) Bearing Ball Temperature*
8. Main Combustion Chamber (MCC) Outlet Neck - Electro-Deposited Nickel (EDNi)*
9. Main Injector Liquid Oxygen Inlet Seam Weld Defects
10. Nozzle Steerhorn Weld Life
11. 4000 Hz Gimbal Bearing Accelerometer Vibration*
12. Fuel Preburner Diffuser Crack
13. Low Pressure Fuel Duct Buckling
14. MCC Liner Leak Control

15. Main Fuel Valve (MFV) Leakage with On-Pad Abort
16. Purge Check-Valve Failure
17. Anti-Flood Valve Leak Detection
18. Fuel Preburner Oxidizer Valve/Oxidizer preburner Oxidizer Valve (FPOV/OPOV) Window Opening
19. High Pressure Fuel Duct Cracking
20. HPFTP Turbine Temperature Sensor Reliability
21. Gaseous Oxygen Control Valve Leakage
22. Controller Delay Line and Diode Block Failures
23. Hydraulic Actuator Servo Coil Redesign
24. Flight Acceleration Safety Cutoff System (FASCOS) Erroneous Vote
25. Baseline Flight Software

<u>High Pressure Turbopump Blade Cracks</u>: NASA assembled a team of 44 specialists from industry, universities, USAF, Rocketdyne, and NASA to analyze the three types of blade cracks observed:

1. HPOTP First Stage Shank Cracks
2. HPFTP First Stage Lobe Cracks
3. HPFTP Second Stage Face Cracks

This team will provide detailed review and evaluation of the design changes currently proposed for solving these blade-life problems. Because these cracks have been observed over a long period of time, considerable work has already been done to provide improved margins and cycle life.

HPOTP 1st Stage Shank Cracks:

- Cracks are caused by high-cycle fatigue
- Cracks initiate at small spots of subsurface carbides and other grain flaws
- Currently planned solution is use of a two-piece damper
- Further improvement in the future may result from the

use of a single-crystal alloy (PW 1480 SC) with the two-piece damper

The two-piece damper is expected to provide a cycle life improvement of about 10-times. It is currently in test with the standard MAR-M-246 material and should be certified for next flight use by October 1987.

HPFTP 1st Stage Firtree Lobe Cracks:

- These cracks are caused and propagated by low-cycle fatigue in the presence of hydrogen where a critical grain flaw porosity exists.
- The cracks can be monitored from one run to the next.
- Considerable structural margin exists even after a crack has propagated significantly. Therefore, they can be inspected for and the turbine replaced before the crack reaches anywhere near a critical depth.
- Several options are under test which will resolve this issue:

  Custom-fitting to reduce strain levels
  Shot-peening to reduce porosity
  Hot-fire wheels to screen out susceptible blades
  Use of PW 1480 SC single crystal blade material.

Whatever combination is finally selected, the safety margin can be expected to be high throughout any given engine duty cycle after inspection. The resolution of the problem is thus more related to life cycle and replacement costs than to safety of operation.

HPFTP 2nd Stage Firtree Face Cracks:

- Similar in cause to the first stage lobe cracks, these second stage turbine blade face cracks in the firtree area are the result of overstrain and initiate at surface carbide spots. They propagate by thermal stress loads and are accelerated by the presence of hydrogen.

- There is a reasonably high probability of initiating these in a blade root (5 percent) and they occur on first mainstage load cycle if they are going to initiate. They tend to be self-arresting but, if run for a sufficient number of duty cycles, can approach critical flaw size.

- Some of the corrective actions for the first stage blades are applicable to these blades and are being tested. These include shot peening, increased radius at the root, addition of a thermal barrier material, and plating. The single crystal material is also a good candidate.

- As with the first stage blades, the cracks arrest on each mainstage cycle. Therefore, conservative replacement criteria can be established that would provide high safety margins on any flight. The corrective design changes have leverage on replacement cycle costs.

Oxidizer Pump Bearing Ball Temperatures: The Phase II pump design with improved whirl margin, damping seals and bearing load sharing has provided greatly increased bearing wear life in tests to date. However, as a result of current studies of critical items and SSME acceptability for flight, a concern has been raised regarding the possibility of ignition of the bearing balls in the high-pressure oxygen environment. Close examination of the balls indicates dark surfaces along the normal run-line circle around the balls. These discolorations indicate potential local microsurface temperatures of the line of up to 1200-1300 degrees F.

Some cases result in dark bearing lines after only one full-power run while others gradually darken over four to six duty cycles. Several changes are planned to reduce the bearing loads and skidding as well as to improve the ball cooling. However, the only real safety issue is a potential for autoignition of the ball surface and a sustained metal combustion zone leading to pump failure and fire. This remote potential is being examined analytically and, to some degree, experimentally. It is the Panel's belief that the results of the experiments will be ambiguous, at best, and that statistical evaluation of the SSME's entire test and flight history can be used to make an adequate risk assessment. Combined with a large amount of other experience in ignition of metals in high-pressure oxidizers and, given the very high thermal diffusivity of a sphere to a line heat source, this SSME history provides a convincing indication of an acceptable configuration having a very low probability of sustained autoignition at least up to the 104-percent power level.

High Pressure Coolant Liner Buckling: This problem has been around for several years and has complex factors involved. First is the range of collapse pressures resulting from configuration variables such as wall thicknesses, weld mismatch, material properties, and actual operating temperature environment. Second is the variation in startup manifold transient pressures resulting from leakage of seals and use of dual pilots. At the bottom line for Phase II pumps, the coolant liner pressures at startup overshoot badly and this gets progressively worse as the seals wear. Many tests show overshoots at values equal to the buckling values for "worst case" configurations. This situation is unacceptable as the term "failure" should be defined, for purposes of risk assessment, as overshoot above those values that would result in a safety factor of 1.4 for the minimum dimension configuration.

The corrective action plan comprises several items:

1. Improved weld quality specifications and inspection techniques.

2. Reduction of nominal coolant liner pressure through re-orificing.

3. Redesign of the static seals' travel capacity to prevent plastic deformation causing current progressive leakage. The seal materials will also be changed to provide higher operating temperature without permanent deformation and protection from hydrogen embrittlement.

These changes and the certification of peak pressure margins of at least 1 1/2 times for the worst-case geometries should provide high confidence in flight safety.

Main Combustion Chamber Coolant Outlet Neck: The structural failure of the coolant outlet neck on engine 2308 in 1985 has led to a detailed re-examination of the specific design and fabrication control for this part. It also raised questions concerning the weld characteristics and inspectability and strength margin criteria for other similar zones in the engine. While tighter control of inspections and X-ray assessments can hope to catch non-fully configured areas in existing and future parts, it appears prudent to modify the outlet design for higher strength and fatigue margins.

The current design in work is based on using an electro-deposited nickel reinforcement layer encompassing all of the neck welds. The operating stress should be reduced by 50 percent. The dynamic stress in the fuel turbine duct region will, however, increase about 40 percent and this must be evaluated carefully, along with all other effects on the rest of the adjacent manifold regions. For the future beyond the next series of flights, a new one-piece machined outlet can provide added simplicity and better configuration control.

4000 Hz Pressure Resonance in Liquid Oxygen (LOX) Inlet Region:

This phenomenon has occurred only rarely in the history of the SSME. Observations on two engines in 1985 gave a more definitive indication of a potential failure mode and has resulted in an in-depth investigation of the causes and potential corrective design changes. The amplitudes of the vibration are very dependent on power level and, of course, the phenomenon became more apparent as a result of operation at 109 to 111-percent thrust. The frequency is independent of power level indicating a structural-hydraulic resonance coupling.

A careful survey of earlier engine data logs indicates that 9 out of 42 engines have exhibited the resonance at levels above 5 g's on the thrust-cone accelerometer.

The issue is not the vibration per se as it is confined to a small region of the engine's head end and, at 4000 Hz, does not propagate to nor stimulate any other significant structure. The concern is the result of a shift in frequency observed in several engines that has been traced to cracking of the splitter vanes in the inlet tee. This, of itself, is also not a safety issue unless the vanes can break off and a piece thereof get into the oxygen region of the main injector and cause distortion or plugging of flow.

The issue can be resolved in several ways. Engines which exhibit this phenomenon do so from the beginning of their life. Thus, they can be screened out and re-built in the inlet region. Although this may be costly, it will be effective. An alternative is to demonstrate that the way in which the vanes are attached to the manifold prohibits any detachment even after the (stress relieving) cracks occur. Thus, no safety issues would exist. Eventually, the vanes could be redesigned to incorporate a less resonance-inducing leading edge shape or, alternatively, the flow region could be otherwise detuned from the 4000 Hz band.

Precursor Program

The work on the Precursor program which, includes a number of significant improvements in engine hardware designed to provide significant improvements in margin above those of the Phase II and II+ programs, were found to be at a literal standstill. The two-duct power head and the wide-throat combustion chamber have been fabricated and an engine partially assembled. Testing of this new configuration is being held in abeyance because of funding limitations and the lack of test stand time availability.

Findings

An extensive re-examination of the design and test history of the SSME was conducted during 1986. The objective of the effort was to identify any safety issues that might have been overlooked in the past and to establish and validate an engine configuration for use in the next series of flights.

The engines planned for the next series of flights will basically be the Phase II engine configuration that was being certified for flight for operation at 109-percent rated thrust during 1985 and 1986. These engines incorporate many of the improved cycle-life turbopump components developed as part of the Phase II improvement program described in the Panel's 1984 and 1985 reports. During the testing in this program several additional issues arose and design modifications to resolve them will be incorporated in the "first flight" engines.

The results of the FMEA re-visit identified a number of areas where changes in hardware, software, redlines, or inspection criteria could reduce the probability or effect of certain failure modes. Such changes will be incorporated in the engines. As of November 1986, 25 such items had been identified. Of these, the more significant ones requiring resolution before flight are High-Pressure Turbopump blade cracks, High Pressure Fuel Turbopump Coolant Liner Buckling, Main Combustion Chamber Coolant Outlet Neck Cracks, and 4000 Hz Vibration phenomenon in the thrust-cone region.

Another issue relating to contact line temperature on the bearing balls in the High Presure Oxygen Turbopump is also receiving much attention.

The engine contractor is making considerable progress in developing a more useful risk assessment and margin validation methodology. This should result in an improved understanding of the safe operating regime of the engine and better control of the critical aspects of the engine configuration.

The Panel was disappointed to find that work on the Precursor (advanced margin) engine hardware is still proceeding very slowly because of limited funds and lack of test stand availability.

Recommendations

The changes described above primarily address hardware reliability, firmer redlines and configuration control and improved hardware cycle life. In only a few instances will there be any significant improvement in margin to failure. The Panel recommends, therefore, that the Phase II engine be constrained to operate at 104-percent rated thrust or less. Furthermore, it must be noted that a significant increase in operating margin of safety can be achieved by operating at 100-percent rated thrust. It would be prudent, therefore, to operate at 100-percent thrust until the Phase II engines have accumulated significant flight operating time so as to provide a meaningful data base.

The Panel recommends that the Two-Duct Hot Gas Manifold and the Large Throat Combustion Chamber be tested and certified as soon as possible. It is the opinion of the Panel that these changes will produce lower stress environments and improved margins at 104-percent and 109-percent thrust levels.

It is also recommended that NASA and its SSME contractor continue the development of improved methods for actually demonstrating critical operating failure mode margins and the more rigorous Risk Assessment analytical procedures. It is suggested that, as part of such procedure, the term "failure" be defined as a violation of any of the governing design criteria for a component rather than as an event such as structural failure or burn-through. By way of illustration, crack growth to the point where a calculated stress margin falls below 1.4X should be called a "failure" rather than when it reaches the "rupture critical flaw size."

E. Shuttle Computer Systems

Among the more complex parts of the Shuttle is its on-board computer system and there is concern that it could be a source of failure in some future Shuttle flight. As part of its overall activity in reviewing safety matters regarding the Shuttle, the ASAP has begun a review of this computer system. Two issues are of principal concern:

1. The configuration of replacement and existing computers to be used in future Shuttle flights.

2. General software development, change, and test procedures used with Shuttle software.

As our study was begun late in the year and it was not possible to contact all relevant parties during 1986, only preliminary observations are available at this point.

Computer Configuration

The current Shuttle computer system uses a set of five computers to operate the vehicle and the experiments on it. Four of the computers are connected in a tri-redundant configuration for high reliability. During critical phases of ascent and re-entry, all four of these computers perform the same operations. If deviations in outputs occur, the offending computer is disabled. In addition, the fifth computer acts as a backup system (making the whole system quad-redundant); it must be invoked manually by the crew and, once so invoked, control cannot be reverted to the primary system.

The hardware in the quad-redundant system has been adequate protection in all flights thus far. The worst actual flight case saw two of the primary computers fail. Once, in a pre-flight test, three of the primary computers failed. The source of each of these failures has been determined and eliminated from all other processors. There has never been a case in which it has been necessary to invoke the backup system.

The computer in use at present in the Shuttle has been obsolete for some time and its limited memory size severely hampers both experiments that people would like to perform during Shuttle flights and the size of flight changes. An upgraded version of the general purpose computer (GPC) has been designed and built. The new GPC is 2.5 times faster than the original, has substantially more (though still somewaht limited) memory, is smaller and uses less power. The original GPC has a mean time between failure (MTBF) of 5,000 hours. The new GPC is projected to be initially delivered with a 6,000 hour MTBF and it is expected that the flight systems will be at 10,000 hours MTBF.

The Problem: The onboard flight computer system will be upgraded using the new computers in late 1988 or early 1989 (corresponding, roughly, to STS-30 or 31). There are two proposals for configuring the new onboard computer system:

1. Use four of the new GPCs for the quad-redundant primary system and one of the original GPCs for the backup, i.e., 4/1.

2. Use the new GPCs for all five computers in the system, i.e., 5/0.

The two alternatives will be designated as the 4/1 and 5/0 designs, respectively. The use of either option involves operating system changes to both the Primary Avionics Software System (PASS) and the Backup Flight System (BFS).

The rationale for the first proposal is that there is considerable experience with the original computer and that by having two different kinds of processors (called "dissimilar redundancy"), the probability of a generic failure that causes loss of a mission is reduced. The arguments for the second are that the first choice forces a spreading of software verification resources among two systems, may complicate the operational procedures used, and may thus actually reduce the reliability of the primary system.

Discussion

The opinions of NASA and Rockwell personnel on the implications of the 4/1 and 5/0 choices vary considerably. The actual implications will depend upon budgetary considerations and testing and design decisions not yet made. There are several important considerations:

1. The ability to quantify the risk protection provided by using dissimilar hardware.

2. The extent and impact of necessary software changes.

3. The impact on software testing procedures.

4. The impact on operational procedures.

5. The ultimate configuration.

6. The relative reliability of the original and new GPCs.

Dissimilar Redundancy: Dissimilar redundancy is accepted by many in the aircraft industry as being an important method of guarding against generic faults. It is used in three operational, three experimental, and seven developmental aircraft types. It is, however, generally agreed that there have not been enough flight hours to verify or disprove its importance. Under the conditions that both the 4/1 and 5/0 designs are operationally equivalent and equally tested and verified, the 4/1 design certainly does provide greater protection (again, it is not possible to determine how much) than the 5/0. It is thus necessary to examine the differences in system operation and the levels of testing possible within cost constraints to try to deduce any difference in risk arising from operational and testing differences.

Extent of Required Software Changes: First, compare the software changes involved in a typical "Operational Increment" (OI): It is important to note that both PASS and BFS must be changed regardless of which option is chosen as it is desired to be able to reconfigure one of the new GPCs to function as a backup system in case of failure of the backup computer system and it is desired to maintain only two sets of code (PASS and BFS) and not three (as would occur if two versions of the BFS were kept). Thus, the basic software changes are the same for either the 4/1 or 5/0 choice. It is also important to note that, once changed, the BFS code will be able to run, unchanged, in either a new or old GPC. As shall be seen, the size changes required to accommodate the new computers are small in comparison to the changes that are normally made during a year's time.

Roughly speaking, the code in the PASS and BFS can be divided into two parts, the kernel code and the application code. The code associated with different applications is typically independent, while most applications make use of the code in the kernel. The system is thus more sensitive to errors in the kernel code.

The kernel code for the PASS requires only a 210-word (out of 104,000 words in the system) change. This code involves two kinds of functions: local delays and synchronization among the processors. On the other hand, operational instructions have involved changes to about 15,000 words of PASS code. Similarly, only 114 halfwords of code in the BFS must be changed, again to manage timing in a machine-independent manner. In this case, the changes only involve initialization code and no run-time code. Up to 7,000 words of BFS code have been changed in an operational instruction. Thus, the size of the operating system code changes to accommodate the computer hardware upgrade is only about 1.5 percent of the size code that has been changed (and tested) in an operational upgrade which occurs, normally, although this 1.5 percent is perhaps more difficult to code than much of the OI code and its affects a greater percentage of the system.

Software Testing: There are two areas in which the 4/1 configuration affects the system negatively and which must, thus, be weighed against the positive benefits of dissimilar redundancy in hardware. The first of these arises from the fact that in a 4/1 configuration, all changes to the BFS software must be tested in both the old and the new GPCs., This testing will occur during the flight software tests performed using the flight simulator in the Shuttle Avionics Integration Laboratory (SAIL). This testing phase is quite extensive and performed prior to every flight to test the software configuration for that specific flight. Thus, duplicate testing would have to be performed for all flights, not