REPORT

OF THE

SSME ASSESSMENT TEAM

JANUARY 1993

National Aeronautics and
Space Administration
Washington, DC 20546

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Washington, D.C.
20546

Reply to Attn of: Q-1

January 1993

The Honorable George E. Brown, Jr.
Chairman
Committee on Science, Space, and Technology
U.S. House of Representatives
Washington, D.C. 20515

Dear Mr. Chairman,

The House of Representatives Committee on Science, Space, and Technology, in its Report No. 102-500, "NASA Multiyear Authorization Act of 1992," requested that the Aerospace Safety Advisory Panel (ASAP) create an independent task force to conduct a thorough assessment of the Space Shuttle Main Engine (SSME). The SSME Assessment Team is pleased to submit the enclosed report, which provides its findings and recommendations.

The Team stands ready to discuss the content of this report at your convenience.

Very Truly Yours,

Walter C. Williams

Walter C. Williams
Chairman
SSME Assessment Team

Enclosure

EXECUTIVE SUMMARY

In response to a request from the House of Representatives Committee on Science, Space, and Technology in its Report No. 102-500 of April 22, 1992, the Aerospace Safety Advisory Panel (ASAP) created an ad hoc task force to conduct a thorough assessment of the Space Shuttle Main Engine (SSME). The membership was drawn mostly from organizations other than ASAP, and this report represents the views of that task force. Its task was to assess the risk that the SSME poses to the safe operation of the Space Shuttle, to identify and evaluate improvements to the engine that would reduce the risk, and to recommend a set of priorities for the implementation of these improvements.

The SSME Assessment Team, as it opted to call itself, convened in mid-1992 and, subsequently, met with and gathered information from all the principal organizations involved in the SSME program. These included the Rocketdyne Division of Rockwell International, the Marshall Space Flight Center of NASA, and the Pratt & Whitney Division of United Technologies Corporation. The information in this report reflects the Program status as of October 1992. From the information received, the Team formed its conclusions and recommendations. Changes in the program status have, of course, occurred since that time; however, they did not affect the Team's conclusions and recommendations.

Background

The constraints on weight, dimensions, and performance, as well as the requirement of reusability, were significant drivers in the design of the SSME. They led to the selection of the staged-combustion engine thermodynamic cycle and system pressures as high as 7,900 psi, about three times as high as earlier rocket engines. The pressure levels and allowable system weight resulted in turbomachinery with unprecedented power-to-weight ratios, as high as 100 horsepower per pound. Weight limitations also led to extensive use of welds and high-strength materials in the structure of the engine. By all accounts, the SSME is a marvel of engineering achievement but fraught with problems resulting from a highly sensitive, interactive cycle and ultra-lightweight design.

The development program had a history replete with problems, not unlike other rocket engine development programs. The original plan to conduct turbopump component-level development tests had to be abandoned because of difficulty in manufacturing components on schedule as well as major failures of component test facilities. As a consequence, the first article was diverted from component- to engine-level tests. The high-pressure turbopumps proved to be the most intractable components and were the cause of many failures, although other components contributed to development difficulties and delays. After the difficulties were assessed, the original objective of certifying the SSME for operation at 109 percent of rated power level (RPL), also called full power level (FPL), was deferred. Instead, certification at RPL became the objective for the first manned orbital flight (FMOF) engine and was ultimately achieved.

A series of three improvement programs followed, ultimately aimed at achieving the original objective of certification at FPL and 55 mission life. Many design changes were incorporated, and the engine achieved certification for operation at 104 percent RPL albeit with many precautionary controls and restrictions such as special inspections and severe service life limitations on many parts. After the Challenger accident, the safety and operating margins of the entire Shuttle system were re-examined and additional changes were incorporated into the SSME. Also, the power-level objective was formally changed to 104 percent RPL with operation at FPL to be employed only in the event of a "contingency abort." The configuration resulting from this effort still required the numerous precautionary controls noted above.

Assessment of Safety

To assess the safety of the SSME, the Team reviewed the results of the most recent Hazard Analysis, Failure Modes and Effects Analysis (FMEA) and resulting Critical Items List (CIL), and Reliability Analyses. In addition, the design and operating margins attributed to engine components were reviewed as well as the methodology of the precautionary controls imposed on the system.

The analyses were thorough and comprehensive. They identified hazards and failure modes and documented the rationales for accepting risks along with controls and precautions being applied to mitigate risks involved for the items on the CIL. Although some parts and components do not meet the specification requirements, operating margins are provided by means of precautions such as service life limits and special inspections. Systems are in place and operating, therefore, to provide assurance that the hardware will not exceed its limits as they are understood.

Reliability analyses of systems that continue to change and evolve are notoriously subject to criticism because they lack statistical and mathematical "purity." Nonetheless, such analyses can provide insight into the order of magnitude of system reliability and its trends with time and hardware improvements. Rocketdyne and MSFC independently performed such analyses using the data base from engine tests and flights. The two organizations employed different mathematical methodologies as well as ground rules for inclusion of data. Remarkably, the results of the two are similar: for a 3-engine cluster, the probability of encountering an engine shutdown (a contained failure) operating at 104 percent RPL is about 1 in 45 flights; the probability of an uncontained (Criticality-1) failure is about 1 in 120 flights. The contained failures will result in the use of an intact abort mode planned for such eventuality so that crew and vehicle will be saved. The consequence of an uncontained failure cannot be predicted, but can easily result in an abort with loss of vehicle or, worse, loss of crew and vehicle. Because the analyses cannot and do not take into account the effects of all the special controls and precautions currently taken with the engines prior to clearing them for flight, the Team believes that the actual single flight reliability of the engine is higher than the numbers would indicate. That consideration, coupled with flight experience, leads the Team to consider that the engine is safe to fly — provided the system of controls is applied vigorously and rigorously.

Proposed Improvements

The foregoing notwithstanding, operating experiences and the continuing occurrence of hardware problems indicate that the SSME is not as rugged as is desired for such a machine. Also, the manpower consumed in executing all the precautions and controls certainly adds substantially to the recurring costs of using the engine. A number of major improvements to the engine, designed to overcome its shortcomings, are in various states of development. They are: single-tube heat exchanger, alternate high-pressure turbopumps, large-throat main combustion chamber, and two-duct powerhead. The Team reviewed the designs and development history and state of each of these components. The designs respond to the known performance, safety, and manufacturing problems of the components they are to replace and, if they achieve their objectives, will greatly enhance engine reliability and safety. Each component has encountered developmental problems that appeared to have been largely overcome at the time of this review. The Team encourages the completion of these developments and their incorporation into the fleet. But because of budgetary and other problems over the course of the years, improvements have been undertaken in a serial fashion, and the current plans for development and certification are not as efficient and coherent as they might be. Detailed consideration should be given to altering the plans so as to effect a "block change" incorporating all these modifications at once.

Conclusions and Recommendations

In summary, the Team considers that it is safe to fly the SSME provided that all special controls are scrupulously followed. The safety and reliability of the engine can be improved substantially by incorporating all of the major changes noted above. These changes will reduce reliance on people and processes for safety and shift its achievement to the inherent ruggedness and operating margins of the hardware. If priorities must be imposed, the consensus of the Team is that, on the basis of safety and reliability impact, the following should prevail:

Priority I: Single-Tube Heat Exchanger
Alternate High-Pressure Oxidizer Turbopump
Large-Throat Main Combustion Chamber

Priority II: Alternate High-Pressure Fuel Turbopump
Two-Duct Powerhead

The changes should be implemented as soon as possible, preferably as a block change rather than as serial changes proposed in current plans. Based on its collective experience, the Team believes that the block change approach would be more economical. However, a detailed study of costs, schedule, and technical aspects of both approaches should be made.

It can be expected that anomalies and new phenomena will continue to occur as operating and test experience is gained. A competent, sustaining engineering function should be maintained to ensure thorough investigation of all such occurrences. Efforts to develop improved fabrication and inspection techniques for the SSME should be continued and encouraged.

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I. INTRODUCTION

In its Report No. 102-500 (see Appendix A), dated April 22, 1992, on the NASA Multiyear Authorization Act of 1992, the House of Representatives Committee on Science, Space, and Technology requested that the Aerospace Safety Advisory Panel (ASAP) create a temporary task force of propulsion experts, including non-ASAP members, to conduct a thorough assessment of the Space Shuttle Main Engine (SSME). This task force was requested to: (1) assess the risk that the SSME poses to the safe operation of the Space Shuttle; (2) identify and evaluate engine improvements that would eliminate or reduce these risks; and (3) recommend a set of priorities for the implementation of these improvements.

Such a group was assembled; its membership is listed in Appendix B. It was co-chaired by individuals affiliated with the ASAP, but the majority of the membership was from other organizations. The group adopted the name "SSME Assessment Team."

During the months of July and August 1992, the Team convened at the Rocketdyne Division of Rockwell International, the designer and manufacturer of the SSME; the Marshall Space Flight Center of NASA, the project management center for the SSME; and the West Palm Beach, Florida, facility of the Pratt & Whitney Division of United Technologies Corporation, designers and manufacturers of alternate high-pressure turbopumps for the SSME. At these meetings, the Team was briefed on the history and status of each organization's participation in the SSME program, their evaluations of the safety and reliability of the engine system (or their parts thereof), and descriptions, status, and evaluations of the hardware improvements on which they were working or had recommended.

Subsequent to the briefings, the Team met to review and discuss its findings and to develop its conclusions and recommendations. From these Team-only sessions, issues and further questions arose that were pursued by individual members and reported to the entire Team. A consensus was agreed upon, and report drafts were written, reviewed, and edited until all members were satisfied with both content and presentation, which reflects the Program status of October 1992.

In the course of the abovementioned process, the Team realized that the recommendations to be made were dependent not only on the technical details and the status of the engine system improvements currently underway or proposed, but also on the planned operational life of the Space Shuttle. In addition, some operational aspects of the Shuttle, in particular abort modes, had to be considered. Any engine improvement that increases its robustness or permits an increase in usable thrust level mitigates the risks associated with aborts. The Team's views were based on the assumptions that the Shuttle would continue in service at its currently planned launch rate beyond the year 2000 and that engine improvements that would act to mitigate or eliminate the need for any abort mode would be considered. These assumptions are implicit in this report.

Section II of the report describes the history of the SSME development and details current deficiencies. Section III provides the findings of the SSME safety assessment, while Section IV presents proposed engine improvements. The SSME Assessment Team's conclusions and recommendations are contained in Sections V and VI, respectively.

The Team would like to acknowledge and express its appreciation for the cooperation and assistance it received from all the organizations and individuals who participated in its activities.

II. BACKGROUND

The Space Shuttle Main Engine (SSME) is the first reusable, computer-controlled, liquid hydrogen/liquid oxygen rocket engine of the 500,000-pound thrust class. The engine is throttleable over the thrust range from 65 to 109 percent of rated power level (RPL) and controlled to start, stop, and maintain a commanded power level and mixture ratio by an electronic controller. Three of these engines, clustered in the aft end of the Space Shuttle Orbiter and supplied with propellants from the External Tank, operate for approximately 8.5 minutes (in parallel, for 2 minutes, with two Solid Rocket Boosters) to launch the Shuttle into orbit. The Shuttle is designed such that any contained engine failure can be safely overcome by employing one of several abort modes. In the event of such an engine failure, some of the abort modes require the two operating engines to run for up to 14 minutes.

The engine system comprises a number of major component assemblies (Figure 1). Among them are: the powerhead, four turbopumps, two preburners, five hydraulically operated main propellant valves, a regeneratively cooled main combustion chamber and nozzle, dual electronic controllers, and a main injector. In addition, there are many fluid lines, ducts, pneumatic valves, and electrical components and wiring. In all, an engine is composed of over 11,000 parts.

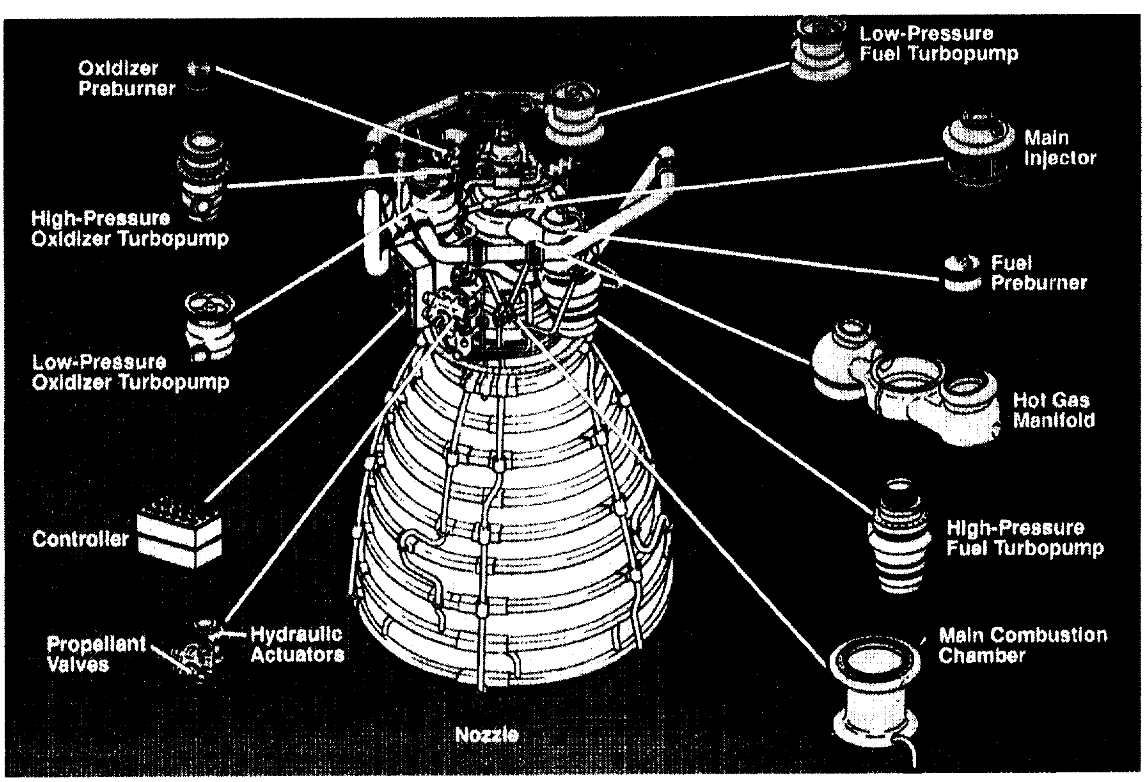

Figure 1. SSME Components

DESIGN DRIVERS

The Shuttle system design requirements of size, weight, performance, and reusability were significant drivers in the engine design choices. Shuttle payload requirements led to the selection of the staged-combustion engine cycle because it would provide the highest Specific Impulse (Isp). In this cycle, combustion of the propellants occurs in two steps. In the first, most of the hydrogen and part of the oxygen from the high-pressure turbopumps are burned in a very fuel-rich mixture in a pair of relatively small combustion chambers called preburners. The products of combustion are ducted to drive the turbines of the two high-pressure turbopumps. After exiting the turbines, these gases pass through the powerhead tubes to the Main Combustion Chamber (MCC) injector, where they are mixed with additional propellants to be burned at very high temperature (approximately 6,000 R) and then expanded through the nozzle to produce thrust. The staged-combustion cycle is inherently highly interactive in that a small change in an adjustable parameter such as a flow or pressure in one part of the system can have dramatic effects throughout the engine.

Size limitations, in combination with the thrust requirement, led to system pressures as high as 7,900 psi. This is a factor of three greater than the system pressure of earlier rocket engines. The pressure level and the allowable system weight resulted in turbomachinery with an unprecedented horsepower-to-weight ratio, as high as 100 horsepower per pound. Weight constraints also drove the engine to employ design choices like: welded instead of bolted joints, the welding of forged parts instead of castings to produce complex parts such as manifolds and volutes, and the use of high-strength materials. Unfortunately, the latter are sensitive to hydrogen and require the use of protective treatment like coatings, gold plating, or weld overlays. In summary, the Shuttle system requirements led to a complex engine design that is difficult to manufacture and maintain.

DEVELOPMENT HISTORY

The SSME development contract was signed in August 1972. Initially, development was to employ the Design Verification Specification (DVS) approach, which requires tests to be performed at the lowest possible assembly level (e.g., component, subsystem, system) to demonstrate that design specifications had been met. In late 1973 and early 1974, numerous problems such as component facility construction delays, weight-driven design changes, and changes to achieve needed structural strength delayed component fabrication and testing. This resulted in a decision to divert the first article of each component from planned tests at the component level to engine-level tests. For example, engine-level testing of the high-pressure turbopumps began 3 months before component-level test began. Subsequently, a number of component test facility failures occurred and this, coupled with a very high rate of hardware attrition in the test program, led to a decision to cancel the comprehensive turbomachinery level test program that had been planned.

The engine-level test program required 50 tests, 11 turbopump replacements, and over 3 months to develop acceptable start and shutdown sequences and reach 50 percent of rated thrust (minimum power level). All effort was then directed towards meeting the specified 109-percent power level [full power level (FPL)] and 55-flight system life. In this process, many problems were encountered; some because of operation under internal conditions more severe than those experienced in previous engine developments. Others were caused by manufacturing defects, operational errors, and the consequences of design assumptions that proved incorrect. Among the more significant problems encountered were: High Pressure Fuel Turbopump (HPFTP) subsynchronous whirl (a rotordynamics phenomenon) and turbine blade failures; High Pressure Oxidizer Turbopump (HPOTP) explosions caused by failures of the inter-propellant seal package and bearing and of the pre-burner and MCC injectors. By April 1981, 19 major engine failures had occurred.

All failures were subjected to detailed failure analysis, and corrective actions were devised and implemented. The elimination of many instruments and their ports and bosses to reduce weight led to difficulty in determining failure causes because data on internal engine conditions were not available. Also, because in the uncontained failures the hardware was consumed by the resulting fire, conclusive evidence of cause could not be obtained. Consequently, multiple changes, identified via failure-tree analyses, were incorporated. Although limited to RPL thrust and severely restricted as to reusability, the SSME was given preliminary certification in March 1980 for the first manned orbital flight (FMOF) of the Shuttle.

FLIGHT CONFIGURATIONS

After the travails noted above, it was decided that the goal of achieving a certified FPL engine should be deferred and that the FMOF configuration engine should be formally certified for RPL. Certification requirements had been evolving and were now formally defined to comprise a series of 13 tests accumulating 5000 seconds of engine operation. The tests included multiple runs covering design-mission profiles, an abort mission profile, and an "overstress" test at 2 percentage points above the specified power level. These tests were to be performed twice on each of two engines, the so-called 2-by-2 rule. This would qualify the engine configuration for five flights. A further requirement for achieving flight clearance was the accumulation of 65,000 seconds of engine operating time. The FMOF configuration completed certification in the Fall of 1980 and was used on the first five Shuttle flights, starting in April 1981.

A series of three improvement programs followed in an attempt to achieve the original development goals. The first, Phase I, sought to increase engine service life and to certify the engine for normal operation at FPL. The many design changes that were incorporated and tested improved service life but did not achieve routine operation at FPL. Instead, the engine was certified at 104 percent RPL, and this basic configuration was used from STS-6 through the Challenger accident. Problems and test failures continued to occur during this period, and more special inspections and part life limits [Deviation Approval Requests (DARs)] had to be imposed to preclude inflight problems.

During this period, a substantial number of major design changes were proposed to improve safety margins and service life, and to achieve FPL for normal operation. However, budget constraints limited the scope of the Phase II improvement program. Particular emphasis was placed on achieving certification at FPL, reducing the many inspection and maintenance requirements (DARs) imposed on the high-pressure turbopumps, and extending their service lives to 5,000 seconds. Other detailed design changes in this program addressed issues such as mitigating high-cycle fatigue problems and reducing temperature spikes during throttle transients.

Progress was being made towards these goals at the time of the Challenger accident. Subsequently, the safety and operating margins were re-examined and the Phase II program was revised. Approximately 40 additional detailed design changes were added, and the power level target was changed to 104 percent RPL with FPL capability in the event of a "contingency abort" (i.e., to avoid a ditching). FPL capability was demonstrated during the certification test program as well as by a short duration [run] at FPL during each flight engine acceptance test. The resulting configuration achieved certification and was dubbed the "return-to-flight" or Phase II engine. Although the engine subsequently accumulated some 90,000 seconds of test time, it still required frequent removal, disassembly, and overhaul of both high-pressure turbopumps (1 to 3 flights), and a large array of DARs remained for the entire engine.

In an attempt to ameliorate the need for frequent turbopump overhaul, a third modification program was initiated in 1988. This was the "10K pump" program, so called because its objective was to certify both turbopumps for 10,000 seconds of service life. The 10K HPFTP achieved a 7-to-8 flight certification in late 1991, was first used in flight in May 1992, and is now being incorporated in the fleet. The 10K HPOTP attempt was less successful; the pump that resulted (P-HPOTP) still requires pump-end replacements every 1 to 3 flights and complete overhaul after 4 to 6 flights.

CURRENT STATUS

The SSME is a highly sensitive machine whose components must be monitored closely to ensure their compatibility and safety. Hundreds of "generic" inspections are contained in the Orbiter Maintenance Requirements Specification Document (OMRSD), all of which require highly skilled, experienced, and dedicated technicians to perform them. In addition, an average of 75 engine-specific inspections and life limitations are required for each engine because of the difficulty in building the parts exactly to drawing requirements. Some of the variations among parts or subassemblies that have been accepted for use have performance effects sufficient to require care and vigilance in the selection of components for assembly into an engine. This process results in the selective assembly of engines.

The foregoing considerations require the expenditure of many man-hours of effort, not only to perform the inspections, overhauls, and requisite acceptance tests, but also to keep and review the records and pedigrees of hundreds of parts to assure the suitability of an engine for flight. Although the engine is classified "reusable," the term cannot and must not be employed as is done with respect to aircraft gas turbine engines.

Known deficiencies have led to steps to achieve confidence in the hardware. Design changes to rectify the problems and to produce more robust hardware have been under continuous development. These development activities have been subject not only to the normal technical problems of any development, but also to the vagaries of budget processes that cause interruptions and discontinuities in the activities.

Despite the reservations that one can have about the flight-worthiness of engines that require such detailed care and attention, they are indeed being used for flight. The question, "Are they safe?," is ever present and is addressed in Section III, Assessment of System Safety.

III. ASSESSMENT OF SYSTEM SAFETY

System safety assessment is a many-faceted process that includes performing Hazard Analyses, Failure Modes and Effects Analyses (FMEA), and Reliability Analyses; developing a Critical Items List (CIL); and examining the design and operating margins of the components. The safety of the Space Shuttle Main Engine (SSME) is continuously addressed by all the organizations involved and by ad hoc groups from time to time. A complete safety re-evaluation of the SSME was conducted after the Challenger accident, and its elements have been subjected to updating as new information became available. The SSME Assessment Team reviewed and evaluated the information resulting from these efforts; its major findings are summarized in this section.

HAZARD ANALYSIS

The Hazard Analysis enumerates all potentially unsafe conditions or events, identifies the potential sources of such conditions, and provides the rationale for the mitigation and/or acceptance of the risk involved. The hazard fault tree in Figure 2 identifies 16 SSME failure modes that could result in loss of crew and/or vehicle due to fire and/or explosion. Seven failure modes are considered controlled through design, inspection and test, or demonstrated reliability. Nine are accepted risks based on analysis and probability of occurrence. Table 1 is illustrative of the reasoning and actions taken to mitigate and control the risks to an acceptable level. The

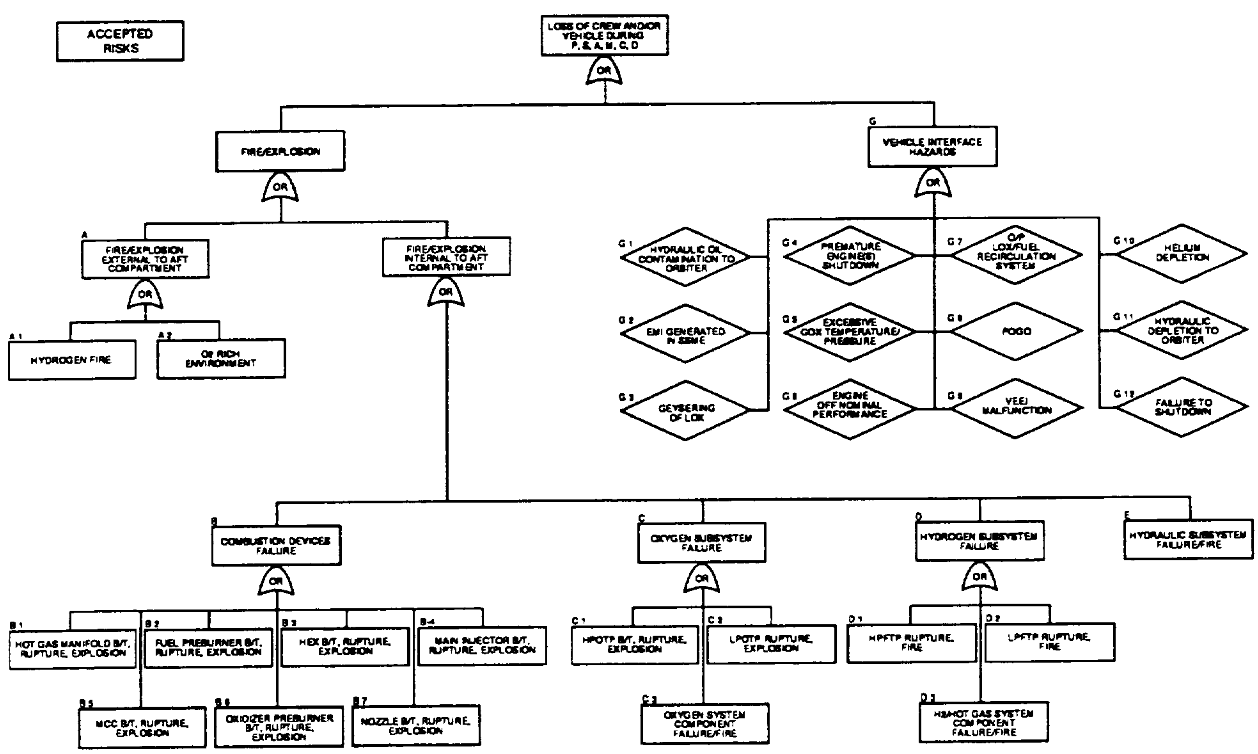

Figure 2. Hazard Fault Tree Example

Table 1. Risk Reduction Actions

Hazard Number	Hazard Title Risk Issue	Risk Reduction Recommendations	Program Action To Reduce Risks
ME-B2	FPB burnthrough, rupture, explosion • POPS during start and cutoff	Reduce the hazard classification from accepted risk to controlled	Based on thermal/dynamic analysis and hot fire history on POPS; the hazard classification for fuel preburner POPS will be reduced to controlled POP data base (1,099 tests, 47 engines) showed no FPB POPS higher than 6,000 Gp-p No FPB Faceplate deformation was ever attributed to a POP Preburner POP issue was briefed to SSRP in meeting no. 3 Changes to the OMRSD DV41AME.010 (new POP criteria, magnitude, and time- frame) have been approved
ME-B3	HEX burnthrough, rupture, explosion • Mechanical damage from foreign objects • Weld/material failure	Develop a single coil heat exchanger design for the SSME that will improve the margin of the flight HEX Reduce material inclusions or stringers	Single tube heat exchanger (ECP-114330) • Design in development phase • Improve tube margin by increasing tube wall from 0.0125 and 0.0265 to a uniform 0.032 thickness ECP 990 requires the use of double vacuum melted ingot to control impurities in the material. Material process has been incorporated Single tube heat exchanger (ECP 11433) eliminated critical weld joints First unit to be installed on Engine 0220 • Testing is scheduled for August 1992 • Single tube heat exchanger is scheduled for STS-68 flight

complete Hazard Analysis contains exhaustive examinations of the hazards present during each of the several phases of engine operation from pre-start to shutdown and, for each phase, addresses the contributions of each subsystem to the hazards of that phase of engine operation and how they are controlled. This analysis was thorough and effective.

FAILURE MODES AND EFFECTS ANALYSIS

The FMEA employs a "bottom-up" approach, in contrast to the "top-down" approach of the Hazard Analysis. It asks, at the lowest levels of each subsystem, "How can this device/part fail and what are the effects and consequences of such a failure on the component and all other interfacing, interacting components?" The consequences of each failure mode identified are classified according to their severity. Failure modes that could lead to loss of crew and/or vehicle fall into the "Criticality-1" (CRIT-1) classification. These items are then collected on a Critical Items List (CIL). The CIL is used as a management tool to focus attention on the mitigation or control of the failure mode via actions such as redesign, use of redundancy, and special inspections or tests.

After the Challenger accident, the Shuttle System FMEA, including the SSME, was performed again under a more stringent set of ground rules and at greater depth than had been used in the original analysis. Table 2 lists the numbers of CRIT-1 items on the original and revised CILs. The changes in the ground rules and depth of analysis

Table 2. Distribution of CRIT-1 Pre- and Post-51L CILs

Subsystem	Current CIL	Pre-51L CIL
Combustion Devices	33	10
Turbo Machinery	39	15
Pneumatic Controls	11	3
Propellant Valves	39	21
Actuators	18	1
Controller/Harnesses	3	0
Igniters/Sensors	23	2
Lines, Ducts, Joints, Orifices	23	21
Totals	189	73

led to the significant increase in CRIT-1 items. The revised CIL led to the introduction of over 100 design, software (S/W), inspection, test, operations, and process changes in the SSME. Table 3 indicates the distribution of these changes among the SSME subsystems. The "top 10" CRIT-1 items of the revised CIL are presented in Table 4, along with the proposed changes and their current status. As changes are incorporated, this living list is updated as the risks are mitigated or eliminated.

Table 3. Distribution of Modifications

Subsystem	Modifications Design	S/W	Process	Ops
Combustion Devices	22	1	7	10
Turbo Machinery	16	0	2	0
Pneumatic Controls	1	1	0	1
Propellant Valves	0	0	1	2
Actuators	3	0	1	1
Controller/Harnesses	8	25	0	4
Igniters/Sensors	4	0	3	1
Lines, Ducts, Joints, Orifices	5	0	1	1
Total	59	27	15	20

RELIABILITY

The FMEA and Hazard analyses identify potential failures. The Reliability analysis determines the probability of failure occurrence. There are two ways to estimate the probability of an engine failure. The first is to determine or estimate the reliability of each component and then combine them mathematically to arrive at an estimated system reliability. No suitable reliability data base exists at the component level for the SSME. Estimating component reliabilities when truly comparable similar components do not exist is, at best, not meaningful and, at worst, misleading. This is the case for the SSME, as no data for components with similar operating conditions can be found on which to base calculations. The second approach is to use and analyze available engine-level test and failure data statistically. This is the approach that has been employed independently by both Rocketdyne and MSFC.

Statistically valid reliability calculations require an extensive data base. Purists can argue, with merit, that the test and flight data on the SSME are limited and, therefore, results of reliability calculations are suspect. Nonetheless, some 62 flight-configuration engines (albeit of differing configurations) have been hot-fired for a cumulative operating time of 462,567 seconds (equivalent to approximately 900 missions) as of the time of this writing. Although these data do not satisfy the conditions required for mathematically pure reliability calculations, they certainly provide a base for developing useful estimates of the range of reliability of the SSME and of reliability trends with time, provided all the assumptions, limitations, and caveats are taken into account.

Table 4. Top 10 FEMA/CIL Components

Rank	Component	Failure Mode	Design/Mfg. Process Improvements	Status	
				Cert.	Flight
1	Heat exchanger	HEX coil fracture or leakage	Single coil HEX eliminates interpropellent welds and increases wall thickness. Simplified assy technique and tooling. State-of-art-tube inspection equipment	Planned FY 93	FY 94
2	High pressure fuel turbopump	Turbine blade structural failure	10K pump improvements; blade pocket and assembly fit checks. Computer tomography inspection	Complete	STS-45
3	High pressure oxidizer turbopump	Turbine piece part structural failure	1st stage disc pilot rib redesign and modified tip seal retainers	Complete	STS-49
			Converted 14 welds to robotic	Complete	STS-45
4	Hot gas system joint G15	Leakage	Added flow recirculation inhibitor and joint effective gap measurement	Complete	STS-34
5	High pressure oxidizer turbopump	Turbine blade structural failure	Modified tip seal retainers and improved damper inspection	Complete	STS-45
6	High pressure oxidizer turbopump	Loss of support, position control, or rotordynamic stability	Improved bearing drying and added weld 3 strain gages	Complete	STS-31
7	Oxidizer preburner oxidizer valve actuator	Fails to respond to position commands	Added improved clearance measurements and functional threshold test	In-process FY 93	FY 94
8	LPFTP discharge duct	Fails to contain hydrogen	Added corrosion inhibitor	Complete	STS-28
			Improved tripod radius inspections	Complete	STS-41R
9	Nozzle assembly	External rupture	Eliminated 18 critical welds on Steerhorn and feedlines	FY 94	TBD
10	High pressure oxidizer turbopump	Loss of axial balancing force	Added improved silver seal bottoming and retainer ring inspections	Complete	STS-45

Rocketdyne Analysis. This reliability analysis used a binomial model for equivalent mission profiles. This approach accounts for the different power levels of operation and treats failures as random and independent. By using a "redesign effectiveness factor" for the changes of reliability effected by implementing design changes subsequent to a failure, the effects of engine configuration changes over time are taken into account. Rocketdyne calculations using the test and flight history of the SSME yield the results shown in Table 5 for a three-engine cluster with an assumed 0.5 redesign effectiveness factor (a conservative assumption). For a typical flight at 104 percent RPL, the calculations indicate that a CRIT-1 failure may be expected every 139 flights and an engine inflight shutdown every 45 flights. The effect of increasing power level above 104 percent RPL is marked. At FPL (109 percent), a CRIT-1 failure can be expected every 20 flights and an inflight shutdown every 8 flights. If a 1.0 design effectiveness factor is assumed (i.e., the failure mechanism is

Table 5. SSME Reliability (3 Engines) With a 0.5 Redesign Effectiveness Factor

Engine Operating Phase	Flights Between Incident	
	SSME Safe Shutdown	CRIT-1 Failure
Liftoff	42	363
Mainstage		
100% RPL	112	254
104% RPL	45	139
109% RPL	8.3	20

fully eliminated), the 104 percent RPL numbers become 336 and 120 for CRIT-1 and shutdown, respectively. The number of flights between these types of failures most probably lies somewhere between these two sets of numbers.

MSFC Analysis. The Marshall Space Flight Center (MSFC) made independent calculations of the reliability of the SSME using the same data base as Rocketdyne, but with slightly different ground rules governing which data to include. MSFC used the U.S. Army Material System Analysis Activity reliability growth model for its calculations. In this model, the data input is the number of failures as a function of cumulative test time. These data are curve-fit to an exponential function that feeds into the reliability calculations. The use of the exponential function to convey reliability growth serves a purpose similar to the redesign effectiveness factor in the Rocketdyne methodology. The MSFC analysis yields 118 as the number of flights between CRIT-1 failures at 104 percent and 48 for a safe engine shutdown. These numbers are roughly comparable to those resulting from the Rocketdyne analysis with a 0.5 effectiveness.

As noted, both types of analyses account for the effects of reliability improvements either by hardware or procedural changes as appropriate. Nonetheless, unanticipated failures continue to occur; some because the changes do not fully eliminate the causal factor(s), others because of incomplete or inexact comprehension of internal loads and environments. Figure 3 shows the engine failures experienced as a function of time. Prior to 1985, testing was conducted at a rate of approximately 33,300 seconds per year. From 1979 to 1985, the mean time between failures was about 8,000 seconds. Starting about 1987, the test rate increased to about 43,000 seconds per year and, for the period from about 1987 to 1990, the mean time between failures increased to about 18,000 seconds, indicating an increase in reliability. Most recently, however, from about 1990 to mid-1992, the mean time between failure dropped to about 9,000 seconds. Thus, although overall experience would indicate that the reliability of the SSME is increasing, it is not possible to predict when failures will occur.

It must be recognized, however, that the abovementioned failures occur on the test stand and include new and rebuilt hardware as well as modified hardware under development. Flight hardware is subject to myriad special inspections, acceptance tests, and servicing between missions. Also, the components and parts are constrained to use well below their demonstrated service life expectancy. Further, redline limits are imposed to minimize the risk of catastrophic failure by shutting down the malfunctioning engine and then employing an abort mode to save crew and vehicle. Some of these controls are described below.

HARDWARE MARGINS AND LIFE LIMITS

The SSME Contract End Item (CEI) specifications stipulate structural design

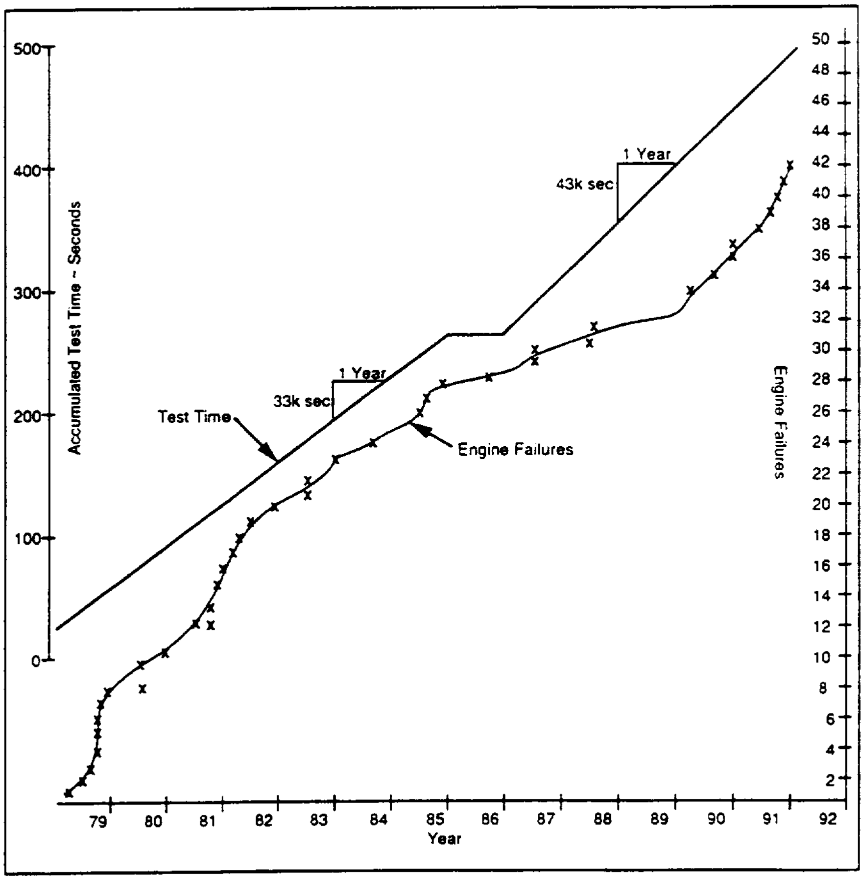

Figure 3. Engine Failure Rate and Accumulated Test Time

criteria, certification test requirements, and fatigue life design criteria. These and other requirements are intended to ensure engine reliability and safety. Originally, the design objective was that the engine would be capable of 55 starts and 27,000 seconds of run time. Recent changes made in the specifications now require 30 starts and 15,000 seconds run time for all components other than high-pressure turbopumps and flexible ducts. The latter must be capable of 20 starts and 10,000 seconds run time. Engineering analysis and component tests are used to establish structural margins of safety and to verify that fatigue life satisfies criteria. However, several engine components do not meet, much less exceed, all the CEI requirements. To ensure that *operating* margins exist, life limits, special inspections, and other criteria and limits are imposed.

Design Margins. Specifications for the design of SSME components require the use of structural factors of safety of 10 percent above yield strength and 40 percent above ultimate strength of the materials employed. Also, life factors for both Low Cycle and High Cycle fatigue properties are stipulated to ensure margin for component life requirements. To account for unavoidable variations in material properties, dimensions, and loads, the design analyses are made using minimum material properties, worst case dimensions, and maximum expected loads. Of course, the designs are only as good as the knowledge of these factors. In 1988, a thorough structural review of the SSME for some 1,735 major parts identified over 250 parts requiring additional analyses or tests. These were performed, and where indicated, design changes were incorporated.

Operating Margins. To ensure the flight safety of components that do not satisfy CEI requirements, additional limits and inspections are placed on them using the DAR procedure. Table 6 presents the current generic life and inspection limits controlled by DAR. These data apply to the entire SSME inventory. In addition to these generic DARs, there are engine-and component-unique DARs, such as shown in Table 7 for engine 2027. Such unique limits are required because of the difficulty of reproducibly manufacturing engine parts with consistent design margins or performance characteristics.

Another method employed to ensure adequate operating margin is the "Fleet Leader" criterion. This criterion stipulates

Table 6. SSME Component Generic DAR Limits

Component	Engine Starts	Accumulated Run Time
HPOTP (Life Limits)		
First Stage Disc	14	-
Pump End Bearings	-	2000 sec
Turbine End Bearings	-	2568 sec
Turbine Bearing Preload Spring	-	3442 EFPL sec
First Stage Blades	21	5000 sec
Second Stage Blades	22	5391
HPOTP (Inspection Limits)		
Second Stage Nozzle	11	-
First Stage Nozzle	14	-
Housing	10	-
Impeller	-	5400 sec
HPFTP (Life Limits)		
First and Second Stage Blades	13	4300 sec
Thermal Shield	17	-
HPFTP (Inspection Limits)		
First and Second Stage Nozzles	15/10	-
Impeller	-	5500 sec
Kel-F Seal	-	5500 sec
Housing	10	-
LPFTP (Inspection Limits)		
Volute	-	3425 EFPL sec
Pressure Sensors (Life Limits)	-	11400 sec
OPOV Seal (Inspection Limit)	Unscheduled Engine Cutoff	1.5-5 sec

EFPL - Equivalent Full Power Level.
* 10k configuration.

Table 7. Engine 2027 Unique Inspection Limits

Nozzle	Dye penetrant inspect aft manifold every test
MCC assembly	Borescope weld 19 after every test
G15 bellows seal	Replace seal after every 2 flights
HPFTP First and second stage discs Housing	Inspect curvic teeth every 11 starts Dye penetrant and eddy current every 30 starts Borescope T/E coolant holes every 10 starts
HPOTP Housing	Inspect at intervals not exceeding 5512 sec Borescope inspect limit to one flight

that a component cannot be used for flight if its accumulated service life exceeds 50 percent of the maximum accumulated operating time or starts of a comparable component, thus providing operating margin.

Finally, operating margin is provided by imposing redlines both on the ground and inflight. These redlines are designed to initiate engine shutdown prior to operation in a manner that could lead to a catastrophic failure. During engine start on the launcher, if any of the redlines is exceeded, the controller will shut down the engine and will not issue the permissives required for Solid Rocket Motor ignition. During flight, if a redline is exceeded, the controller will shut down that engine and the crew will have to fly the appropriate abort mode.

Although the Reliability analyses indicate that the probability of encountering a CRIT-1 failure during ascent is of the order of 1 in 120, or 1 in 45 for an engine shutdown, the data base used for these calculations include both development test runs and certification runs. Also, all special precautions represented by added inspections, more frequent inspections, life limits, and so on serve to increase the actual reliability of the flight unit. The actual reliability cannot be stipulated or stated precisely. *But, as long as all these controls are implemented in an expert, disciplined, and vigilant manner, the engine can be considered safe to fly.*

ABORT OPTIONS

In the event that an engine failure does occur despite all the precautions taken, a final safety feature in the Space Shuttle system — the aborts — can be activated. Some engine failures can be "contained," that is, no debris escapes the engine and the engine is shut down without collateral damage to other Shuttle systems. Other failures may be "uncontained," with debris escaping the engine's confines and probably damaging other systems or engines. The latter is called "catastrophic" as there is a high probability, but no certainty, that it would cause loss of vehicle and crew.

Failure of an SSME during ascent will cause the crew to initiate one of two abort modes depending on when, during ascent, the failure occurs. The modes are: intact aborts in which it is possible to achieve orbit or return vehicle and crew to a pre-selected landing site; or, a contingency abort which provides the opportunity to maintain vehicle integrity and control for inflight crew escape. A contingency abort is usually indicated when a second engine failure occurs; a situation that would require expert piloting.

No abort mode can be executed prior to Solid Rocket Booster separation.

Among the intact abort types are: Abort to Orbit, Abort Once Around, Trans-Atlantic Landing, and Return to Launch Site (RTLS). The names are descriptive of what is entailed except for the RTLS abort, which requires dissipation of propellants, a powered turnaround including flying backward, an atypical jettison of the External Tank, and a landing near the launch site. RTLS is a quite complicated maneuver that requires very skillful piloting and flying through previously unexperienced flight conditions.

IV. PROPOSED IMPROVEMENTS

Operating experiences and the continuing occurrence of hardware problems indicate that the Space Shuttle Main Engine (SSME) in its present configuration does not have the ruggedness that is desired for so critical an element of the Space Shuttle system. It requires continuous expert and disciplined labor to gain the confidence in the hardware needed to commit a set of engines to a flight. In recognition of this situation and with intimate knowledge of the weaknesses of the engine, the SSME Project has, over the years, initiated the development and certification of a number of individual major design changes to the engine. The objectives of these changes are to make the engine more robust (increasing margins); to eliminate, or mitigate to a great extent, the more worrisome of the Criticality-1 (CRIT-1) failure modes; and to improve the ability to manufacture the hardware exactly to print. This would shift engine safety from its current great dependence on people and procedures to inherent and reproducible properties of the hardware. Some of these changes have reached the certification test stage. Others are in earlier stages of development. The candidate improvements are discussed below.

SINGLE-TUBE HEAT EXCHANGER

The current heat exchanger (HEX) (Figure 4), which converts liquid oxygen to gaseous oxygen for pressurizing the External Tank (ET) oxygen tank and the POGO

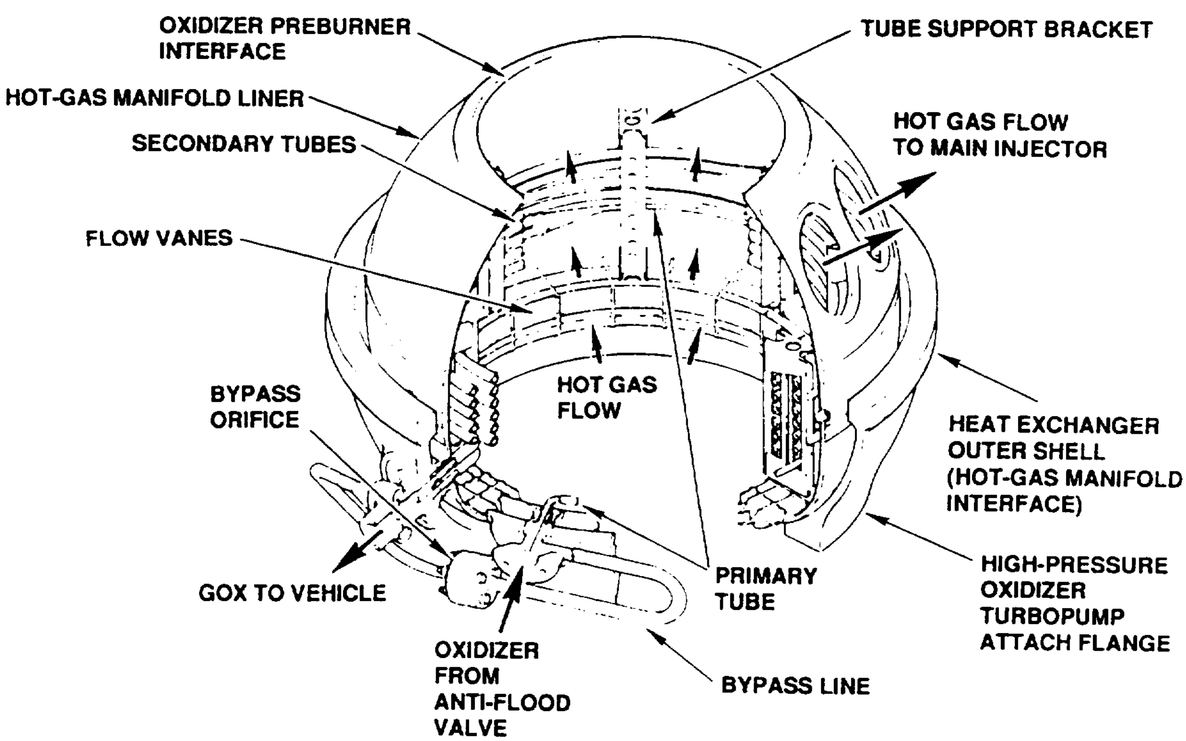

Figure 4. Heat Exchanger Assembly

suppression subsystem, continues to head the list of CRIT-1 components for the SSME. The heat exchanger is located in the oxidizer side of the Hot Gas Manifold (HGM) in the path of turbine exhaust gases from the High Pressure Oxidizer Turbopump (HPOTP) that provide the heat needed to effect the change of state of the liquid oxygen.

Salient features of the current two-tube HEX and the proposed single-tube replacement are shown in Figure 5. The current HEX consists of a primary tube, a bifurcation joint, and two secondary tubes. The source of safety concern is the existence of seven critical welds in the oxygen-containing thin-walled (as thin as 0.0125 inches) tubes that isolate the oxygen from the fuel-rich hot gases. It is difficult to control welding and these welds cannot be fully inspected. Should one of the welds fail, the consequence would be rapid, uncontrolled combustion in the HGM leading to a burnthrough or explosion. The single-tube HEX has no welds exposed to the hot gases, and its tube wall thickness is a much more rugged 0.032 inch. The structural advantages of this design are evident from Table 8. Further, 30 welds were eliminated from the assembly and all remaining welds were designed so that critical flaw sizes can be detected and the welds can be fully inspected.

Such a redesigned HEX had been proposed for a long time; however, the technology to produce the very long (40 feet) jointless tube of the appropriate material has only recently been developed. Incorpo-

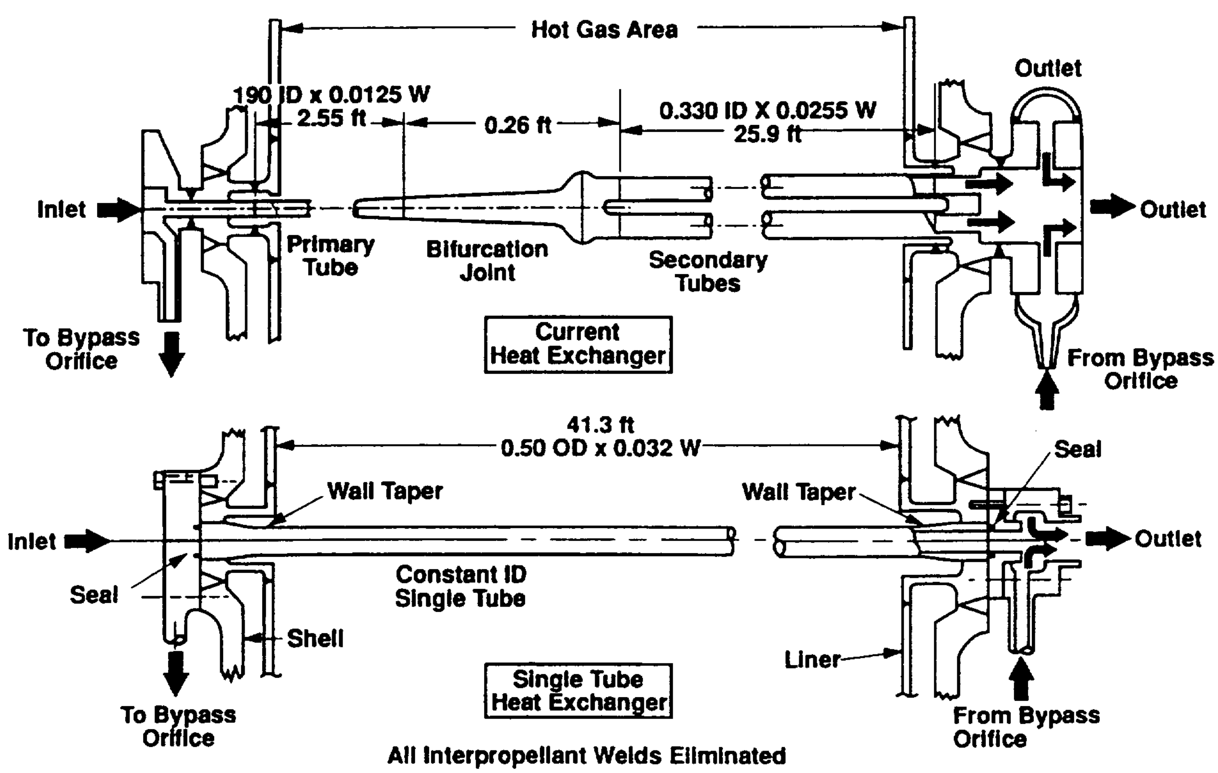

Figure 5. Single-Tube Heat Exchanger and Current Bifurcated HEX

Table 8. Single-Tube Heat Exchanger Structural Margins (FPL Engine Conditions)

Factor of Safety	Single-Tube HEX	Bifurcated HEX
Yield	1.5	1.3
Ultimate	5.0	3.9
Endurance	3.2	1.2

ration of the new HEX will certainly reduce the amount of time currently expended in painstaking postflight mass-spectrometer leak testing to ensure the integrity of the inter-propellant welds and tubing. This modification has been installed on an engine and is scheduled to enter certification testing.

PRATT & WHITNEY ALTERNATE TURBOPUMPS

As indicated earlier in this report, the most challenging and troublesome components of the SSME are the high-pressure turbopumps. Engine system requirements led to discharge pressure levels of about 8,000 psi for the oxygen pump and 6,000 psi for the fuel pump. The weight and size constraints led to lightweight, high-speed, high-temperature and high-efficiency designs. For example, the High Pressure Fuel Turbopump (HPFTP) uses a two-stage turbine with uncooled blades at a turbine inlet temperature in excess of 2,000 R to produce about 70,000 horsepower at 36,000 rpm to drive the hydrogen pump. This machine is of the size and weight of an automobile engine but produces the horsepower equivalent of 28 diesel locomotives. The HPOTP runs at about 26,000 rpm to produce over 28,000 horsepower.

The current machines have been difficult to manufacture repeatably and have been the source of many of the test failures experienced, including uncontained failures. In ground test, there were 42 engine failures. Of these, 8 were attributable to the turbopumps; 1 during the start phase and 7 during steady operation, 3 of which were catastrophic. In the SSME CIL, 14 of the top 25 items are associated with the turbopumps (testing has validated the ranking). Moreover, the turbopumps require extensive inspections and frequent removal for overhaul and consequent retest.

As noted earlier, the current turbopumps have been the subject of a series of major improvement programs, the latest being the "10K" program. This program had more success with the HPFTP than with the HPOTP. The latter is limited to one to three flights before removal for overhaul because of bearing wear indications. The HPFTP, which met the 10K objective and is permitted seven to eight flights before overhaul, still requires very detailed inspections between flights and extreme care during manufacture. The welded "sheet metal" construction employed in the HPFTP's complex flow paths continues to limit the turbopump's life and to be a high-maintenance item requiring frequent removal for crack repair. Also, a recently discovered turbine blade material quality problem requires computer tomography screening of all blades.

Remedies were sought to address the continuing problems with the turbopumps prior to the initiation of the 10K program. In 1985, it was concluded that, within the constraints presented by the existing designs, no group of physically possible modifications could produce the more rugged, reproducible, and reliable machines needed. A decision was made to design and develop a new set of high pressure turbopumps. These pumps were not to be burdened with the weight restrictions imposed on the existing machines and the designs were to be responsive to the lessons learned from the experiences of more than a decade with the current turbopumps. Pratt & Whitney (P&W) was selected to develop the new machines, which are referred to as the "Alternate Turbopumps." The major objectives and design differences between the current and the alternate turbopumps are given in Table 9. Of particular note are: 115 percent RPL as the design point, the use of single-crystal turbine blades, the use of advanced precision castings instead of built-up welded sheet metal for complex parts, and the elimination of coatings against hydrogen embrittlement by use of improved materials. In addition, the machines are designed to contain a turbine blade failure and enhance the probability of a safe shutdown.

Table 9. Alternate Turbopump Design Approach

• Incorporate lessons learned with emphasis on increased safety margins
• Increase performance and structural margins
• Utilize 115% power level for maximum design condition
• Utilize single-crystal blades
• Eliminate welds and sheet metal
• Eliminate thermal and hydrogen environment coatings
• Reduce number of rotating parts (50%)
• Provide safe shutdown in event of turbine blade failure
• Design for inspectability, producibility, and operability

The Alternate Turbopump Program (ATP) employs the Design Verification Specification (DVS) methodology with its extensive testing at the subcomponent level. In addition, use of a turbopump assembly hot-fire facility permits exploration and characterization of the operating map of each machine separately, prior to turbopump operation on an engine. Another advantage of these machines is their careful design for maintainability; thus allowing a turbopump to be disassembled and rebuilt in about 2 weeks in contrast to the 4 to 5 weeks required for the current turbopumps.

The program has not proceeded as smoothly as had been anticipated; as in any such development, problems have arisen that have caused delays. The nature of the more significant problems encountered for each machine and the status as of this writing are given below.

HPOTP. The current HPOTP has been the most troublesome turbopump on the engine. The major design features of the ATP HPOTP are contrasted with those of the current HPOTP in Table 10. Once developed, the new machine should be much more rugged than its predecessor. Testing at the engine level began in late 1991. Unfortunately, the new machine ran into a number of problems, including turbine inlet cracking, turbine bellows failure, turbine bearing outer race cracking and, most intractable, high synchronous vibration of the rotor assembly. The inlet problem resulted from a previously unrecognized adverse radial temperature gradient (400 to 600 R) in the gases from the engine preburner. The next two problems were attributed to a manufacturing problem. Corrective actions were devised for these and implemented.

The synchronous vibration problem has been under study for 1-1/2 years. Several attempts to correct the problem during that period proved unsuccessful. A multi-organizational team of experts in rotor dynamics was formed to resolve the problem, and a systematic approach led to the incorporation of several HPOTP design detail changes. Since then, the HPOTP has

Table 10. Summary of HPOTP Features

Objective	Alternate Turbopump	Current
Minimize welds through fine gain investment castings	7	300
Eliminate uninspectable welds	None	250
Provides subcritical rotordynamic operation		
Stiffen rotor system	Integral Tiebolt/Disk	Shaft coupled to 1st disk, bolted to 2nd disk
Minimize rotating elements	28	50
Provide significant suction (NPSP) margin	40%	Marginal
Minimize LOX cooled bearings	1	4
Eliminate coatings/closeouts required for hydrogen embrittlement protection	None	Gold coating/weld closeouts
Reduce shaft RPM	22400	28000

demonstrated, in engine-level tests, over 5,700 seconds of satisfactory operation at 104 percent RPL. These were accumulated in some 24 tests including 9 mission duration runs. The only untoward finding from these runs was greater-than-expected wear in a bearing. Some changes to the bearing support structure should solve this problem. Testing at FPL and the accumulation of additional development test time in the final configuration must occur before certification of the HPOTP can begin. Certification testing is currently scheduled to begin in the Spring of 1993 and to be completed in mid-1994.

HPFTP. The features of the P&W HPFTP and the existing 10K HPFTP are compared in Table 11. As in the case of the HPOTP, the new machine should be much more rugged and durable. Engine-level testing of the ATP HPFTP began in May 1991. The turbopump demonstrated ability to operate at 109 percent RPL and accumulated 2200 seconds of operation during 23 tests at several power levels. These development tests revealed several design deficiencies. Among them were: cracking of the turbine inlet that was associated with thermal transients, lift-off seal leakage, ball bearing inner race cracks, and a high-cycle fatigue crack at the corner of a second-stage turbine blade. These problems were investigated and corrective actions were developed and implemented in all cases except the blade crack. The efficacy of these fixes was demonstrated during a number of runs. The blade crack fix could not be demonstrated at that time because it involves changing the number of second stage stator vanes from 54 to 76, which requires a new casting, and has a longer lead-time than the other changes.

In December 1991, the HPFTP program was placed on hold for 2 years because of budgetary constraints and to concentrate development resources on the more critical and difficult problems of the HPOTP. Since then, an IR&D-funded HPFTP was tested

Table 11. Summary of HPFTP Features

Objective	Alternate Turbopump	Current (10K Config.)
Minimize welds through fine gain investment castings	None	469
Eliminate uninspectable welds	None	315
Rotordynamic control		
Stiffen rotor system	Integral Tiebolt/Disk	Shaft coupled to 1st disk, bolted to 2nd disk
Minimize rotating elements	14	30
Provide significant suction (NPSP) margin	90%	15%
Eliminate turbine blade thermal barrier coating through single crystal alloy	None	NICRALY

at the MSFC Technology Test Bed (TTB) engine facility (a highly instrumented SSME) to determine if the modified pump would cause any engine system effects over the operating envelope of the SSME. During the three test runs, the HPFTP was operated over the extremes of allowable inlet conditions, power levels (up to FPL), and mixture ratios. No adverse engine system effects were observed.

In summary, the ATP designs represent a significant improvement in the inherent design margins and durability of the current turbopumps. These margins have been enhanced through the elimination of welds and "sheet metal" construction, reduction in the number of rotating parts, and elimination of protective coatings for thermal and hydrogen embrittlement effects. Moreover, the design for inspectability and maintainability permits simple and rapid turbopump assembly and disassembly. The design is such that, with manufacturing techniques employed, it is possible to produce hardware within drawing requirements repeatably. The "price" for obtaining these improved turbopumps, aside from fiscal, is a reduction in Shuttle payload capability of 900 pounds due to the increased engine weight.

The completion of the development program and the certification testing still remains. The 2-year hiatus in the HPFTP program can only be detrimental to the achievement of the goal of a set of rugged, reliable turbopumps for the SSME and may also increase costs because of program stretch-out and duplicate certification testing.

LARGE THROAT MAIN COMBUSTION CHAMBER

As noted earlier in this report, the chamber pressure required for the SSME is several times that of any large rocket engine developed previously. In combination with the staged-combustion cycle, this drives the turbomachinery and other system pressures to new heights as well. Anything that reduces these pressures while retaining thrust and specific impulse levels also serves to reduce the internal operating conditions and to increase the operating margins of engine components, their durability and reliability. Certainly, such changes would be of great import to the turbomachines as well other system components.

As early as 1981, the SSME Project proposed that an increase in the throat diameter of the Main Combustion Chamber (MCC), along with some other modifications to the main combustion system, could provide the desired relief for the turbomachinery operating environment. This modification was not approved as part of the SSME improvement program, but was relegated to a "technology" activity status with minimal resources. Only recently has the Large Throat MCC (LTMCC) become an integral element of the safety and reliability improvement program.

The MCC is a cylindrically symmetrical, regeneratively cooled pressure vessel that contains the high-temperature (6,000 R) burning propellant gases and initiates their expansion through the integral chamber throat before they enter the nozzle. The MCC uses part of the liquid hydrogen discharged from the HPFTP as a coolant to maintain the MCC internal wall temperature within acceptable limits. Forced convection cooling is the primary method for cooling the wall and is obtained by channeling the hydrogen through a large number of rectangular cooling slots within the chamber wall. Convective cooling is supplemented by providing film cooling to the interior (or hot) wall by injecting jets of hydrogen along the wall through small holes in the main injector face plate.

The LTMCC differs from the current MCC in several ways. The throat diameter has been increased 11 percent from 10.305 to 10.883 inches, which allows a decrease in chamber pressure by 9 percent. The contour of the chamber also changes and the throat plane is shifted downstream from the injector face by 0.7 inch (Figure 6). The

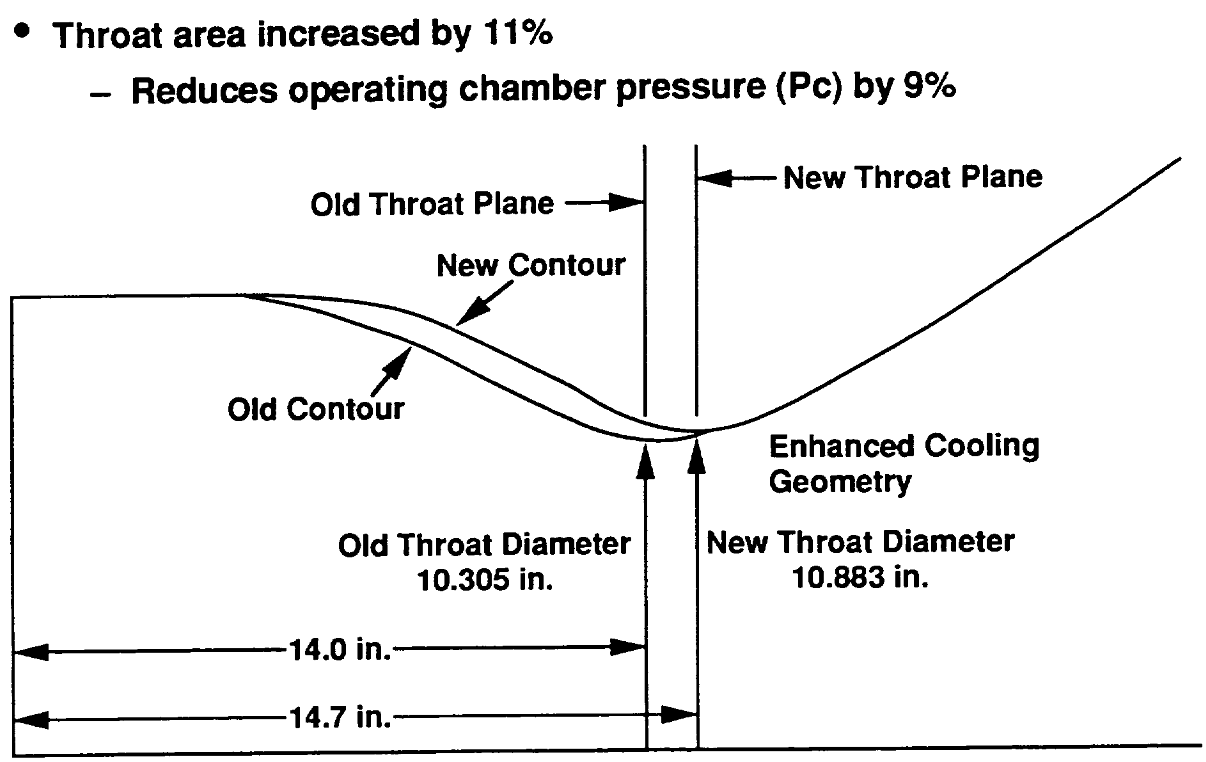

Figure 6. Large Throat Main Combustion Chamber (LTMCC)

increased throat dimension permits an increase in the number of coolant channels to 430 from the current 390 and the accompanying reduction in hot wall thickness. These changes reduce the operating temperature of the hot wall by approximately 60-to-100 R, increasing its life by about 200 percent. This lowered temperature serves to reduce the occurrence of pin-hole leaks and channel cracks. The increased number of coolant channels also increases the magnitude of hot-wall-to-channel-wall bond area, thus lowering operating bond stress by 17 percent, which increases the structural margin of these bonds by 32 percent over its current level.

In addition to the functional changes described above, investment cast manifolds with wrought liners are used instead of the welded construction of these components in the current MCC. The cast manifolds significantly reduce the number of welds (from 79 to 26) in the manifolds, and those that do remain are fully inspectable. Cost of manufacturing and fabrication time also decreases.

The introduction of the LTMCC has impacted other engine components (see Table 12). These relatively minor impacts require some redesign and recertification of the affected component. The Low

Table 12. SSME Operating Condition Comparison at 104% RPL

Parameter		Current Phase-II MCC	LTMCC	Delta
Thrust	lbf	488352	488352	
Chamber Pressure	psia	3126	2843	-9.0%
Mixture Ratio	O/F	6.011	6.011	
Suction Oxidizer Flowrate	lbs/sec	926.59	925.43	
Suction Fuel Flowrate	lbs/sec	154.15	153.96	
Total Suction Flowrate	lbs/sec	1080.74	1079.39	
Isp	sec	452.9	453.4	
HPOTP Main Pump Discharge Pressure	psia	4341	4084	-5.9%
Boost Pump Discharge Pressure	psia	7306	7190	-1.6%
Shaft Speed	rpm	27938	27658	-1.0%
Turbine Discharge Temperature	R	1335	1201	-10.1%
HPFTP Pump Discharge Pressure	psia	6348	6037	-4.9%
Shaft Speed	rpm	34936	34328	-1.7%
Turbine Discharge Temperature	R	1694	1550	-8.5%
Oxidizer Preburner Pressure	psia	5187	4803	-7.4%
Fuel Preburner Pressure	psia	5200	4784	-8.0%
LPOTP Discharge Pressure	psia	422	401	-5.0%
Shaft Speed	rpm	5107	5005	-2.0%
LPFTP Discharge Pressure	psia	295	293	-0.7%
Shaft Speed	rpm	15804	15740	-0.4%

Pressure Oxidizer Turbopump (LPOTP) inducer has to be redesigned to change the blade incidence angle. This redesign has been initiated and a development unit has been water-flow- tested and hot-fired on the TTB engine. While the ATP HPOTP was designed to be compatible with both the LTMCC and the current MCC, the current HPOTP would require a redesign of the main inducer to reduce cavitation and a change to the preburner stage diffuser to eliminate vane stall characteristics that occur at the lower power levels.

Use of the LTMCC lowers the combustion chamber pressure by 9 percent at 104 percent RPL. Thrust is maintained by the change in the operating points of the turbopumps. A comparison of the operating conditions and margins of the engine with the LTMCC with those with the current MCC is given in Table 12. In general, with the LTMCC, operation of the engine at 104 percent RPL is less stressful than operating the current engine at 100 percent RPL. Similarly, operating the engine with the LTMCC at 109 percent RPL is equivalent to the current engine operating at 104 percent RPL (Figure 7).

While the LTMCC increases the operating margins as noted above, the reduction in chamber pressure and area ratio would result in a reduction of 2.2 seconds in specific impulse and consequent loss in vehicle payload capability. To reduce this loss, it is planned to eliminate the acoustic cavities and their associated coolant flow, reduce chamber film coolant flow, and use the chamber in combination with the Two-Duct Powerhead, which deletes the main injector baffles (cf., Table 13). Experience with such changes to the combustion system in hydrogen/oxygen systems and test results

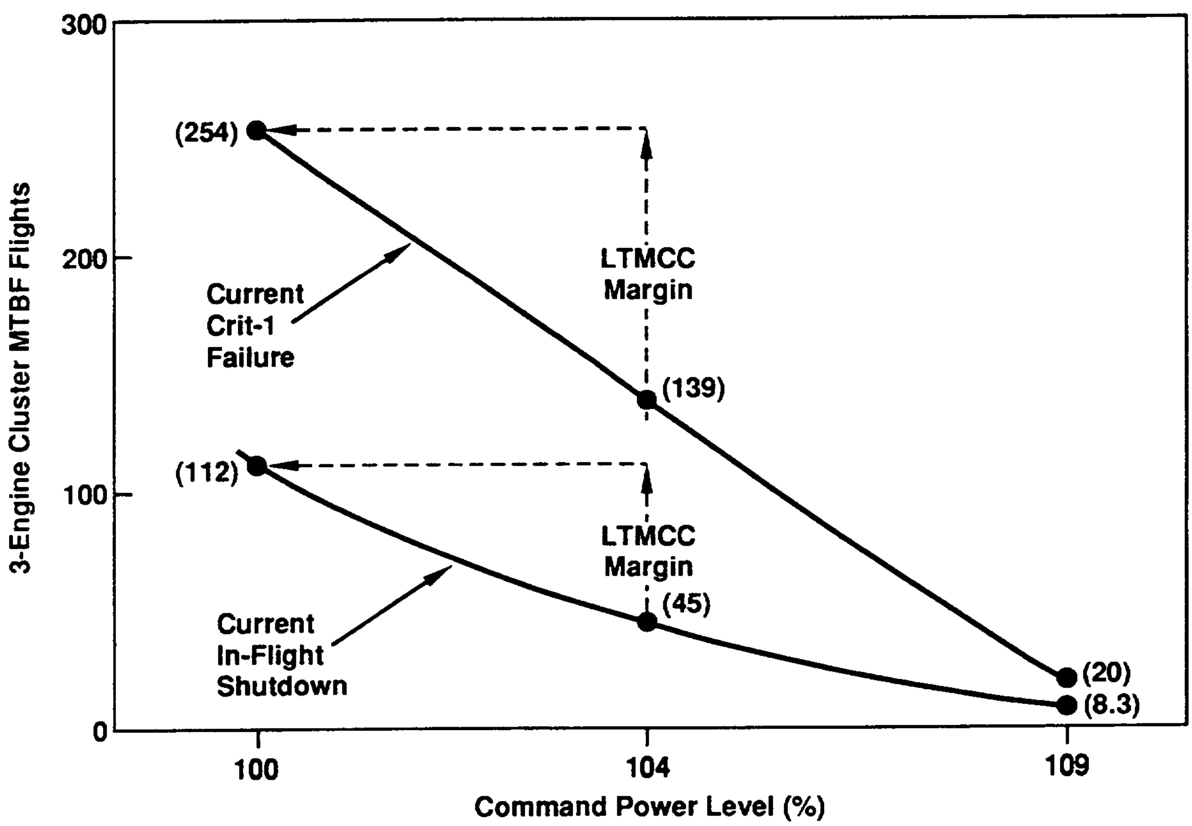

Figure 7. Current SSME MTBF

Table 13.
Two-Duct Powerhead Improvements

• Increased hot gas flow area
• Improved contour for hot gas flow
• Eliminated center transfer duct
• Improved main injector flow shield design
• Shortened preburner injector elements
• Improved structural integrity of coolant ducts and liquid oxygen inlet manifold
• Eliminated 76 welds
• Removed main injector baffles

of the LTMCC technology program indicate that removing combustion stabilizing devices from the system is acceptable.

The removal of the MCC injector baffles produces an improvement in MCC cooling. The baffles were originally included to prevent combustion instability from propagating. Although testing to date has shown adequate stability, thorough stability testing during completion of the development and certification programs is prudent.

To date, there are four LTMCCs in various stages of manufacture and assembly. LTMCC unit 6001 was installed on Engine 0208, test run for 26 starts, and accumulated 3,716 seconds of operating time. It was also installed on Engine 0217 and tested for 830 seconds in two runs. On Engine 0208, injector baffles and acoustic cavities were removed and subjected to eight "bomb" test sets to determine the sensitivity of this configuration to combustion disturbances. All of these tests demonstrated rapid recovery from the disturbance created by the bomb, recovering within 6 milliseconds, which is essentially the same as that of the original configuration. The criterion for acceptable recovery is 28 milliseconds. Other aspects of performance were reported to have met or exceeded expectations. The condition of the chamber after 28 tests was excellent with no indication of cracking or pin-hole leaks.

Improvement of operating margins associated with the LTMCC may lead to the availability of the more desirable abort mode options. The operating margin of the SSME at FPL with the LTMCC is comparable with that of the current engine at 104 percent RPL. In the event of an engine shutdown, advancing the throttle to FPL makes possible a greater time span for the abort-to-orbit mode and a reduction of the time when RTLS mode is required by about 20 to 30 seconds. More detailed study is required.

TWO-DUCT POWERHEAD

The current SSME powerhead (referred to as the Phase II powerhead), shown in Figure 8, is an assembly of eight major parts. One part, the HGM, serves as the structural base for mounting the MCC and its injector, the two preburner injectors, the HEX, and the two high-pressure turbopumps. The current HGM has three ducts connecting the high-pressure fuel turbine discharge annulus and the MCC injector dome. These ducts yield non-uniform velocity and pressure profiles of the hot gas flow entering the MCC injector dome. This causes severe dynamic loading on the MCC injector liquid oxygen (LOX) posts. The flow distortion also causes a rather large pressure drop through the ducts, resulting in a loss in performance. Also, the significant lateral pressure differential created across the HPFTP adds to its structural loads, especially on the "sheet metal" parts. The HGM has very thick walls, about 2-1/2 inches, and many welds are used to make the assembly. Many of the items in the CIL that are associated with the powerhead are of

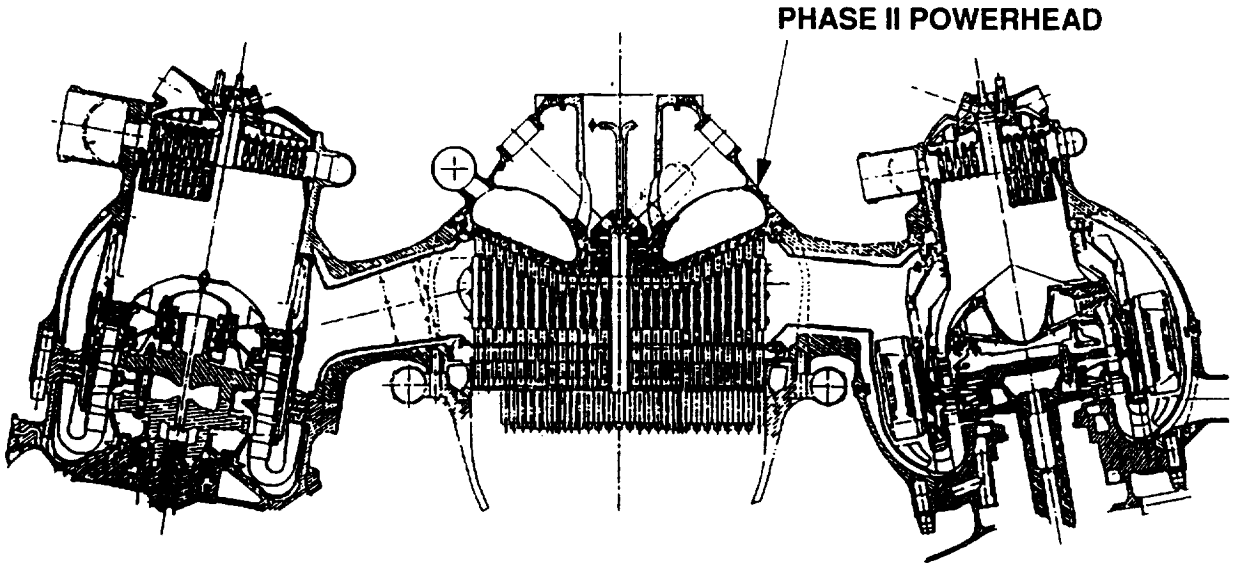

Figure 8. Phase II Powerhead

concern because they are exacerbated by the poor flow conditions it creates.

During the early 1980's, a program was initiated to modify the powerhead to mitigate or eliminate these problems. This program introduced a new component referred to as the Phase II+ powerhead (two-duct powerhead). The most significant features of the redesign are indicated in Figure 9, with the three circular cross-section ducts replaced by two elliptical cross-section ducts. This and other modifications significantly improved flow uniformity, decreased turbulence levels and pressure drops, and improved the ruggedness and hence the reliability of the assembly. A summary of the changes is given in Table 13, indicating the components affected. For example, the flow area of the MCC injector flow shields have been increased by 34 percent and the dynamic loads on the LOX posts are reduced by 16 percent. The HPFTP transverse pressure gradient is reduced by 60 percent, reducing this part of its structural load significantly. Changes to the liquid oxygen inlet elbow and tee have increased both their high- and low-cycle fatigue design life by an order of magnitude. The number of welds in the assembly has been reduced by 24 percent.

Testing to date indicates a need to fine-tune the film cooling flows for the MCC walls to eliminate blanching and erosion. This is in process. Formal certification of the powerhead will coincide with that of the single-tube HEX and is scheduled to start in late 1992 and end in 1994.

PERFORMANCE IMPACTS

The forementioned improvements will impact Shuttle system performance. In the

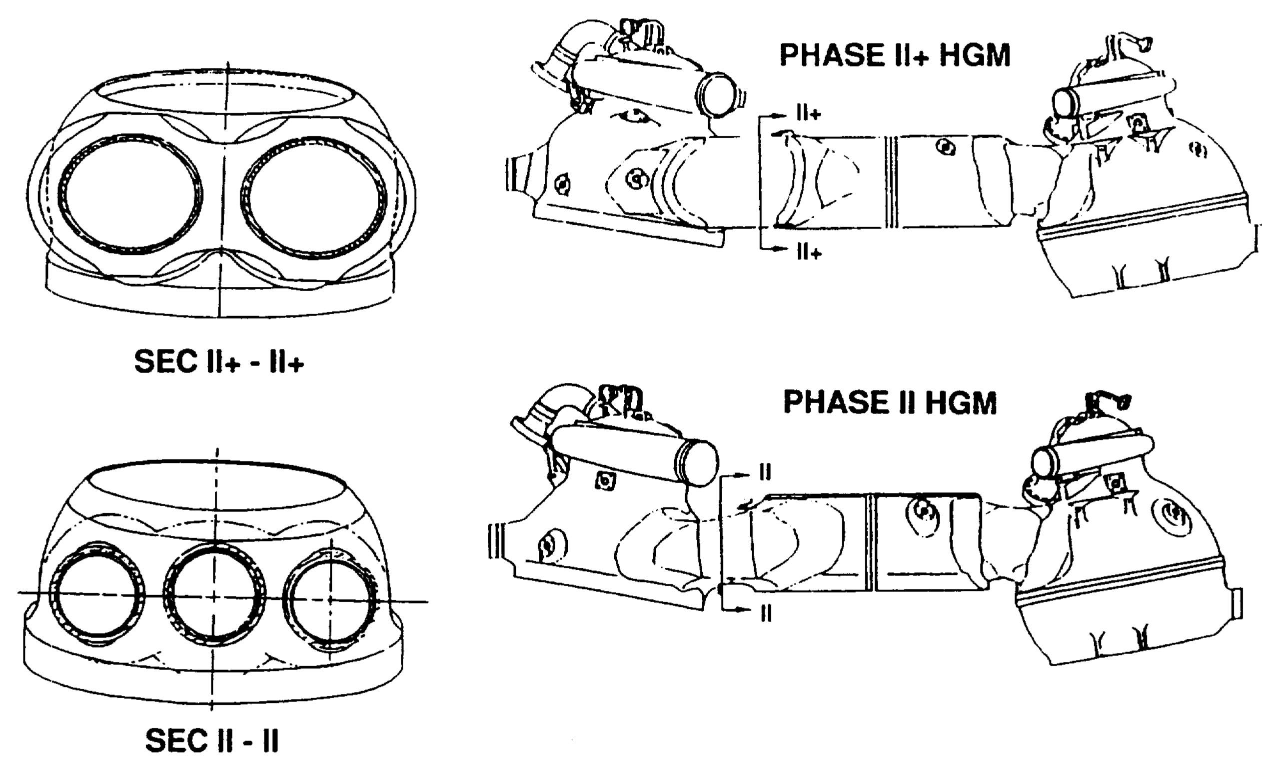

Figure 9. Powerhead (Comparison)

case of engine Isp, as shown in Table 14, certain losses and gains are attributable to the various changes. Regarding the reduction of leakage in the new MCC, the optimistic estimate is that there will be a net gain of 0.95 seconds. Conservatively, the estimated net effect on Isp would be a gain of about 0.35 seconds or a net gain in payload capability of about 350 pounds.

Estimated effects of the proposed structural changes involved are indicated in Table 15. If all improvements are incorporated, the weight of an engine will increase 685 pounds or 2050 pounds per ship set. The overall effect of the changes (using the conservative effect of Isp) is an approximate 1700-pound decrease in payload capability. This is the "price" of increasing the safety and reliability of the SSME and is well worth it.

PRIORITIES

There is no simple, mathematically rigorous way to establish priorities among the major changes to the SSME described in the preceding paragraphs. Any attempt to assign priorities based on a mathematical scoring system would be highly subjective. The Team's consensus was that priorities should be based on the evaluation of each item's impact on engine safety and reliability. This led to the following priority groupings:

Priority I:	Single-tube HEX
	ATP HPOTP
	LTMCC
Priority II:	ATP HPFTP
	Two-Duct Powerhead

Within each grouping, the items are presented in priority order. No other major

Table 14. SSME Large Throat MCC Engine Performance

Specific Impulse Change Due to Large Throat MCC Incorporation	
	Delta (Sec)
Large Throat MCC Area/Chamber Pressure Acoustic Cavity Flow Elimination Boundary Layer Coolant Hole Flow Reduction MCC Total:	 -2.2 +0.5 +1.0 -0.7 Seconds
Phase II+ Powerhead Baffleless Main Injector	 +1.0
Total Specific Impulse Change	+0.3 Seconds (95% Confidence)
Expected Additional Gain Due to MCC Leakage	+0.05 to +0.65

Table 15. Effects of Improvement on SSME Weight

MCC Standard (today) MCC Weight Rocketdyne Proposed Production Large Throat	 470 lbm 620 lbm	 +150 lbm over today
Turbomachinery HPOTP Rocketdyne (today) ATD (expected flight weight) HPFTP Rocketdyne (today) ATD (expected flight weight)	 575 lbm 741 lbm 770 lbm 989 lbm	 +166 lbm over today +219 lbm over today
Powerhead Phase-II (today, 3-duct) Phase-II+ (2-duct, baffleless, Single-Tube HEX)	 1267 lbm 1417 lbm	 +150 lbm over today
	Total Delta (per engine):	+685 lbm

modifications are under development or consideration at this time.

CERTIFICATION

Figure 10 shows the current schedule for development and certification of the proposed improvements. It is apparent from the figure that the sequence of availability of the improvements is not in concert with the priorities just presented. Also, because of the hardware-related factors, there will be multiple certifications of some improvements. For example, the ATP HPOTP will first be certified with the current MCC and will have to be re-certified with the LTMCC. Also, the resulting configuration will only fly for a very few

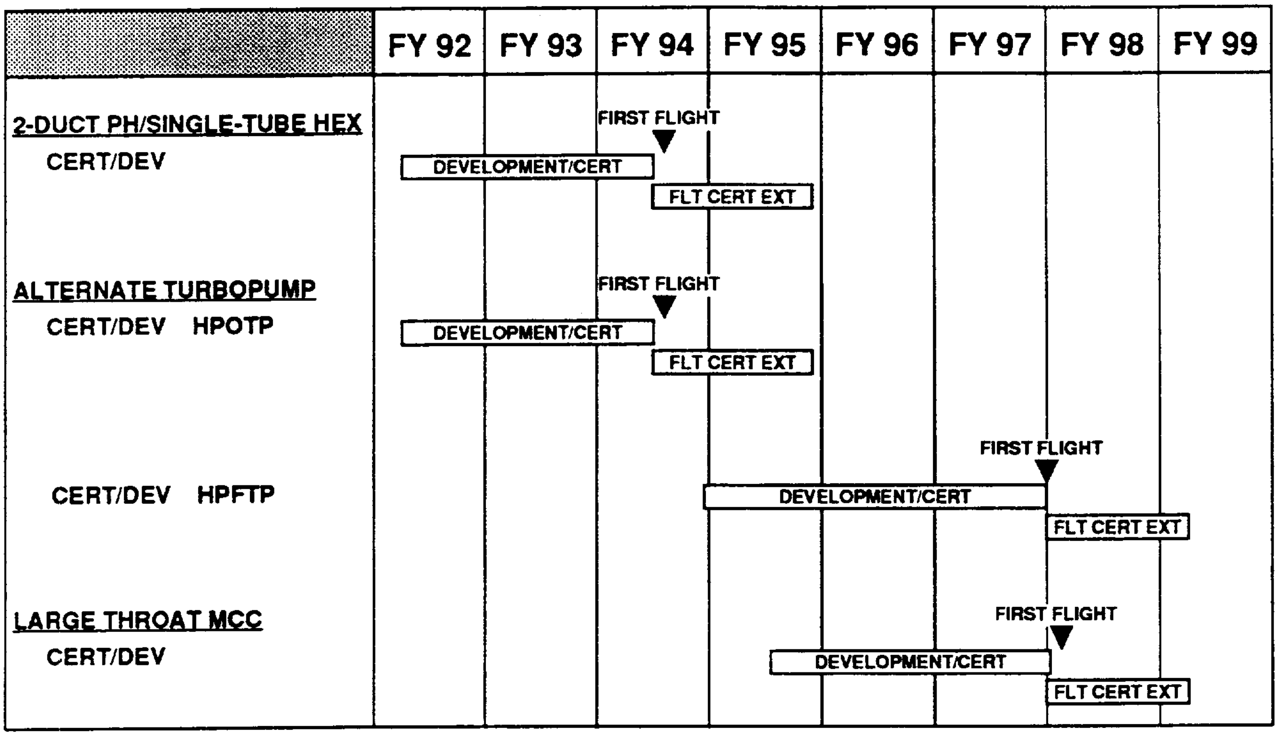

Figure 10. Current Implementation Schedule for SSME Improvements

years before it is replaced. Engine-level testing is a very expensive activity, approximately $1500/second, with at least 40,000 seconds required for certification. Therefore, it would be advisable to examine modifying current plans to determine if a more logical and effective program can be devised. Such an examination should consider the possibility of reorganizing the program so as to create a "block change"; that is, one incorporating all the changes at once to create a new model of the SSME. This would require a very detailed assessment of all the factors involved in such a programmatic alteration. Among the factors to be considered is the number of engine test stands needed in this process—it being possible that, with a different program plan, all three facilities might not be needed and the concurrent expenditure could be avoided. Intuitively, such a block change approach should be less expensive in the long run and reduce duplicative testing and certify the block in the ultimate flight configuration only. This may delay some certifications and require expediting others.

OTHER OPERATIONAL CONCERNS

During the course of the Team's review, other engine operational concerns surfaced that demand attention before they become major safety risk factors; these are discussed below.

"Pops". Occasionally, the oxidizer preburner experiences sudden, short-lived rapid combustion phenomena, possibly detonations, evidenced by sudden spikes in engine-mounted accelerometer readings. These have been called "pops," some of which have resulted in accelerometer readings as high as 10,000 g. Until recently, such large pops have occurred only after engine cutoff had been initiated, generally about 2.3 seconds into the process. Recently, pops of 11,000 to 12,000 g have been experienced during engine start-up in contrast to the 1,000 g previously experienced.

Based on post-event inspections, a criterion has been developed that states that pops yielding 6,000 g or less requires no special action; those above that magnitude require a "flat face" inspection of the injector plate to ensure that no physical deformation has occurred and that none of the brazed joints have been damaged. To test the validity of this criterion, a preburner injector that had been deformed by 0.085 inch is being kept in the test program.

There are several concerns about pops: their unpredictability, lack of understanding of the phenomenon, and lack of knowledge as to what is the upper bound of the disturbance. Attempts are being made to investigate making small changes in the injector manifolds to minimize the accumulation of propellant behind the faceplate, a suspect mechanism. Also, modifications to valve timing during shutdown are being investigated in an effort to minimize the fuel backflow resulting from an imbalance between chamber pressure and supply pressure during the transient. Finally, although bomb testing and operating experience indicate that the engine is inherently stable, the magnitude of the disturbance during pops might be sufficient to trigger combustion instability, especially if the stabilizing devices like acoustic cavities and main injector baffles are removed. Obviously, a continuing analytical and experimental effort to understand and eliminate or control the phenomenon is indicated.

Instrumentation. A source of continuing concern has been the failure of flight sensors used for redlines. Although the systems employ redundant sensors and logic to exclude readings from failed units, the failure experience is not salutary. Should a number of sensors in one redline instrument system fail, an unnecessary engine shutdown and abort could occur. This is especially true of the temperature instruments used to measure turbine discharge temperatures of the high-pressure turbopumps. Of necessity, the sensing element of the thermistors is a very fine wire that is easily broken. Over the years, a series of design modifications of the sensor assembly has had moderate success in increasing ruggedness, but failures continue to occur. Also, extreme care in manufacture is required to produce a usable device. Not only must development of the current type sensor continue but an alternate, more rugged technique should be sought for sensing temperatures.

Valve Actuators. The hydraulic actuators that operate the propellant control valves are critical parts of the engine system. The hydraulic segment of the actuators is fully redundant and is backed up with a pneumatic system that is designed to allow a safe shutdown in the event of a multiple failure in the hydraulic system. Prior to the Challenger accident, two on-pad aborts were associated with loss of redundancy in the actuator system. The Launch Commit Criteria require that all redundant systems be operating for a launch. Design changes were incorporated in both the actuator and the hydraulic fluid systems to improve reliability. Since then, an actuator hangup has occurred during a component checkout. The cause of the malfunction was determined to be galling between the spool and sleeve that transfers the valve from hydraulic to pneumatic control in the event of multiple failure in the hydraulic part of the actuator. Fixes for this problem are being actively sought.

Sustaining Engineering. Similar problems will continue to arise as operating experience accumulates. This is true of all propulsion systems, including aircraft gas turbine engines and automotive engines. Each program must, therefore, maintain an active and competent sustaining engineering team to investigate all anomalies as they occur and develop any necessary corrective action.

V. CONCLUSIONS

Based on its review of the history, status and plans of the Space Shuttle Main Engine (SSME) program, the SSME Assessment Team concludes the following:

1. It is safe to continue to fly with the current engines provided that the current precautions and procedures such as special inspections, life limits, and configuration control continue to be implemented in an expert, disciplined, and vigilant manner.

2. The safety and reliability of the SSME can be improved substantially by incorporating changes that increase the inherent ruggedness and operating margins of components, thus reducing reliance on people and processes.

3. All of the major safety and reliability improvements currently in development should be implemented as they respond to known major concerns. They are listed in priority order based on estimated impact on engine safety and reliability:

Priority I: Single-Tube Heat Exchanger

Alternate High-Pressure Oxidizer Turbopump

Large-Throat Main Combustion Chamber.

Priority II: Alternate High-Pressure Fuel Turbopump

Two-Duct Powerhead.

4. Implementation of these changes should permit a less restrictive use of thrust in the event of an abort, thus permitting an improvement in the choice of abort mode options.

5. These changes should be certified as soon as possible. The certification and implementation should be performed as a block change rather than a serial change as specified in the current plan. This should eliminate duplicate certifications and ensure that the changes take effect in the configuration that will fly.

6. Although the Team did not possess the degree of expertise required to perform an in-depth of analysis for a valid cost comparison between the two approaches, it concluded, on the basis of the experience of its members, that the block change approach would be more economical than serial changes.

7. Anomalies and new phenomena (e.g., "pops" and sensor malfunctions) are expected to continue to occur or be discovered as operating and test experience is gained. All such occurrences must continue to be investigated thoroughly and require a competent sustaining engineering activity.

8. Although not specifically addressed in the body of this report, the program aimed at developing improved fabrication and inspection techniques for the SSME should be continued and encouraged.

VI. RECOMMENDATIONS

Based on its conclusions, the Team recommends:

1. Certification and implementation of all of the major safety and reliability improvements given in Conclusion Number 3.

2. Implementation of proposed changes as a block change. Conduct an in-depth evaluation of cost, schedule, and technical impacts of the block change approach versus the current serial plan; include in the study long-term effects on costs such as recurring costs.

3. Continuation of the practice of thorough investigation of all anomalies that occur in flight and tests such as "pops"; the development and implementation of corrective actions; and maintenance of an effective sustaining engineering activity.

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APPENDIX A

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION MULTIYEAR AUTHORIZATION ACT OF 1992

APRIL 22, 1992.—Committed to the Committee of the Whole House on the State of the Union and ordered to be printed

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Mr. BROWN, from the Committee on Science, Space, and Technology, submitted the following

REPORT

[To accompany H.R. 4364]

[Including cost estimate of the Congressional Budget Office]

The Committee on Science, Space, and Technology, to whom was referred the bill (H.R. 4864) to authorize appropriations to the National Aeronautics and Space Administration for research and development, space flight, control and data communications, construction of facilities, research and program management, and Inspector General, and for other purposes, having considered the same, report favorably thereon with an amendment and recommend that the bill, as amended, do pass.

54-558

ating margins within the SSME which is generally recognized as the riskiest element of the Space Shuttle.

The Wide Diameter Throat and the Alternative Fuel Turbopump should be pursued as rapidly as possible. Accordingly, the Committee encourages NASA in the strongest possible terms to undertake these initiatives as quickly as possible.

Safety Assessment of the Space Shuttle Main Engine

The Committee requests that the Aerospace Safety Advisory Panel (ASAP) create a temporary task force of propulsion experts to conduct a thorough assessment of the Space Shuttle Main Engine (SSME). The Committee believes that this temporary task force should include propulsion experts drawn from academia and elsewhere to augment the propulsion experts who are already affiliated with the ASAP.

The Committee requests that the temporary task force: 1) assess the risks that the SSME poses to the safe operation of the Space Shuttle; 2) identify and evaluate safety improvements that could eliminate or reduce these risks; and 3) recommend a set of priorities that the task force believes should be followed on implementing specific improvements.

Basically, the Committee wishes to receive an unbiased assessment that could answer questions such as the following: How safe is the SSME? Is it safe enough? If not, what improvements need to be made? How quickly should these improvements be brought into the operational inventory? What will be the cost of making these improvements? What are the likely risks and consequences if these improvements are not made? etc.

The Committee would like to receive a final report from the temporary task force no later than February 1, 1993.

The Committee directs that the NASA Administrator provide the temporary task force with whatever: (1) data; (2) access to facilities, records, analyses, and personnel; and (3) financial and administrative support that may be required for the temporary task force to comply with this Congressional request.

Section 102(b)(2)—Space Shuttle Operations

President's request for fiscal year 1993 and estimates for subsequent years:	
Fiscal year:	
1993	$3,115,200,000
1994	3,115,200,000
1995	3,115,200,000
Committee recommendation:	
Fiscal year:	
1993	3,105,200,000
1994	3,142,500,000
1995	3,180,200,000

Committee authorization recommendation

This section authorizes $3,105,200,000 in fiscal year 1993, $3,142,500,000 in fiscal year 1994, and $3,180,200,000 in fiscal year 1995 for Space Shuttle Operations. The authorization for fiscal year 1993 represents a decrease of $10,000,000 below the President's request. This decrease represents a general reduction in Research

APPENDIX B

SPACE SHUTTLE MAIN ENGINE ASSESSMENT TASK FORCE

(SSME ASSESSMENT TEAM)

Chairman	Dr. Walter C. Williams Aerospace Consultant Tarzana, CA
Co-Chairman	Dr. Seymour C. Himmel Aerospace Consultant Lakewood, OH
Members	Mr. Thomas B. Mobley Director, Advanced Technology Martin Marietta Manned Space Systems New Orleans, LA
	Dr. Bruce A. Reese Aerospace Consultant Huntsville, AL
	Mr. Eusebio Suarez-Alfonso Aerospace Corporation Los Angeles, CA
	Dr. Richard Weiss Director, Propulsion Directorate Phillips Laboratory Edwards AFB, CA
Executive Secretary	Mr. Chris Singer NASA Headquarters Washington, DC
Staff Assistant	Ms. Patricia M. Harman NASA Headquarters Washington, DC 20546