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SSME LIFETIME PREDICTION AND VERIFICATION, INTEGRATING ENVIRONMENTS, STRUCTURES, MATERIALS; THE CHALLENGE

Robert S. Ryan, Larry D. Salter, George M. Young, III, and Paul M. Munafo
Marshall Space Flight Center
Huntsville, Alabama

ABSTRACT

The planned missions for the Space Shuttle dictated a unique and technology-extending rocket engine. The high I_{sp} (performance) requirements in conjunction with a 55-mission lifetime, plus volume and weight constraints, produced unique structural design, manufacturing, and verification requirements. Operations from earth to orbit produce severe dynamic environments, which couple with the extreme pressure and thermal environments associated with the high performance, creating large low cycle loads and high cycle alternating stresses above endurance limit which result in high sensitivity to alternating stresses. Combining all of these effects resulted in the requirement for exotic materials, which are more susceptible to manufacturing problems, and the use of an all-welded structure. This paper discusses the challenge of integrating environments, dynamics, structures, and materials into a verified SSME structure to meet a 55-mission lifetime while producing unprecedented performance. Included also are the verification program and developmental flight results. Rocketdyne Division of Rockwell International Corporation, under contract to Marshall Space Flight Center, is the prime contractor for the development of the Space Shuttle Main Engine (SSME).

INTRODUCTION

The Space Shuttle mission requirements and the resulting propulsion system requirements have led to very stringent and technology-extending structural design, verification, manufacturing, and operational approaches. Being a manned vehicle, Space Shuttle dictated that the engine be of the highest possible reliability (References 1 and 2).

The Space Shuttle missions require the engine to have high performance I_{sp} of 455 seconds, a thrust of 375,000 pounds (sea level), long life (55 missions), minimum maintenance, and to be achieved within stringent weight and volumetric constraints. These concepts and requirements led to a new approach, "line replaceable units (LRU's)," that could be installed either in the field or factory. Acceptance and/or verification of LRU's are accomplished separately from the engine system (Reference 3).

In order to achieve the high performance (I_{sp}), a two-stage pump system is used in conjunction with preburners which burn the fuel rich, furnishing the power for the pumps. This extremely hot fuel rich gas feeds the main combustion, efficiently developing the engine thrust. This system results in unprecedented operating regimes of temperatures, pressures, and rotating machinery speeds. The high rotary speeds and the combustion processes create mechanical, acoustical, and fluctuating pressure environments. Figure 1 is a schematic showing typical pressures and temperatures. The volumetric and weight constraints drive the design toward a high concentration of energy and minimum structure sizing (thickness, etc.). The energy concentration can be illustrated by observing the size of the high pressure fuel pump, which generates 70,000 horsepower within an envelope 18 inches in diameter by 30 inches long and rotates at speeds up to approximately 40,000 rpm (References 1, 2, 4, 5, 6, 7, 8, and 9).

The structural design problem is further complicated by the multivaried operating regime (throttling to 65%) and the requirement to gimbal the engine ± 10 degrees at a 10 degree/second rate for vehicle control authority. The engine starts on the ground, operates in the atmosphere and then in a vacuum, and shuts down, producing large thermal and pressure cycles for each burn. Since the nozzle expansion ratio is a key parameter to high performance, a compromise between atmosphere and vacuum is required, leading to a very complex, additional set of environments during ground start.

Volumetric and weight constraints introduce designs which create additional fluctuating environments. For example, curved ducts, bellows, valves, and changing duct/valve diameter create higher velocities, unsteady flow environments, and acoustic pressures which are additive to the normal turbine fluctuating pressures and combustion induced noises.

Combining all of these environments leads to three classical design problems, (1) strength - pressures, thermal loads, and inertial loads; (2) low cycle fatigue - pressure and thermal cycles associated with each firing that is unprecedented in rocket engine design, and (3) high cycle

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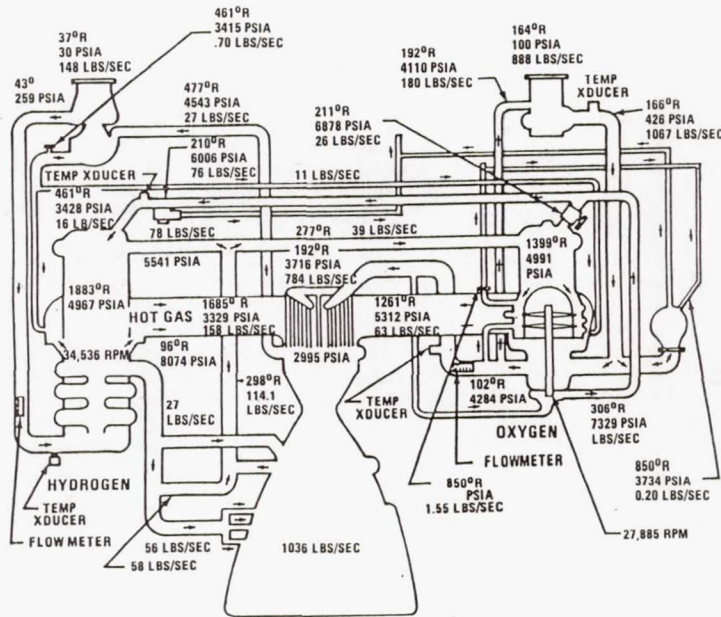


FIGURE 1. SSME PROPELLANT FLOW SCHEMATIC

fatigue/fracture mechanics - flow, combustion, and mechanically induced. Strength and low cycle fatigue problems have been solved by material selection and design considerations, leading to an all-welded design using exotic materials. The other major challenge was high cycle fatigue and fracture mechanics. The SSME operating conditions generate environments where many parts are operating at or beyond their endurance limits, producing a limited lifetime. The design point on the SN curve is very flat, making lifetime very sensitive to small changes in alternating stresses (5% alternating stresses change lifetime up to an order of magnitude), manufacturing errors, and material deterioration (see Figure 2).

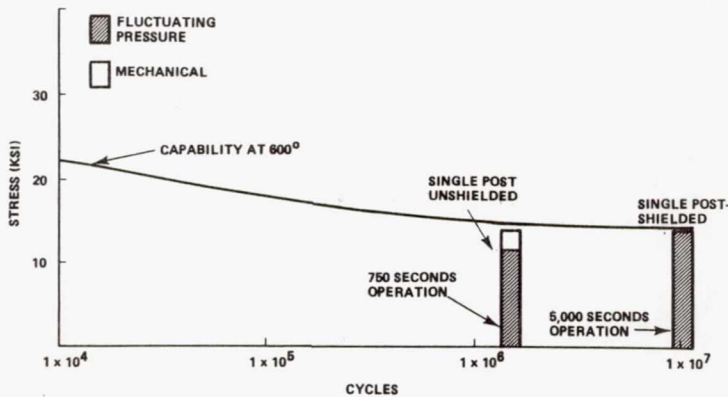


FIGURE 2. ALTERNATING STRESS VERSUS LIFETIME

Taking the above-mentioned considerations, integrating them into a structural design, manufacturing the design, and final verification of an acceptable product results in a very compelling program. This was the challenge of the SSME Program. The requirements of this program where each are subsets of the challenge are:

1. Develop and characterize special materials.
2. Develop accurate environment predictions and verification techniques.
3. Develop accurate structural dynamic and stress models and their verification.
4. Develop a fracture mechanics and nondestructive evaluation (NDE) program.
5. Develop extensive verification procedures (DVS).
 - Analysis.
 - Test.
 - Hot firing instrumentation.
6. Develop accurate and technology-challenging manufacturing and quality control procedures.

Design adequacy is assured through implementation of a Design Verification Specification (DVS), which is a detailed set of well-documented tasks with government/industry verification with complete signoff on each. Tasks are broken out in terms of engine systems, valves and ducts, rotary machinery, combustion devices, and controller. The tasks are all inconclusive in terms of analysis, tests, and hot firing verification. Each discipline and subsystem maintains current documentation of all analyses and test procedures and results keyed to the DVS. In addition to the DVS, many system requirements are placed on total engine verification accomplished in single and multi-engine ground firings.

The approach used in meeting the design challenges in the areas of strength, low cycle fatigue, high cycle fatigue, manufacturing, and material processing followed classical techniques. Figure 3 shows this approach where environments are predicted, models developed, loads calculated, material properties determined, and design stresses developed. As a result of tests, component firings, engine developmental firings, and DVS, the design verification cycle becomes one of iteration where changes in each discipline are made as additional information and design deficiencies are uncovered. As a result of following this approach, no major failure has occurred during SSME developmental firing for parts that could and did go through the rigorous 7½ hours, each axis, vibration testing. Failures have occurred but only in those areas not amenable to total lifetime testing as components.

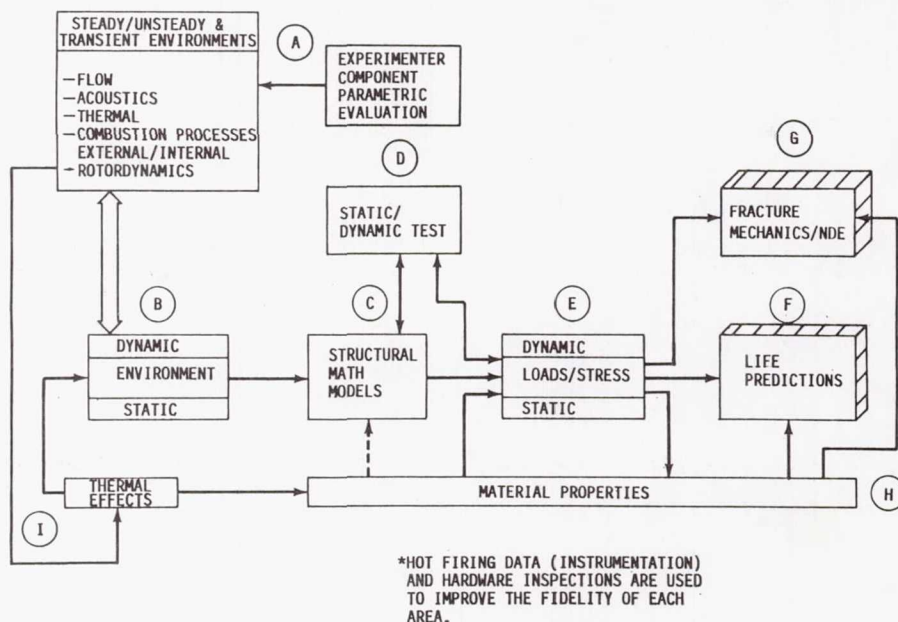
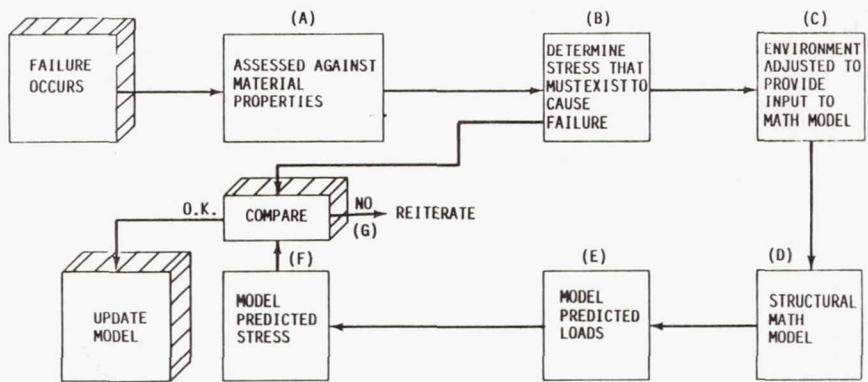


FIGURE 3. CLASSICAL DESIGN/ANALYSIS FLOW SCHEMATIC

The major challenge that faced SSME design was those parts which were sensitive to flow environments and not amenable to DVS testing. Analytical procedures were not, in general, accurate enough to predict environments and the engine could not be penetrated in all areas to measure the environments (References 10-15).

The criticality of the lifetime of certain engine components and the complex environment prediction problem have led to an alternate approach for determining high cycle fatigue limits, see Figure 4. A component failure is used as an empirical failure reference point, determining the stress level required for failure from the SN curve (minimum properties, maximum predicted temperature and pressures). The environments are "backed out" of these empirically derived data using the analytical dynamic model. The environments thus derived serve as a means of evaluating new designs and higher engine performance levels, as well as determining life limits.

The challenges of each of the major disciplines will be discussed. How these techniques were applied to the challenge of three typical design problems associated with lox posts, nozzle, and turbine blades will be illustrated.



- (1) EMPIRICALLY UPDATED MODEL CAN BE USED TO PREDICT REDESIGNED CONFIGURATION CAPABILITY.
- (2) THE INPUT ENVIRONMENTS ARE NOT ACCURATELY CHARACTERIZED
- (3) RESULTS ARE WELL ANCHORED BUT ARE ONLY RELATIVE IN TERMS OF ANY GIVEN ELEMENT DATA BASE.
- (4) ANALYSES AND TEST ARE BEING USED TO UPDATE AND IMPROVE FIDELITY OF ENVIRONMENTS (C)

FIGURE 4. SSME LIFETIME VERIFICATION ANALYSIS FOR SPECIAL PROBLEM AREAS

ENVIRONMENTS

The key to meeting the challenge of SSME design for lifetime prediction and verification is an accurate determination of the static and dynamic environments. As discussed previously, in the high pressure and high temperature regimes and in rotating machinery, large mean stresses exist which drive the accuracy requirements higher for both static and dynamic environments. Classically, these environments fall into the categories of thermal, mechanical, flow, and acoustics.

THERMAL ENVIRONMENTS

Definition of SSME component thermal environment is required to determine material properties, structural loads due to thermal gradients, and component performance. The challenge of this requirement is characterized by the following:

- Temperature extremes from -420°F to 1800°F.
- Complex fluid flow patterns.
- Intricate geometrical shapes.

- Exotic superalloy materials.
- Transient as well as steady-state phenomena.

This challenge was met by instrumentation at critical locations, analytical extrapolation of measured temperatures, and calculation of temperatures at internal locations inaccessible to instrumentation. In many cases, post-test hardware inspection revealed evidence that resulted in additional instrumentation and revision of models used in the initial characterization.

Instrumentation techniques vary from externally attached thermocouples and "plug in" type resistance thermometers to specially assembled "one of a kind" instrumentation systems for high response, wide range, transient measurements, such as that installed to assess high pressure fuel turbopump turbine inlet conditions. Special test fixtures and experimental models representing engine hardware were also used in instances where instrumentation of actual engine operation could not be effectively accomplished. This was necessary for thermal assessment of shields for the main injector lox posts. In addition, limited use of thermal coatings, temperature sensitive paints, and even metallurgical evaluation of metal discoloration contributed to establishing the limits of SSME thermal environments.

Analytical models of SSME components were used to evaluate temperatures at locations other than those discretely measured. In general, thermal models must interface with analyses of fluid flow fields to achieve boundary conditions and with structural analysis tools for meaningful evaluation of thermal effects on SSME capability and life. Examples of computer analysis codes employed in SSME thermal analysis are SINDA, NASTRAN, BLAYER, and TSONIC.

Analysis results are evaluated and updated by comparison to periodic inspection of actual SSME hardware. The spectrum of models utilized ranges from one-dimensional, constant property, steady-state hand calculations of average material temperatures to integrated three-dimensional, variable property, transient thermal/stress analysis of fatigue life.

Frequently, evaluation of test anomalies and/or component failures requires rapid assessment of component temperatures at specified locations. These analyses are performed with small special-purpose computer programs or hand calculations. Important hypotheses or conclusions reached in this manner are generally verified with more comprehensive analysis or by testing.

MECHANICAL VIBRATION ENVIRONMENTS

Mechanical environments are design drivers for many components, such as valves, ducts, and bellows. The sources of these vibration environments are rotating machinery, combustion, shock, valve actuation, etc. Figure 5 depicts the approach for working these environments. Initial design values were scaled from previous engine programs, such as H-1 and F-1. A comprehensive hot firing measurement program was developed for updating these predicted environments during the developmental firings. Vibration criteria have been gathered and put in statistical form for all major components at each power level. These data were statistically evaluated and stored in data banks.

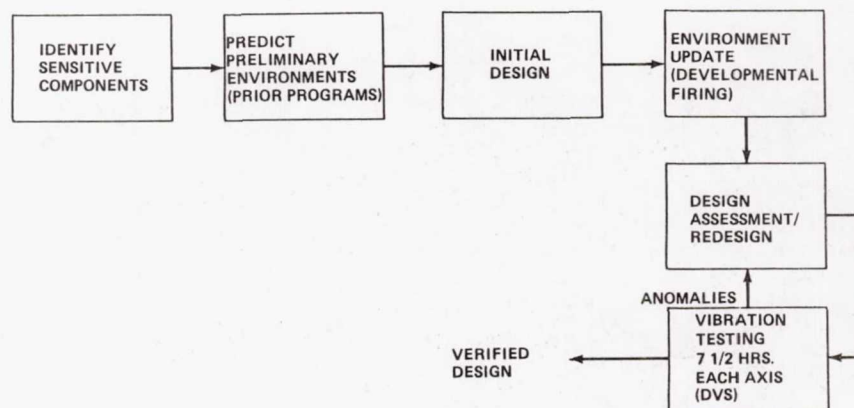


FIGURE 5. SSME VIBRATION ENVIRONMENT AND COMPONENT RESPONSE PROCEDURE

These vibration data serve as the criteria for vibration testing the components 7½ hours in each axis. This is a very comprehensive data base and has resulted in no major component failure of any parts that have passed vibration testing (not all components are amenable to vibration testing). In many cases, this testing showed design flaws that were corrected with the components subsequently passing the vibration testing. The combination of hot firing data acquisition and the DVS testing using these data solved the challenge associated with design and verification against vibration environments.

FLOW ENVIRONMENTS (FLUCTUATING PRESSURES)

As discussed previously, the sensitivity of the lifetime of SSME parts to alternating stresses places a demanding challenge on environment predictions, both static and fluctuating. The sources of these fluctuating pressures are blade pass from rotating machinery, acoustical resonances, turbulent flow, and flow instabilities. The challenge was met using previous engine test data, standard flow data from flow in ducts and bellows, etc., one- and two-dimensional codes, instrumentation during engine development hot firings, and special component flow tests. In all cases, the predicted environments were anchored using hot firing data, since predictions inherently have uncertainties incompatible with design accuracy requirements. Limited instrumentation access to the engine flow areas has restricted the amount of hot firing data that could be acquired. Data have been acquired in the hot gas manifold near the lox post, in the pump discharge areas, and in certain valves. Development of special instrumentation was required in the turbines and hot gas manifold. Stringent requirements exist for design, development, and verification of this instrumentation. As a result, an alternate approach was used for component failure cases by backing the environments out from the level of alternating stresses required to produce failure. The basic requirements for defining fluctuating environments have been met for the current engine. Challenges still exist in this area for 109% power level verification and upgrading to higher power levels. In the examples given later, some of these approaches will be briefly discussed.

DYNAMICS

Conventional state-of-the-art finite element structural modeling and response techniques have been used for the SSME to predict design and verification data. The challenge has been the choice of elements, material properties, and boundary conditions which are key since each component was analyzed as a unit. Two- and three-dimensional models were used throughout the program. Analysis of the total engine system has been limited since local conditions drive the individual component design with small influences from system dynamics. The basic approach has been to 1) develop finite element models of each component or subsystem; 2) construct generalized force distribution of the environments: flow, fluctuating pressures, thermal, mechanical vibrations; 3) determine resulting loads in order to arrive at design loads for strength, cyclic loads (low and high cycle) for lifetime predictions, see Figure 3.

Analytical models have been anchored using special dynamic test using sine sweep, modal dwell, and random testing techniques. Further verification has been obtained from developmental firing instrumentation in terms of strain gauges and accelerometers. Special dynamic tests have been run for total engine system, powerhead, lox post, nozzle, main fuel and oxidizer valves, and high pressure lox and fuel pump cases and rotors. Dynamic models have been adequate in all cases to define dynamic responses.

STRUCTURAL ANALYSIS

Stress, fracture mechanics, and strength analyses and tests, their accuracy and efficiency, and choice of design criteria are key elements in meeting the design challenge of the SSME to meet the mission, lifetime, refurbishment, and operational requirements. Conventional state-of-the-art stress analysis techniques were utilized throughout the design and development of the engine components. In the preliminary design phase, hand analysis solutions and selected finite element models were utilized to size the structure. As the program progressed and the design became more solidified, the majority of the critical components were analyzed through the use of either two-dimensional or three-dimensional finite element models, as applicable. In many cases, common models were used for both the dynamic and stress analyses, and, in some instances such as the turbine blades, the same model was used for detailed dynamic, thermal, and stress analyses. The finite element models included both elastic and plastic solutions as required. The design margins or factor of safety requirements utilized in the engine design were:

- Factor of safety on ultimate = 1.50 pressure only.
- Factor of safety on ultimate = 1.40 combined loads.

- Factor of safety on yield = 1.10.
- Factor of safety on low cycle fatigue = 4.0.
- Factor of safety on high cycle fatigue = 4.0 or 10.0, depending on adequacy of SN curve data base.
- Factor of safety on creep = 10.0.

The overall design goal was infinite life with at least a factor of 1.0 on the endurance limit, except for the rotating components in the turbomachinery where the factor of safety of 1.4 was used. When other design constraints prohibited meeting this design goal, the safety factors on life were utilized. Miner's rule for accumulated damage was generally used for assessing components subject to the combined effects of low cycle, high cycle, and creep damage. The majority of the engine components subjected to high cycle fatigue environments operate on the flat or close to the flat portion of the SN curve due to the combination of the 27,000-second life requirement and the operating frequency of the component, see Figure 2. This contributed to several high cycle fatigue failures during the research and development phase of the program, for example, the main injector lox post, which experienced several failures. In retrospect, it could be questioned whether it would have been prudent to design all life sensitive components to a higher factor against the endurance limit, such as 1.25, rather than 1.0. The larger factor would result in tradeoffs between weight, reliability, development costs, and performance.

The early design phase was further complicated by the lack of complete characterization of material properties for all of the extreme temperatures and environments. Much of the early analyses had to be accomplished with estimated properties until adequate characterization could be completed when all environments were finalized and schedule and cost permitted.

The structural reliability (ultimate load and life capability) was verified by such methods as hot firing developmental and certification testing, component static structural tests, proof tests, and laboratory vibration tests. These tests were utilized to verify the structural reliability of the critical components. Appropriate instrumentation, pressures, temperatures, environments, loads, cycles, etc., were utilized where applicable and practical for this accomplishment.

FRACTURE MECHANICS ANALYSES

The objective of the fracture mechanics analyses was to assess the flight engines fracture critical components for flightworthiness based on fracture mechanics logic and nondestructive inspection history. Fracture critical components were selected using the following guidelines:

1. Components made of Inconel 718 and whose operating conditions involve exposure to gaseous hydrogen temperatures which are determined to result in accelerated flaw rates.
2. All shrapnel-producing hardware such as turbine disks, pump inducers, or impellers.
3. Major structural elements loaded in tension or bending.
4. All turbopump housings.

Engineering judgment was applied with consideration of component function, failure effects, design complexity, and known material characteristics. The above selection logic resulted in approximately 300 fracture critical locations involving approximately 60 components on the engine. Figure 6 is a flow diagram of the fracture mechanics verification analysis procedure.

The application of fracture mechanics for the engine components was based on the following simple logic:

1. Determine the maximum size of any undetected flaw that may be present in the subject structure at the time it enters service.
2. Based on the results of 1., calculate the number of service loadings that will cause the undetected flaw to grow to critical size, thereby precipitating failure.
3. Compare the predicted number of service loading cycles before failure with the design requirements.

The information necessary to perform step 1. may be obtained from either proof testing or the inspection procedure used to detect flaws. When proof testing is used to determine the maximum

undetected flaw size, the analysis is called proof test logic. The stresses imposed during proof testing are related to the material fracture properties through fracture mechanics formulas which predict the maximum undetected flaw that would not precipitate proof test failure. When proof testing does not provide adequate structural assurance, NDE is used and based on the undetectable flaw size.

The preferred method for determining the maximum undetected flaw is the proof test logic approach, but due to the characteristics of the materials (tough ductile materials that exhibit stable flaw growth), this approach was only applicable to a few aluminum components. The NDE approach was, therefore, utilized extensively through the engine, both on the fracture critical and nonfracture critical components. It was the general policy to proof test all pressurized hardware, where feasible and practical, to a proof factor of 1.20 times limit design operating pressure, for 5.0 cycles to assure good quality hardware and a measure of structural integrity.

A program has been baselined which subjects high time hardware to teardown inspections periodically throughout the program to verify the fracture mechanics/NDE logic approach. As a result of these inspections, adjustments will be made to the procedure as required.

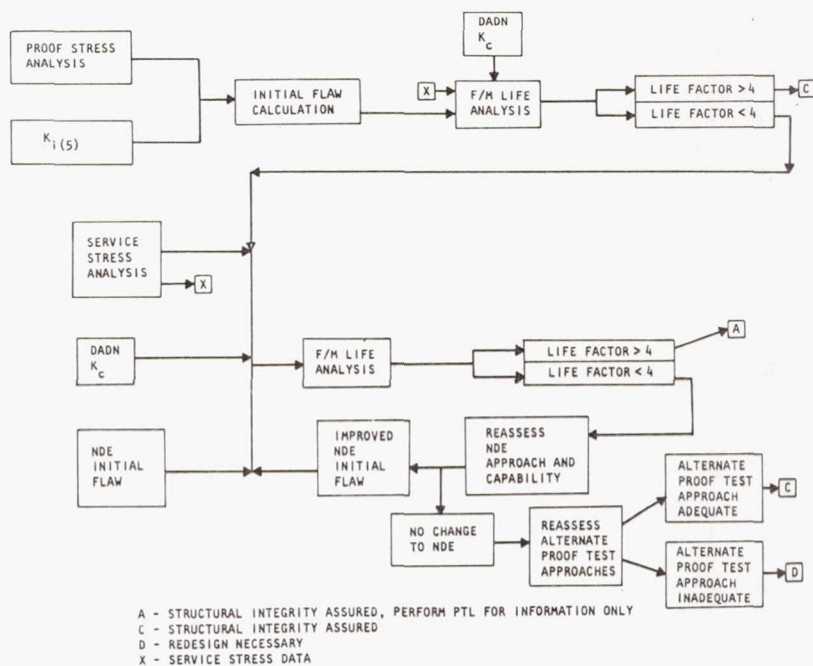


FIGURE 6. VERIFICATION ANALYSIS PROCEDURE

MATERIALS

The combination of design envelope requirements, complex service environments, and severe load conditions described in the preceding sections led to material performance criteria that were different from those normally encountered in high performance engine systems. Resistance to time-dependent, steady-state load conditions (i.e., creep and stress-rupture strength) were of minor importance due to the short operating lifetime of the SSME. Classical stress corrosion, while a consideration in material selection, was not encountered during the test and operational phases. Even the traditional material design allowables, ultimate and yield strength, within obvious limits would be viewed as having a relatively minor impact on the SSME design. Material considerations of major importance included high cycle fatigue (HCF), low cycle fatigue (LCF), and hydrogen environment embrittlement (HEE). Fracture mechanics/flaw growth characteristics had to be determined under conditions of HCF, LCF, and HEE (References 16 and 17). Finally, there was the extremely critical ability of the material to be "forgiving" with respect to unusual or unplanned manufacturing practices; this property will be loosely referred to as "fabricability" in the following discussion.

HIGH CYCLE FATIGUE

Although the life of the SSME is short in terms of operating time, high frequency vibrations and pressure fluctuations drive many of the structural components into the HCF-critical regime. A major deficiency existed in the HCF data base, due to the need for special-purpose materials that were not characterized in existing material properties manuals. This was compounded by operating conditions and temperatures which had major effects on HCF properties, often making it necessary to generate additional HCF properties for materials that were covered in the design literature. Synergistic effects of residual stress from transient loads and the relaxation of residuals during mainstage operations could only be measured in the laboratory. The effectiveness of standard HCF control procedures, such as shotpeening and stress relief, had to be confirmed under the operating environments of the SSME. The result was a long and continuing process, as follows:

1. Define the operating conditions.
2. Develop design criteria using available data and (conservative) rules for lower-bounding HCF behavior.
3. Fill the required need for additional data in the laboratory.
4. Check the validity of the assumptions made in 2.

The process is continuing, e.g., the turbine blade material, directionally-solidified MAR-M-246(Hf), has been evaluated for at least eight operating temperatures, five stress ratios ("R"), six test frequencies, and under numerous empirical conditions simulating turbine operating conditions. Figure 7 shows some of the data, addressing the question of test frequency effects. The evaluation of the HCF behavior of the turbine blade material is still in progress.

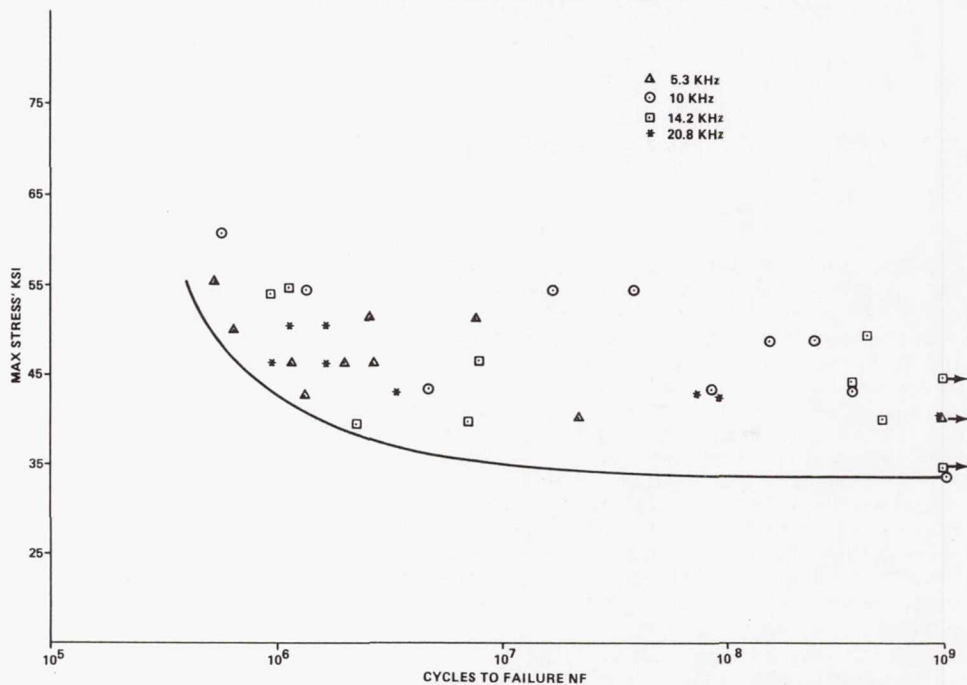


FIGURE 7. HIGH CYCLE FATIGUE DATA FOR MAR-M-246(Hf) DIRECTIONALLY SOLIDIFIED TURBINE BLADE MATERIAL, GENERATED AT ULTRA-HIGH FREQUENCIES

LOW CYCLE FATIGUE

Many areas in the SSME experience LCF conditions, loosely defined here as cyclic strain in the inelastic range. LCF level strains occur during transient startup and shutdown conditions, or as a result of thermal deformations during mainstage. Generally, one or two LCF cycles are applied per operating cycle, but the strain levels are very high, well in excess of the engineering yield strain. LCF data were obtained for all of the structural materials on the SSME and were used to develop design modifications to ensure adequate LCF life. This process is continuing; many SSME components are LCF-life limited.

HYDROGEN ENVIRONMENT EMBRITTLEMENT

Not to be confused with classical hydrogen embrittlement, HEE refers to the real-time effect of hydrogen on ductility and strength. It is generally limited to certain alloy systems operating in the inelastic strain range, but one of the affected material systems is the nickel-based alloys, which include the major structural material in the SSME, Inconel 718. HEE does not usually occur at cryogenic or elevated temperatures; it is only a design consideration at temperatures that would otherwise be considered benign, close to room temperature. A thin layer of nonsusceptible material is an adequate shield against HEE, hence control measures frequently include electroplating of copper, gold, and other materials. In cases where the area in contact with gaseous hydrogen is the underside of a closeout weld and is inaccessible for plating, welding techniques have been developed and characterized which involve an underlay and root pass made from a nonsusceptible material, see Figure 8. When possible, design modifications have been made to eliminate the conditions that cause HEE, such as stress concentrations (e.g., inelastic strains). Non-traditional concepts of materials usage have emerged in the control of HEE. For example, one common procedure involves modifying the operating temperature to move it out of the HEE range.

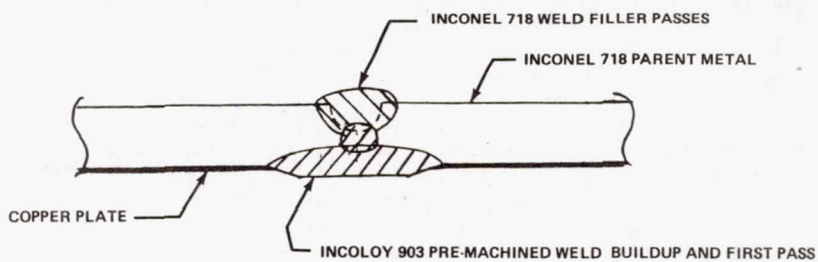


FIGURE 8. SPECIAL WELD UNDERLAY CONFIGURATION FOR CLOSEOUT WELDS IN HYDROGEN SYSTEMS

FABRICABILITY

Building an SSME is a sequential operation involving expensive, long lead items, usually joined by welding. Manufacturing discrepancies are inevitable, and it would not be feasible to scrap an assembly each time a major discrepancy occurred. Perhaps more than any other characteristic, "forgiveness" with respect to repairs and unconventional processing is a major consideration in material selection. For example, despite being susceptible to damage from a hydrogen environment, as noted above, Inconel 718 is the major structural material of the SSME. Laboratory tests have shown that the weld tensile and HCF properties are unaffected after as many as sixteen repairs in the same location. Solutionizing and aging times and temperatures can be varied over a wide range, with little effect on mechanical properties, so that furnace brazing and heat treatment can be accomplished in one operation. Undercuts due to mismatching are routinely filled in by welding and fairing, and the part is restored to design material requirements by heat treatment. Inconel 718 can be structurally welded to a large number of dissimilar materials by a number of welding processes, using many different filler materials. All of the preceding fabricability-related characteristics have been evaluated in the laboratory, and the resulting material design allowables have been documented. Additional requirements will develop as the SSME design continues to evolve in the direction of increased performance.

TYPICAL EXAMPLES

Typically, SSME lifetime problems have been characterized and solved in a unique manner. The large sensitivity of lifetime to small changes in alternating stress, temperatures, etc., moves beyond fluid flow analysis accuracy capability dictating that lifetime be determined from hot firing data in conjunction with analysis (Reference 10). The approach was discussed previously, see Figure 4. Using this approach in conjunction with the LRU concept has produced an acceptable solution to the challenge. Examples are now given of how the challenge was met.

LOX POSTS

The main injector is part of the hot gas section, which is the heart of the SSME. It includes a hot gas manifold, primary and secondary face plates, a lox dome, and 600 lox posts or feed tubes between the lox dome and the primary injector plate. Figure 9 shows a top plane view of the lox post array with the three transfer tubes from the hydrogen preburner and the two transfer tubes from the lox preburner.

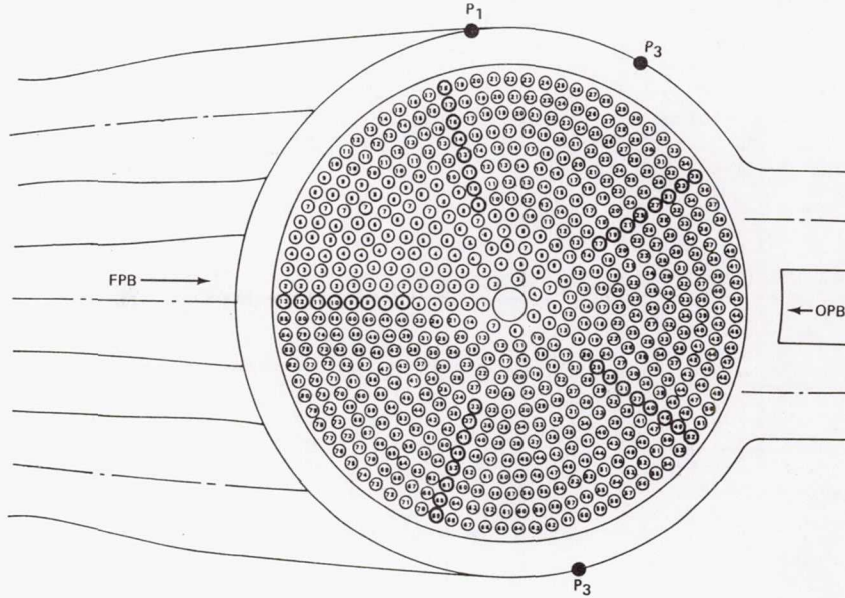


FIGURE 9. TOP PLANE VIEW OF LOX POST ARRAY

High velocity gas at a temperature of approximately 1800°F flows through the injector, then through the gap at the base of each post and around the tip of the injector plate, where it mixes with the liquid oxygen flowing down the center of the post. This flow environment, coupled with mechanical vibrations and variable dynamic characteristics, produces severe high cycle fatigue loading on the lox posts. This is augmented by high static stresses resulting from the thermal and static pressure loads. Flow shields (see Figure 10) have been added to the outermost row, but the posts are still high cycle fatigue life limited, and there have been two related engine failures during demonstration firings.

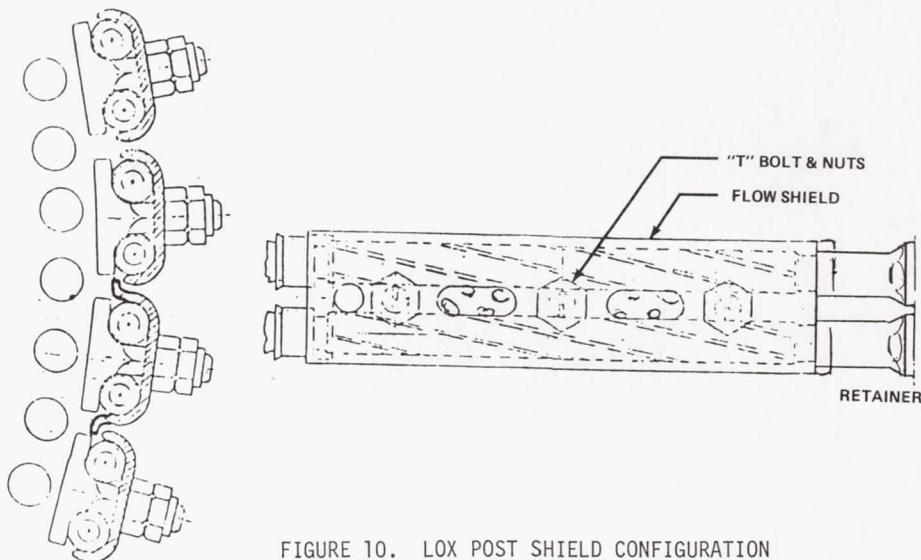


FIGURE 10. LOX POST SHIELD CONFIGURATION

Metallurgical analysis determined that the failure mechanism was high cycle fatigue, initiating in the threads of the face plate retainer. Sources of alternating stress at that point are mechanical oscillations, vortex shedding, and fluctuating pressures (flow and acoustics). Static loads arising from thermal gradients and internal flow induced pressures are superimposed as a high mean stress to the alternating loads. Despite the presence of the flow shields, the highest fatigue loads and most frequent occurrence of fatigue cracks are in the outermost posts, row 13.

The approach used to rationalize the hypothesized failure mode was the approach shown on Figure 4. Certain aspects of the problem can be handled analytically with good success. For instance, the analysis has shown a mechanical and fluctuating pressure environment in the 1200 Hz regime, which couples with and drives the modes (natural frequencies) of the posts; these analytical modes have been verified experimentally and by instrumented lox posts in hot firings. Cold flow tests of the hot gas manifold, powerhead, and lox post were used as a test bed for flow characteristics.

Demonstrated lifetimes from single engine firings have been combined with analytical data to arrive at lifetime predictions. Figure 2 is a plot of alternating stress capability versus number of cycles, taking into account static loads and temperature effects. Two empirical data points have been assumed: 1) a 750-second failure time for a single post, as observed in one engine test, and 2) the 5,000-second cracked post case demonstrated for shielded posts. The first bar is the alternating stress for the single post mode (750 seconds) showing the combined stress induced by mechanical and fluctuating pressure. The analysis was adjusted to predict high cycle fatigue failure in 750 seconds using mechanical and fluctuating pressure forcing function ranges based on best estimates from hot firing measurements. The second bar is the two-post flow shield predicted alternating stresses for mechanically and flow-induced oscillations using a model adjusted in the same manner (Reference 10). The model has been used to redesign the posts to assure long life and to increase engine performance from shield removal. The redesign involves a two-phased approach. Phase 1 is a change of material from CRES 316L to Haynes 188S (used in FPL engine configuration), raising the alternating stress allowable by approximately a factor of two. The second phase is a heavier post, which will further increase the alternating load capability.

TURBINE BLADES

The high pressure fuel turbopump (HPFTP) is a three-stage centrifugal pump that is directly driven by a two-stage hot-gas turbine. The turbine is powered by hot gas (hydrogen rich steam) generated by the fuel preburner. Hot gas enters the turbine and flows across the shielded support struts, through the first and second stage nozzles and blades, and is discharged into the hot gas manifold. Requirements for high performance within a restricted envelope have led to a complex, cyclic-load-producing configuration of 13 struts, 41 first stage nozzle vanes, and 59 second stage turbine blades. There have been numerous instances of cracking in both the first and second stage turbine blades at the locations shown in Figure 11. Although none has precipitated an engine failure, turbine blade life improvement remains a major goal in the SSME Program.

Loads analysis and lifetime prediction for the HPFTP turbine blades have presented problems similar to those encountered in the lox posts. Major problems have included environment definition, dynamic modeling, and static and alternating stress distribution. The environment definition is extremely complex for both the thermal and fluctuating pressure standpoints. The blades are near the preburner and use the hot preburner gas as the source of their power (flow forces). These environments are not uniform due to baffle posts, struts, etc., and the blade geometry. Fluctuating pressures present the same problem, plus the clear introduction of harmonics due to the struts and the multiblade passages. Dynamic modeling is complicated by the basic geometry, hot surface, boundary conditions at the wheel, and special dampers for reducing blade response. Stress is composed of static centrifugal force, power bending, steady-state thermal, cyclic thermal (start and shutdown transients), and fluctuating pressure components. Significant factors in the alternating stress are 1) tuning of strut wakes with blade lower modes, 2) multiblade relative motion of adjacent blades, 3) variable damping coefficients and lockup, 4) changes through engine operating range, and 5) startup and shutdown thermal and pressure cycles.

Each instance of blade cracking has been addressed using an analytical/empirical approach similar to that described for the lox posts; loads and stresses are calculated by analysis, and the models are adjusted as required to be compatible with observed phenomena. A detailed finite element model has been generated for the blades. Detailed definition of the forcing functions has been accomplished by accurate modeling of the strut/nozzle/blade configuration, and the output has been matched to results obtained from special air rig and "whirlygig" tests. Basic material strength and fatigue data have been obtained over a range of operating stresses and temperatures. Figure 12 shows the form of the engineering solution with all of the data taken into consideration, including the observed frequency of the particular blade cracking incident under investigation. Curve 1 is for rated engine

power level (RPL) assuming 5,000 seconds of life. Curve 2 is full or maximum engine power level (FPL) and 5,000 seconds of life, while curve 3 is the same power level assuming 2,500 seconds of life. The mean stress for RPL is 46 Ksi, and for FPL, it is 55 Ksi. The blade operating temperature is in the 1,600 to 1,700 degree range, resulting in a low allowable alternating stress.

At the present time, there are no serious blade cracking problems. Each instance of blade cracking has been solved by material-related improvements or environment modifications. Periodic inspections are required, however, and the average blade changeout interval of 3,000-5,000 seconds is far short of the design goal of 27,000 seconds. Studies for long-term improvement in blade life are in progress. Improved materials are being considered, including advanced superalloys in the single crystal form, and environment reduction techniques are under study.

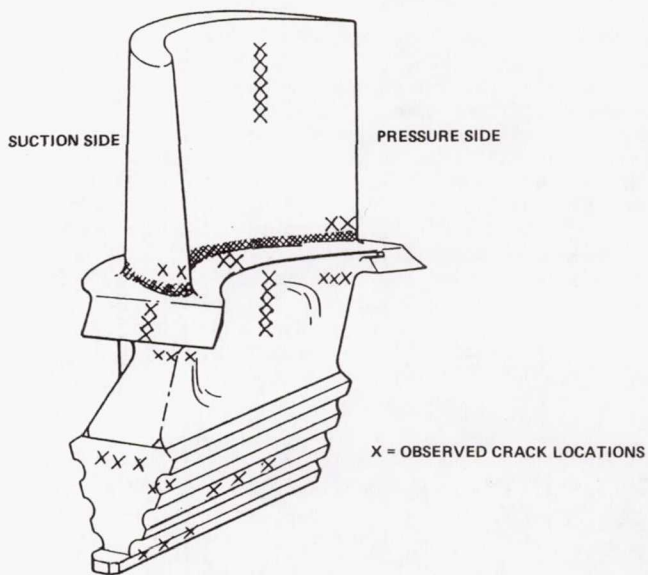


FIGURE 11. AREAS OF HIGH STRESS AND OBSERVED CRACK FORMATION

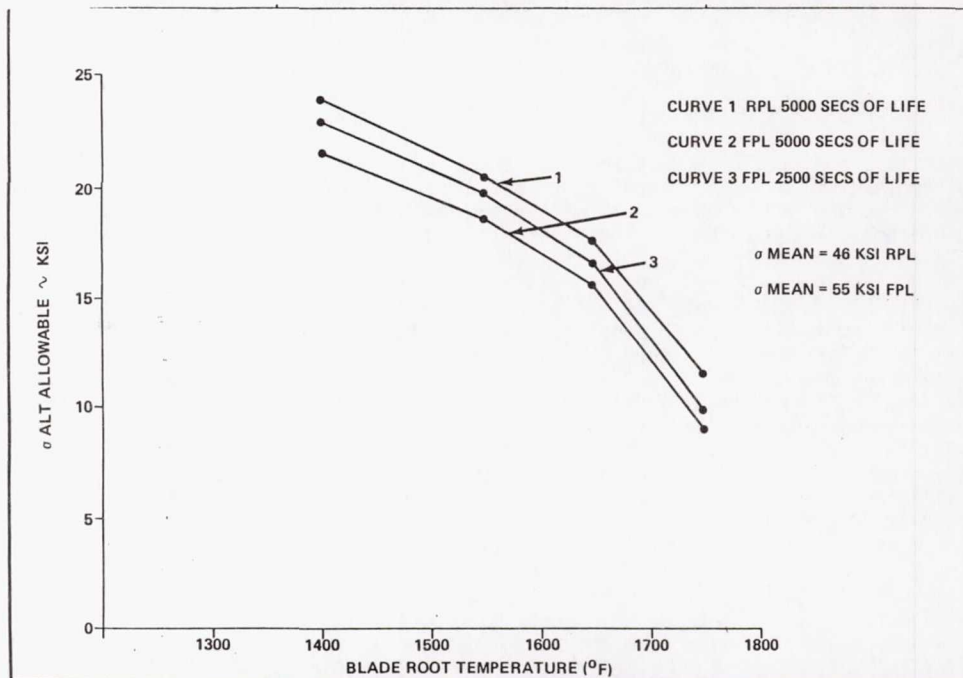


FIGURE 12. ALTERNATING STRESS VERSUS BLADE ROOT TEMPERATURE ALLOWABLE

NOZZLE AND STEERHORN ENGINE SIDE LOADS

The SSME nozzle has three engine downcomer coolant lines that take hydrogen from the main fuel valve to the aft nozzle manifold. The aft nozzle manifold feeds the coolant tubes which in essence is the engine nozzle. Two of these coolant lines have failed during hot engine firings due to high cycle fatigue. Figure 13 gives the basic configuration, showing the downcomer line (steerhorn). A history of cracking nozzle tubes has also plagued the engine.

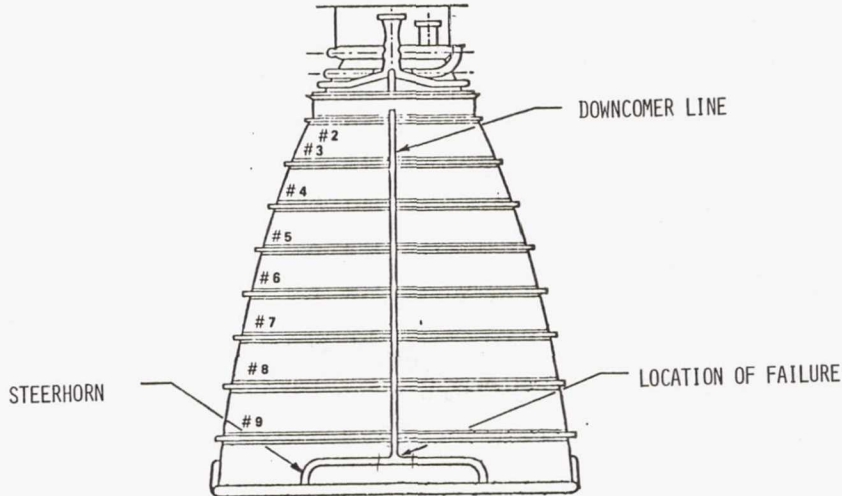


FIGURE 13. DESCRIPTION OF NOZZLE SYSTEM

The loads on the line nozzle system arise from firing of a high-expansion-ratio nozzle under ground atmospheric conditions. The plume does not fill the nozzle until the internal pressure is greater than atmospheric pressure. As the nozzle plume flow velocity increases, it passes through a region where a Mach disc or cone exits the nozzle. Two distinct phenomena occur during this thrust buildup phase. The first occurs around 600 to 700 psia chamber pressure. In this case, the plume is basically cylindrical in nature and is directionally unstable, moving around radially within the nozzle. The loads induced by this case drive the actuator design. The second occurs around 1,200 psia where the Mach cone leaves or enters the nozzle, creating high local shock loads. Figure 14 shows a typical thrust buildup and shutdown curve and stress response measured on the nozzle steerhorn. The side loads response is clearly shown in this figure. The large strain amplitude occurs due to the excitation of the $n = 0$ (expansion mode) and the $n = 6$ (shell mode). Notice that the response is very sharp and around 250 Hz (the insert shows a blowup of the response) (References 10, 13, 14, 15, and 18).

Figure 15 depicts the $n = 6$ shell mode on the right-hand side. The left-hand side of the figure shows the shell mode frequencies as a function on n -number. At the bottom of the figure is a spectrum of the measured acceleration of the engine nozzle aft manifold showing presence of all n modes but by far the larger peak occurring for the $n = 0$ and $n = 6$ modes.

The presence of this large load at the discrete frequency of 250 Hz (near resonance with nozzle modes) created many engine design and program problems, particularly during the developmental firing program. Two things had to be accomplished. The undersized steerhorn had to be fixed so that firings could continue, and the steerhorn had to be redesigned for operational flights. Since initially an internal nozzle pressure forcing function was not available, it was decided to take the hot-firing measured accelerations at the aft manifold and use these to base drive a dynamic model of the steerhorn. The first major result obtained was that just thickening the tube helped the problem. The increased mass offsets the increased stiffness so the frequency stays the same. The nozzle-induced driving force is not changed; therefore, the increased mass increases the steerhorn loads proportionally to the mass increase. As a result, a sensitivity analysis and redesign matrix was pursued as a means of obtaining a solution.

The conclusion of this study was that the horizontal run of the steerhorn must be fixed to the nozzle stiffness ring to reduce loads. This meant that a steam loop had to be incorporated above the hatband to take out thermal induced expansion loads. The other main result was that for the T area (original design) a nickel-plating would provide adequate life for developmental engine firings and first Shuttle flights. The redesigned steerhorn was incorporated on the FPL engines.

ENGINE 0007, TEST 901-250

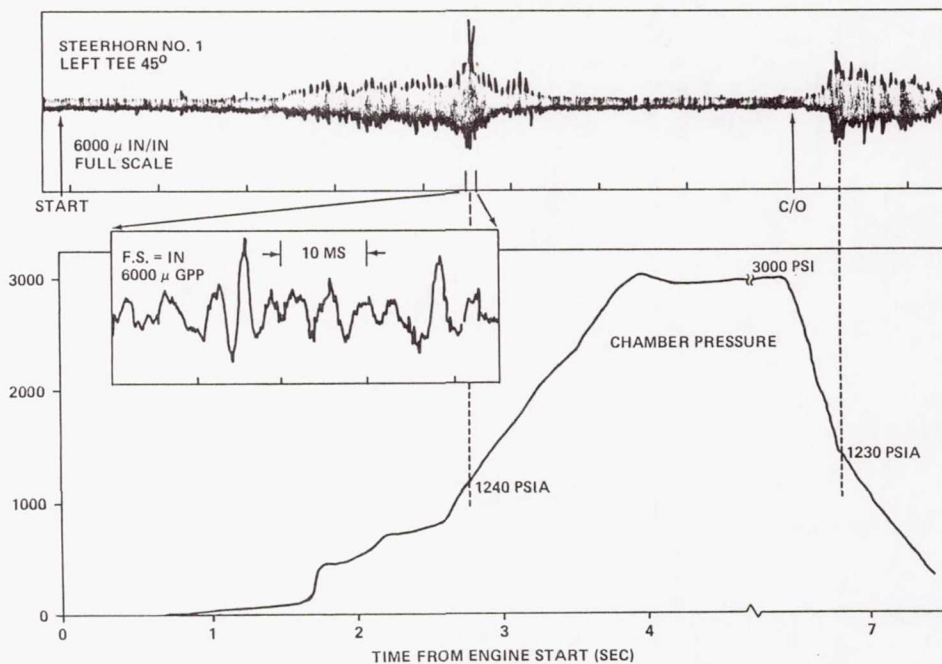


FIGURE 14. STEERHORN STRAINS IN TRANSIENT OPERATION

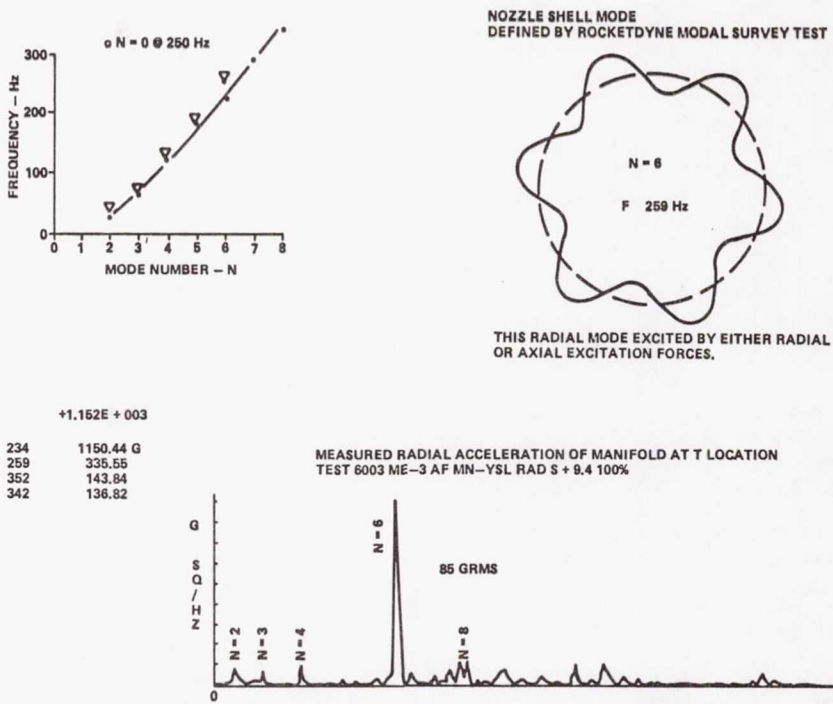


FIGURE 15. NOZZLE SHELL MODE DEFINED BY ROCKETDYNE MODAL SURVEY TEST

Two test programs were instituted to finalize these loads and the redesign: Scale model engine cold-flow test and full-scale flight nozzle dynamic test. The dynamic model used in this analysis was verified in a full-scale dynamic test. Analytical modes had good agreement with test modes. The cold-flow model test varied the flow rate, etc., and determined the forcing functions. A full set of pressure gauges was mounted so that the force distribution could be determined. These results were scaled to full scale.

Using these test-derived forcing functions, a dynamic response analysis was made for both the original design and the redesigned steerhorn configurations (steam loop). Good agreement with hot-firing data was obtained. The reduction in loads is approximately 40 percent for the redesigned case, providing infinite life. Table 1 is a summary of stresses measured in hot-firing data for the nonsteam loop configuration.

TABLE 1. HOT-FIRING DATA SUMMARY

DATA BASE	STRAIN AT T LOG DISTRIBUTION*			
	START		CUTOFF	
	MEAN	3σ	MEAN	3σ
A1 (14 TESTS)	3,262	10,537	5,033	15,642
A2 (20 TESTS)	3,876	16,503	1,636	6,529
MPT (3 TESTS, 7 ENGINES)	6,270	20,685	4,916	12,088
MPT & A1	4,064	18,469	4,938	13,552
COMBINED ALL STANDS (41 TESTS)	3,954	17,084	2,722	21,528
COMBINED ALL STANDS ALL MEASUREMENTS ALL EVENTS 41 TESTS		19,053		

*CONTAINS NO EXTRAPOLATED DATA.

Test stand A-2, which has a simulation for altitude (reduced pressure), showed different characteristics from the other stands. Based on this analytical work and the statistics of the hot-firing data, a lifetime prediction of the redesigned steerhorn was accomplished verifying a redesign that would meet the 55-mission lifetime requirement.

CONCLUSIONS

The design, manufacturing, and verification of the SSME has been one of the major challenges in obtaining an operational Space Shuttle. Basic problems have been met with a high performance engine and acceptable refurbishment requirements. Additional efforts are required for efficient refurbishment regimes and to have the potential for higher performance to meet future Shuttle mission requirements.

The first six Shuttle flights had engine performance as predicted with no failures. Using the LRU concept, some pumps were changed out as planned. The engine system has met the basic design challenges.

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