Structural Requirements for the Space Propulsion Engine Systems

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In January 2004, the National Aeronautics and Space Administration (NASA) was given a vision for Space Exploration by President Bush, setting our sight on a bold new path to go back to the Moon, then to Mars and beyond. As NASA gets ready to meet the vision set by President Bush, failures are not an option. Reliability of the propulsion engine systems will play an important role in establishing an overall safe and reliable operation of these new space systems. A new standard, NASA-STD-5012, Strength and Life Assessment for Space Propulsion System Engines, has been developed to provide structural requirements for assessment of the propulsion systems engine. This standard is a complement to the current NASA-wide standard NASA-STD-5001, Structural Design and Test Factors of Safety for Spaceflight Hardware, which excluded the requirement for the engine systems (rotatory structures) along with pressure vessels. As developed, this document builds on the heritage of the multiple industrial standards related to strength and life assessment of the structures. For assuring a safe and reliable operation of a product and/or mission, establishing a set of structural assessment requirements is a key ingredient. Hence, a concentrated effort was made to improve the requirements where there are known lessons learned during the design, test, and operation phases of the Space Shuttle Main Engine (SSME) and other engine development programs. Requirements delineated in this standard are also applicable for the reusable and/or human missions. It shall be noted that "reliability of a system cannot be tested and inspected but can only be achieved if it is first designed into a system." Hence, these strength and life assessment requirements for the space propulsion system engines shall be used along with other good engineering practices, requirements, and policies.

Introduction

NASA has a very well-defined program and process to develop a set of standards for use in design, development, and certification of flight hardware. This was necessitated to provide uniformity across NASA centers and in response to the federal law[1] which requires the use of industry standards, where available.

In response to this standard's development activity, a new standard for Structural Strength Requirement, NASA-STD-5001[2], was developed and released. Since the release of this standard, all new programs have been using this standard as the first choice for designing new spacecraft and vehicles. However, at the release of this document, rotatary hardware (engines) and pressure vessels were not included in the scope of this document.

As we initiated new propulsion system engine development programs, since the commencement of the new standard, NASA-STD-5001, it was noticed that no NASA-wide standard and/or industry standard is available which outlines the Strength and Life Assessment Requirements for the Space Propulsion System Engines. Although a historical standard, Marshall Space Flight Center's MSFC-HDBK-505[3] could still be used. It was also realized that there are some requirements which need to be enhanced based upon the lessons learned. MSFC-HDBK-505 (and as modified by the Prime contractor and accepted per Contract End Item) was primarily used as a basis for the design of the SSME. Hence, a request was made and accepted by the NASA Technical Standards Program to develop a dedicated Strength and Life Assessment Requirements for the Space Propulsion System Engines.

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Procedure

Design of high-performance engines for space application requires an interaction of multiple inputs as shown in Figure 1. A good criteria plays a strong role since operating environments are very harsh (extreme cryogenic or high temperatures, high pressures, propellant/material interaction), and there is a need for keeping the low weight for maximum payload capacity, etc.

While developing this standard, the developer took special care to assure that criteria should be concise and based upon good engineering judgment (since, a criterion for primary application in space industry should not constrain innovation and stifle creativity.) A balance is required to assure reliable mission operation yet be lightweight and affordable. Also:

a. Regardless of popular belief, engineers are human beings; we are prone to make errors. Hence we need design margins to guard against the errors.

b. Objective of the good "structural assessment" is to predict success, not failures.

c. Engine/Component reliability cannot be analyzed *in*, it must be designed *in*.

Hence, this new standard was developed with the following as its basis:

1. Use historical requirements, where possible

2. Incorporate lessons learned, where applicable

3. Adopt/refer to non-Government voluntary standard (industry) where available and applicable

As proposed, this standard provides strength and life assessment requirements for all NASA space propulsion system engines. Life, as used in this standard, refers to fatigue and creep. In addition, test requirements for qualification and verification assessment are specified

Strength Criteria

Design safety factors are intended, as listed in popular textbooks, to cover for:

a. To allow for accidental overloading of structure, as well as for possible inaccuracies in the construction and possible unknown variables in analysis of the structure.

b. Although not commonly used, perhaps a better term for this ratio is factor of ignorance.

c. A factor of safety is used in the design of structures to allow for (1) uncertainty of loading, (2) the statistical variation of material strengths, (3) inaccuracies in geometry and theory, and (4) the grave consequence of failure of structures

Hence, a set of factor of safety are defined. These requirements are mostly based upon the historical requirements currently being used and are expressed by reference to other standards. Currently, factor of safety requirements are verified using the primary stresses/strains which do not account for secondary stresses/strains (e.g., thermal and/or misalignments). Hence, a new requirement for strain to crack initiation margin is being proposed for total loads. Having a factor safety requirement for total strain will guard against a design which may result in strain to crack initiation. In addition, it is recognized that for some applications, it may be appropriate and necessary to use additional design factors such as fitting factors, casting factors, impact factors, etc., in conjunction with the factors of safety specified in Table 1. For example:

a. Brazed, welded, and bonded joints require other special factors consistent with their processing and criticality, but shall be at least as severe as those in Table 1.

b. Margins of safety on performance-driven clearances (for example, in turbo machinery) are generally calculated using a safety factor of one. Margins of safety in situations intended to prevent impact, such as an engine fully gimbaled, shall use a safety factor of 1.4 at MDC loads, i.e., the clearance must be zero or positive at 1.4 X MDC loads.

c. The factors in Table 1 shall be used with well-behaved and well-understood materials. For materials not in this category, additional factors may be required. For example, titanium alloys have been shown to be susceptible to failure near the yield load. For titanium alloys, the maximum peak stress (the total concentrated stress from all sources, i.e., MDC loads) shall be less than 80 percent of the material minimum-yield strength.

Fatigue Criteria

The requirement established here enhances the requirements in the fatigue analysis area. It shall be recognized that the propulsion system is a critical element of the spacecraft system and has been found to be the primary cause of failure[5] (Figure 2).

During the initial design of the SSME, a Fatigue Analysis Factor (FAF) of 1.0 and a Service Life Factor (SLF) of 4.0 was used. In certain cases, where high-cycle fatigue properties were based upon limited or no data, a SLF of 10 was used. This resulted in extensive repair, inspection and hardware refurbishment to guard against operation-related fatigue cracking noted during the ground test program, and post-flight inspection. Subsequently, as high pressure turbopumps were redesigned, fatigue criteria were revised to use a FAF of 1.15 and SLF of 10.0. This criterion resulted in a reduced rate of fatigue-related cracking. It is interesting to note that SSME prime contractor, Rocketdyne, also realized that fatigue-related criteria needed an enhancement and proposed that for redesign of SSME components, a minimum of 500 cycles with a FAF of 1.5 for low-cycle fatigue and a factor of 1.0 on endurance with a FAF of 1.25, or equivalent alternate stress, for high-cycle fatigue shall be used as a good design practice[6].

Similarly, for the Space Transportation Main Engine[7] program a SLF of 10 was proposed to guard against low and high-cycle fatigue cracking along with a FAF of 1.15 in 1992. Hence, during the write-up of the proposed requirements, a balance was made to strengthen the criteria for rotatory parts of the engines where failures are less forgiving and maintain the current requirements for the stationary components but use the service life factor of 10.0 to reduce the potential of fatigue-related cracking and assure it does not result in weight penalty.

Hence it is proposed that all structural elements shall be designed and analyzed to demonstrate the following factors:

(1) A FAF shall be multiplied by the limit stress/strain prior to entering the S-N design curve to determine the low-cycle/high-cycle life. The FAF shall be:

FAF = 1.25 Rotating components

FAF = 1.15 Non-rotating components

(2) Service Life Factor. The low-cycle factor (LCF) and high-cycle factor (HCF) analyses shall demonstrate a minimum calculated life of 10.0 times the service life.

Test Verification

Based upon the experience gained during the SSME test verification process and weibayes statistical analysis, it is recommended that at least six units be tested for extended duration to assure the reliability of the mission. (Figure 3)

For multiple units/multiple use propulsion systems, the following criteria needs to be considered in order to establish test program requirements:

a. Reliability for initial mission use requires minimum amount of testing regardless of mission-life requirements

b. Basic material/load scatter, difficulty in measuring localized strains

- Reliability for continued engine use requires sustained ground testing

- Multiple units at or near fleet leader are required

Summary

The purpose of the proposed standard is to provide a consistent set of requirements in the design and assessment of space propulsion system engines. As we design/develop new engine systems which use the philosophy of minimum-risk. These enhanced requirements should help alleviate the fatigue-related cracking, improve reliability, and reduce the redesign and maintenance cost. These requirements are intended to provide strength and life criteria in conjunction with other good engineering practices; e.g., attention to details while designing the stress concentration areas to avoid sharp radii, specifying appropriate surface finish. Hence, these strength and life assessment requirements for the space propulsion system engines shall be used along with other good engineering practices, requirements, and policies.

Acknowledgements

The author is indebted to Mr. Gwyn Faile for guiding, mentoring, and developing the criteria; and to his colleagues across the other NASA centers in reviewing and providing constructive comments. The author is also appreciative of the NASA Technical Standards Program office for funding the development of this standard. Additionally, author also acknowledges that some material presented here was adopted from miscellaneous presentations prepared by other present and past NASA colleagues.

References

1. OMB Circular A-119: Federal Participation in the Development and Use of Voluntary Consensus Standards and in Conformity Assessment

2. NASA-STD-5001: Structural Design and Test Factors of Safety for Spaceflight Hardware

3. MSFC-HDBK-505, Structural Strength Program Requirements

4. NASA-STD-5012 (draft): Strength and Life Assessment Requirements for Space Propulsion System Engines

5 NASA-Pub8-1086, adopted from Launch Space magazine article written by Charles Gunn (January 1999)

6. Rocketdyne Memo: Structural Analysis Procedures: SSME Redesign Guidelines

7. MSFC-HDBK-1997: Space Transportation Main Engine Structural Strength and Life Program Requirements

Figure 1

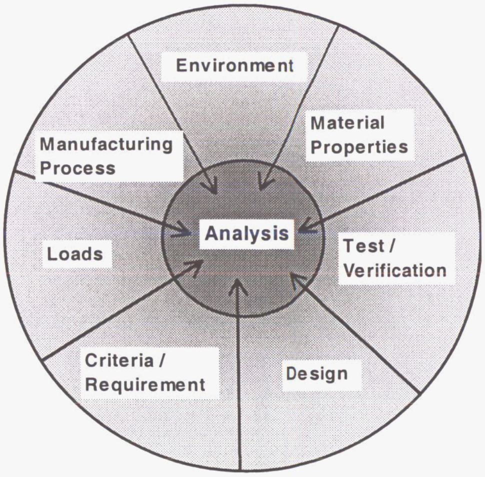


Figure 2

Lessons Learned

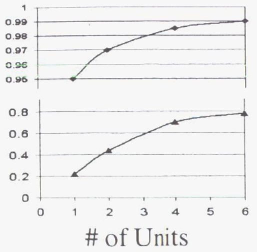
External, independent review teams judging the flight readiness of a vehicle should keep in mind the following key lessons gleaned from the past 20 years of space launches:

1. Propulsion systems are the primary cause of all launch failures. All propulsion test and checkout anomalies/failures demand special attention and review.
2. Hardware built out of normal sequence and hardware that has been reworked are major causes of failures. The processes, procedures, quality inspections, and particularly the re-test results demand special review.
3. There are no small, inconsequential changes in flight-critical components or subsystems. Systems engineering and every affected technical discipline must be involved in the assessment of all new systems and their changes. If a change is not recertified by test, the rationale must be thoroughly examined.
4. Test results that are "in-family," but near the edge of the acceptable envelope, should be thoroughly examined. Usually there is a subtle message. Always believe test data until they are conclusively proved wrong beyond all doubt.
5. All test anomalies/failures must be thoroughly understood and convincingly explained. All hardware that is potentially related to an unverified system anomaly/failure must be purged from the system before launch.
6. The flight environments and dynamic loads that set the qualification and acceptance test levels of each flight-critical component must be rigorously validated by a continuum of flight measurements and analyses.

% Reliability with 95% confidence

(Assumption: Weibays distribution,

no failure)



First mission of 500 seconds assuming each unit has been tested for 30,000 seconds

Mission at or near Fleet leader/2 assuming each unit has been tested at or near Fleet leader

Figure 3

Table 1—Minimum Analysis Factors Of Safety And Strength Test Factors

Engine Hardware Type	**Load**	**Mode of Failure**	**Analysis Factor of Safety** [1]	**Test Factors** [2]	
				Qualification	**Acceptance/ Proof** [3]
Metallic Structures and Components					
Yield	mechanical only	net section	1.10 [4]	NA	NA
Ultimate	mechanical only	net section	1.40	1.40	NA
Ultimate	MDC	stability	1.40	1.40	1.20
Ultimate-pressure or rotation	MDP or spin	net section	1.50	1.50	1.20 [5, 6]
Ultimate	MDC	point strain	2.00 [4]	1.40	1.20
Pressurized components (pressure vessels, lines, fittings, fluid return sections and hose, bellows, etc.)	MEOP, MDP, or MDC as applicable	MIL-STD-1522 or ANSI/AIAA S-080, ANSI/AIAA S-081, AFSPCMAN 91-710			
Fasteners and Preloaded Joints					
Yield	MDC	net section	1.10 [4]	NA	NA
Ultimate	MDC	net section	1.40	1.40	1.20
Joint Separation	MDC	separation	1.20	1.20	1.20
- Safety Critical [7]	MDC	separation	1.40	1.40	1.20
Composite and/or bonded structures and components – ultimate strength					
Uniform areas	MDC	point stress	1.40	1.40	1.20 [5]
Stress concentration areas	MDC	point stress	2.00	1.40	1.20 [5]
Bonds/joints	MDC	point stress	2.00	1.40 [5]	1.20 [5]
Ablatives	MDC	point stress	1.70 [8]	1.40 [5, 8]	1.20 [5]
Pressure checkout with personnel present					
Yield	checkout pressure	Note 9	1.50 [4]	NA	NA
Ultimate	checkout pressure	Note 9	2.00	NA	NA

Notes:

1. Margins must be written using the specified analysis factor of safety for all the specified loads and modes of failure.
2. Minimum factors which shall be used in the test program to be defined in the SAP for a specific project.
3. Fracture control may require higher factors if the proof test will be used for flaw screening.
4. For titanium alloys, the maximum peak stress (the total concentrated stress from all sources, i.e., MDC loads) shall be less than 80 percent of the material minimum yield strength.
5. These tests are always required.
6. Test pressure = MDP x 1.20 x ECF ≥ 1.05 x MDP
   Test speed = √ (MDC speed^2 x 1.20 ECF) ≥ √ (MDC speed^2 x 1.05)
7. Joints for which separation would be a catastrophic event.
8. Analysis and test factors apply at end of life. Qualification test occurs on a hot-fired (fully ablated) flight-type test article.
9. Net section for metallic, point stress on ultimate only for composites or adhesive bonds.

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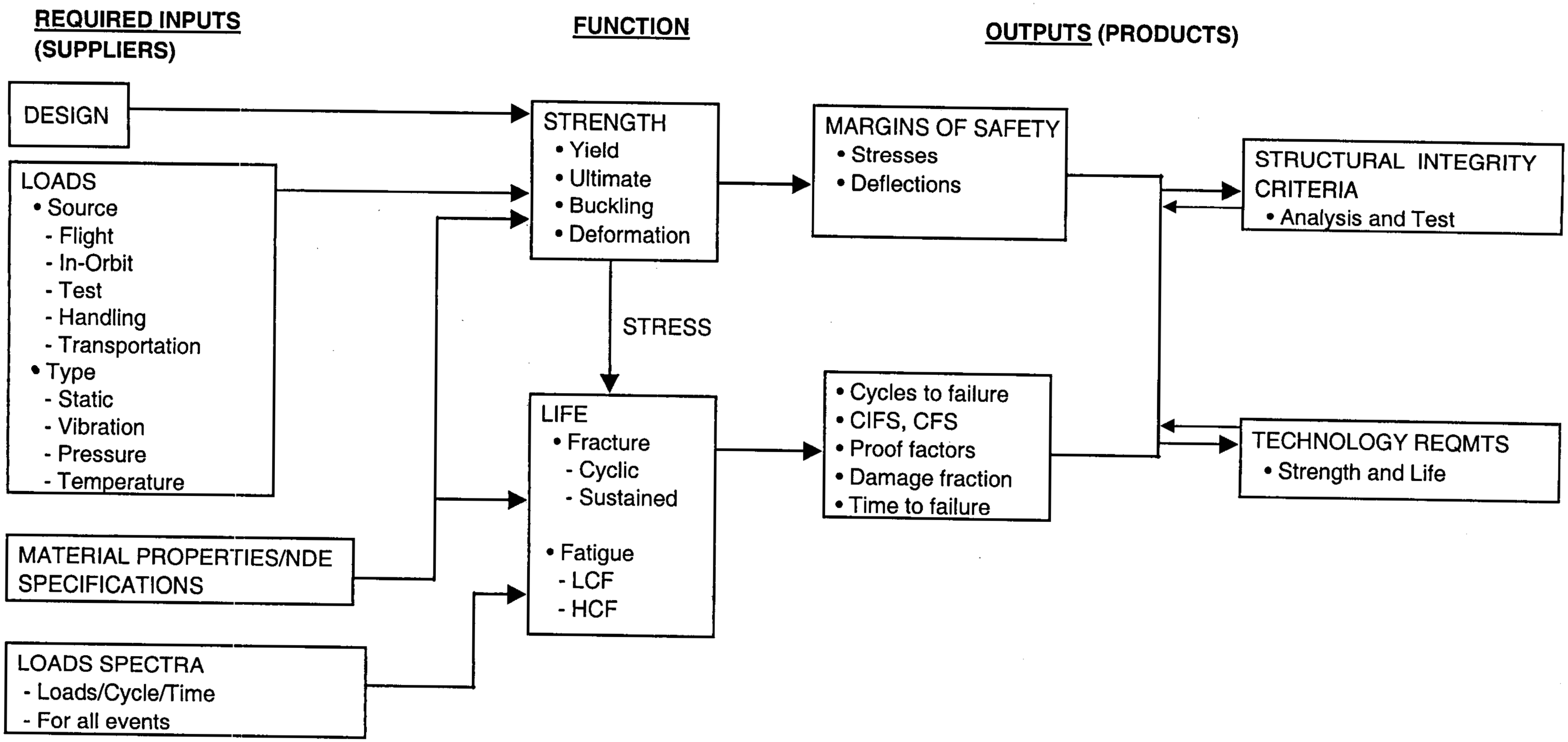
STRUCTURAL ASSESSMENT PROCESS

- **Goal: To recommend structural margins which provide a hardware structural framework for best supporting the achievement of the requirements given current state of the art knowledge of analytical tools, loads, and material properties.**
  - Ensure structure has the capability to successfully withstand the specified loads for the required life.

- **How we meet those objectives:**
  - Analyze structural integrity and determine design capability to withstand applied forces and environments
  - Develop test requirements and evaluate test results
  - Design Verification
  - Assure appropriate margins are maintained with respect to applicable standards and criteria

STRUCTURAL ASSESSMENT PROCESS

Ensures that the structure has the capability to successfully withstand the specified loads for the required life



REQUIRED INPUTS
(SUPPLIERS)

DESIGN

LOADS
- Source
  - Flight
  - In-Orbit
  - Test
  - Handling
  - Transportation
- Type
  - Static
  - Vibration
  - Pressure
  - Temperature

MATERIAL PROPERTIES/NDE SPECIFICATIONS

LOADS SPECTRA
- Loads/Cycle/Time
- For all events

FUNCTION

STRENGTH
- Yield
- Ultimate
- Buckling
- Deformation

STRESS

LIFE
- Fracture
  - Cyclic
  - Sustained
- Fatigue
  - LCF
  - HCF

OUTPUTS (PRODUCTS)

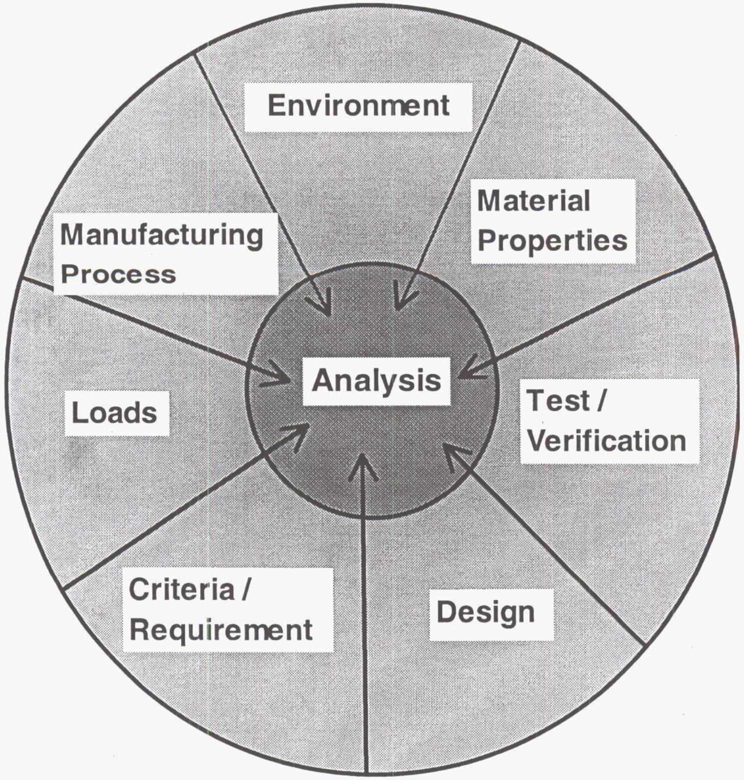
MARGINS OF SAFETY
- Stresses
- Deflections

- Cycles to failure
- CIFS, CFS
- Proof factors
- Damage fraction
- Time to failure

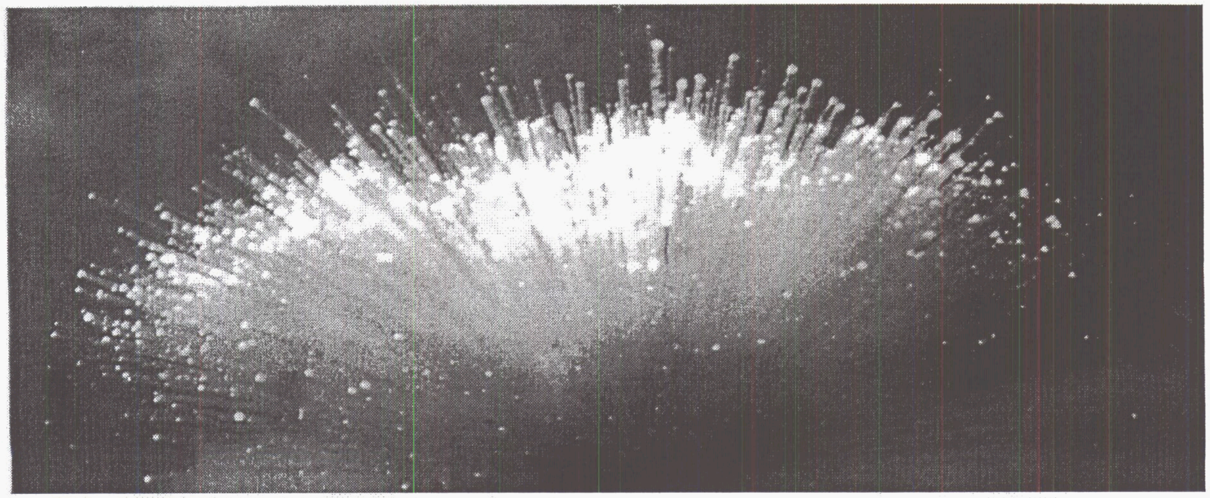
STRUCTURAL INTEGRITY CRITERIA
- Analysis and Test

TECHNOLOGY REQMTS
- Strength and Life

Structural Analysis System



LESSON LEARNED



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1. Propulsion systems are the primary cause of all launch failures. All propulsion test and checkout anomalies/failures demand special attention and review.
2. Hardware built out of normal sequence and hardware that has been reworked are major causes of failures. The processes, procedures, quality inspections, and particularly the re-test results demand special review.
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6. The flight environments and dynamic loads that set the qualification and acceptance test levels of each flight-critical component must be rigorously validated by a continuum of flight measurements and analyses.

Ref: NASA-Pub8-1086

Safety Factors/Service Life Factors

- **Factors of safety (safety factors).** Multiplying factors to be applied to limit loads or stresses for purposes of analytical assessment (design factors) or test verification (test factors) of design adequacy in strength or stability.

- **Service life factor (life factor).** A multiplying factor to be applied to the maximum expected number of load cycles in the service life to determine the design adequacy in fatigue or fracture.

- **These factors protect against?**
  - Analysis assumptions
  - Manufacturing anomalies
  - Damage (possibly unknown)
  - Environmental anomalies

- **These factors do <u>not</u> protect against uncertainties related to other disciplines e.g.**
  - Material
    - Properties scatter
  - Loads
    - Variation

Safety Factors

- Regardless of popular belief, engineers are human beings, we are prone to make errors. Hence we need design margins to guard against the errors”
- Objective of the good “structural assessment” is to predict success, not failures
- Criteria shall address unique application requirements
  - A systematic, inter-disciplinary, integrated approach which has intentionally incorporated design margin (e.g., lesson learned)
- Engine/Component reliability can not be analyzed in, it must be designed in

- Hence, this new standard was developed with following as the basis:
- 1. Use historical requirements, where possible
- 2. Incorporate the lesson learned, where applicable
- 3. adopt/refer to non-Government voluntary standard (Industry) where available and applicable

Safety Factors

Table 1—Minimum Analysis Factors Of Safety And Strength Test Factors

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Pressure checkout with personnel present					
Yield	checkout pressure	Note 9	1.50[4]	NA	NA
Ultimate	checkout pressure	Note 9	2.00	NA	NA

Fatigue Criteria

-Fatigue Analysis Factor (FAF). A FAF shall be multiplied by the limit stress/strain prior to entering the S-N design curve to determine the low-cycle/high-cycle life. The FAF shall be:

FAF = 1.25 Rotating components

FAF = 1.15 Non-rotating components

-Service Life Factor. The LCF and HCF analyses shall demonstrate a minimum calculated life of 10.0 times the service life.

(Proposed criteria is an enhancement/modification of the current criteria used for the SSME design, Rocketdyne fatigue criteria, and proposal by Rocketdyne for redesign of SSME components to reduce the fatigue related cracking)

Rocketdyne Fatigue Criteria

Baseline

Volume 2
Section 5.0, Part 5.1

5.0 FATIGUE AND CREEP RUPTURE ANALYSIS

5.1 FATIGUE AND CREEP RUPTURE DESIGN CRITERIA

Each Rocketdyne component that experiences cyclic loading during operation, excluding cyclic wear, will be designed to the following fatigue criteria:

Low-Cycle Fatigue Life = 4 x service life operational cycles

High-Cycle Fatigue Life = Life at 1.25 x the equivalent alternating stress for all stationary components
or
Life at 1.4 x the equivalent alternating stress for all rotating components.

Proposed for Redesign

Volume 5
Section 1.0, Part 1.8

Although contractual requirements specify a factor of four on both high- and low-cycle fatigue life, and a factor of 1.4 on stress rupture, prudent design practice should reflect the following goals:

A factor of 1.25 on endurance limit for three sigma equivalent alternating high-cycle fatigue stresses and a factor of 1.0 on endurance limit for a 10% increase in gas temperature (temperature in Rankine) or 50 degrees, whichever is larger.

A transient shock fatigue life greater than 10,000 cycles.

A low-cycle fatigue life greater than 500 cycles at 1.5 x predicted cyclic strain range.

An ultimate safety factor of 1.4 on 30-hour stress rupture strength at the predicted operating temperature, and a factor of 1.0 on 75-hour stress rupture for a 10% increase in gas temperature (temperature in Rankine) or 50 degrees, whichever is larger

Fatigue Factor: Why 10 and A-basis material properties?

Fatigue:

- Design life with LCF factor of 10 increases durability.
- Factor of 10 encourages design choices which reduce fatigue sensitive components, premature fatigue crack initiation, increased inspections, and early component retirement.
- Most LCF strain-life data in the low life regime are driven by necking effects due to tensile overload with large plastic strains.
- Fatigue factor of 4 used for SSME -SSME QRAS analysis around .999.
  - SSME AT pumps use extra factor of 1.15 of material curve resulting in equivalent factor of 6-7.
- Just about all structural failures in rocket engines are related to fatigue.
- Used in Fastrac 60K Engine, and also proposed during the STME engine.

"A-Basis" material properties:

- Fatigue life curve is on Log scale, this masks a lot of variability.
- "A-Basis" minimum by definition is .99 probability with 95 % confidence.
- To reach .99999 against failure, a margin against A-basis minimum is a must.

Causes of Fatigue Problems

Stress Concentrations-

Small fillet radii, weld mismatch, weld bead, heat affected zones, porosity, abusive machining.

Thermal Gradients-

Through thickness gradients, thermal shock, local operation at minimum material capability due to temperature distribution of part.

Material Property effects-

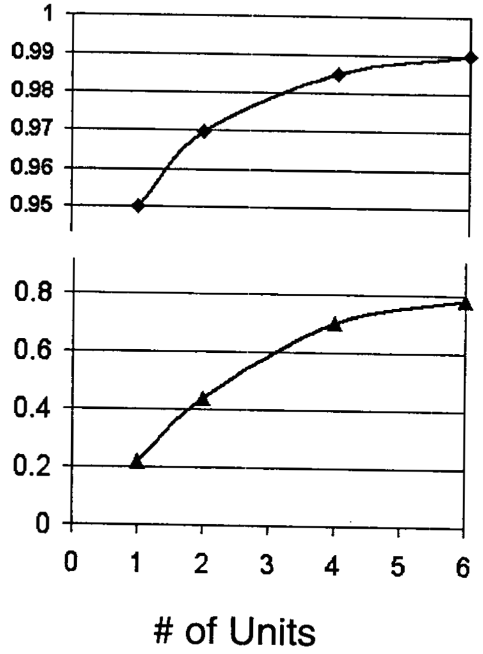
Surface finish, hydrogen embrittlement, steam effects, shot peening reversals.

Design solutions for increased fatigue margins do not increase weight.

Increased fatigue margins promote creativity and attention to detail areas in the design cycle.

Test Requirement

- Test Requirement Determination: For multiple units/multiple use propulsion system, the following need to be considered to establish the test program requirements:
  - Reliability for initial mission use requires minimum amount of testing irrespective of mission life requirements
    - * Basic material/load scatter, difficulty in measuring localized strains
  - Reliability for continued engine use requires sustained ground testing
    - * Multiple units at or near fleet leader are required



% Reliability with 95% confidence

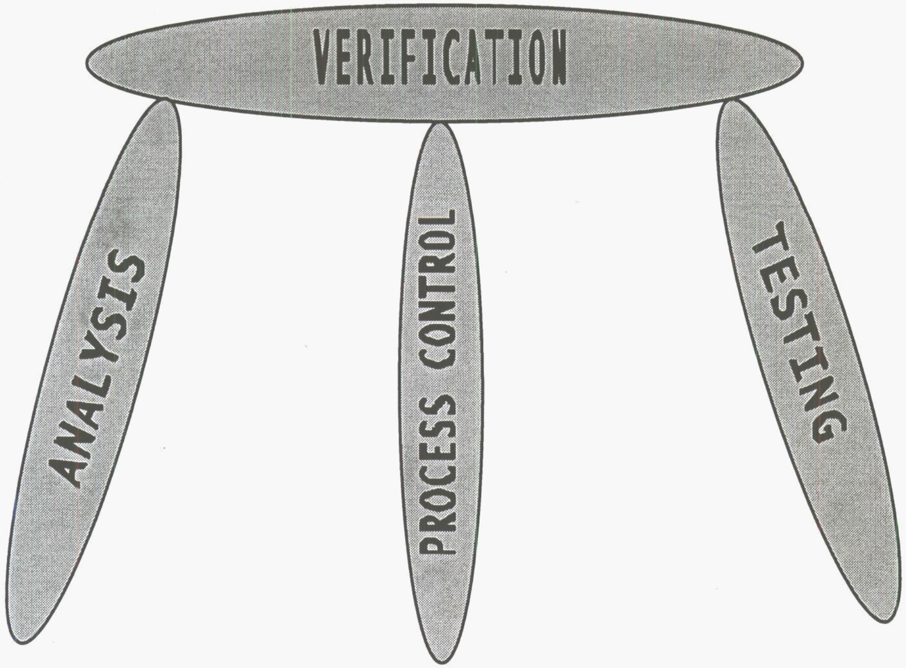
(Assumption: Weibays distribution, no failure)

First mission of 500 seconds assuming each unit has been tested for 30000 seconds

Mission at or near Fleet leader/2 assuming each unit has been tested at or near Fleet leader

Hence, Six units are recommended. (also, supported by the SSME test verification process)

VERIFICATION PROCESS



VERIFICATION

ANALYSIS

PROCESS CONTROL

TESTING

-If all these three elements of design verification system are systematically and satisfactory completed, a design is considered to be verified and acceptable for service
-Inspection, post completion of testing, is must for proper verification
-0Selection of appropriate hardware for testing i.e., represents fleet tolerance is another important factor
-Test Configuration shall representative of flight configuration

CONCLUSION

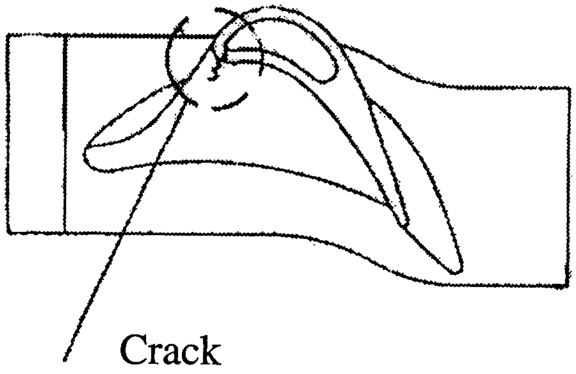
- **Increased structural margins result in greater reliability.**
- **Current SSME factors of safety and current knowledge of material properties & load environment provide similar to SSME hardware life management issues.**
- Improvement in life reliability demands robustness: Higher factors of safety and increased knowledge of materials and load environment.
- <u>There are no shortcuts in the improvement of structural capability/reliability of rocket engine hardware.</u>

SSME Examples of Fatigue life limiting problems

- Powerhead: G6 flange cracks, transfer tube liner cracks, preburner liner cracking.
- Main Injector: Interpropellant plate cracks, LOX post stubs.
- MCC: Inlet & outlet life.
- Nozzle: Steerhorn, aft manifold slam ring bolt hole cracks.
- HPOTP: Turbine housing seal groove, turbine disc, turbine blades.
- HPFTP: Turbine sheet metal, turbine inner ring, turbine disc, turbine blades.
- HPOTP-AT: Turbine inlet, turnaround ducts, turbine blades.
- HPFTP-AT: Discharge housing vanes, turbine inlet, turbine housing, turbine vanes, turbine blades.

EXAMPLE: HPFTP/AT Turbine Blade

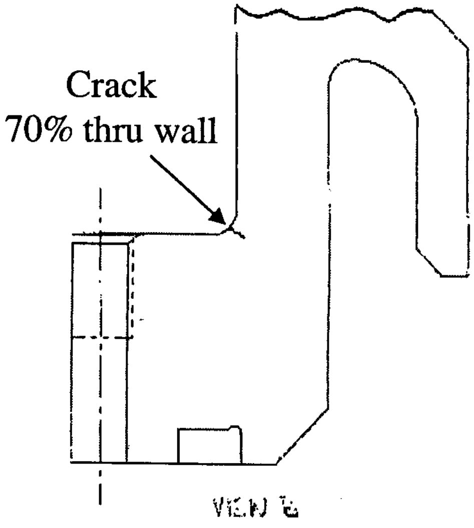
- **SSME Examples of LCF life limiting problems encountered:**
- **HPFTP-AT Turbine Blade Core Tip cracking (10/97):**
  - First stage blade tip cracks were found in 118 of 362 turbine blades out of 8 pump builds.
  - Finite element model stress analyses indicated significant increases in stress (118 vs. 56 ksi nominal) due to the smaller radius, flats and reduced edge wall thickness.



- **Solution**
  - Increased leading edge nominal radius from .0125" to .25".
  - New ceramic core manufacturing die that relocated the parting line away from the core leading and trailing edges was being fabricated.
  - Changes were reflected in certification testing.
- **Conclusion**
  - Increased fatigue life due to attention to detail area with good design practice of increasing radius.
  - No weight effects.

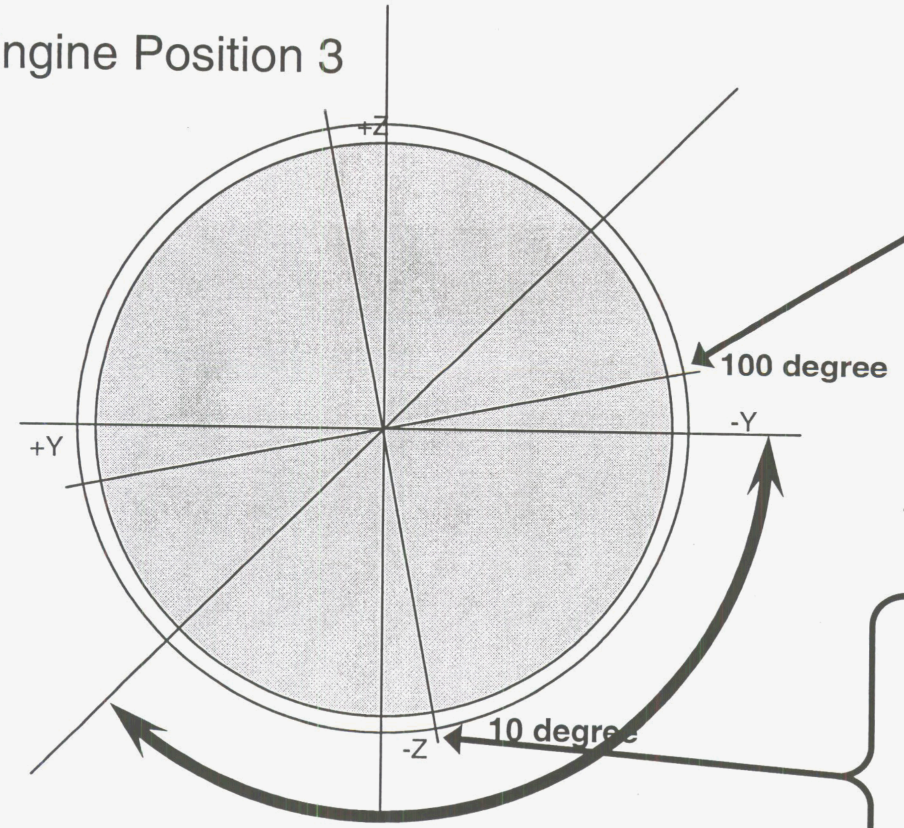
EXAMPLE: HPFTP Turbine Housing

- **SSME Examples of LCF life limiting problems encountered:**
- **HPFTP-AT Turbine Housing Fillet Cracking.**
  - XXX FPI inspection of the turbine housing revealed extensive cracking in the barrel to diaphragm fillet. Unit 9-1 had 32 starts and 19292 seconds.
  - LCF and fracture toughness testing results in GH2 indicate lower than expected values at 500 deg F.
  - Attempted radius increase from .070" to .105". Program decided that design was too far along and change had potential for unknown interaction with 2E response.
- **Solution:**
  - Gold coating and improved surface finish to increase LCF life. 5x improvement shown in testing.
  - Long term redesign initiated.
- **Conclusion:**
  - Fatigue life increased.
  - Increased cost due to the introduction of gold coating late in program.
  - No weight effects.

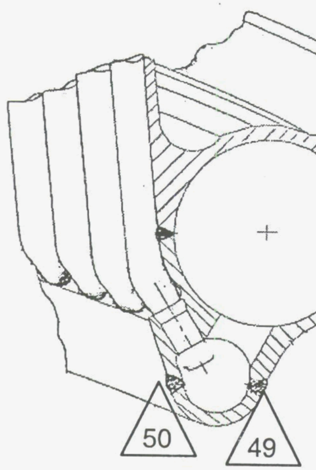


EXAMPLE: SSME Nozzle Aft Manifold

Engine Position 3



Current Ablative Area



100 degree location

Location	Allowable LCF Life	
	No Braycote	Braycote
50 O.D.	**41**	**41**
50 I.D.	83	71
49 I.D.	500	425
49 O.D.	833	833

10 degree location without ablative

Location	Allowable LCF Life	
	No Braycote	Braycote
50 O.D.	84	84
50 I.D.	276	74
49 I.D.	**25**	**7**
49 O.D.	51	51

10 degree location with ablative

Location	Allowable LCF Life	
	No Braycote	Braycote
50 O.D.	**50**	**50**
50 I.D.	262	223
49 I.D.	625	531
49 O.D.	833	833

* Note: The six o'clock position is the zero degree location

EXAMPLE: Nozzle Stubout Cracking

-Four nozzles with confirmed fatigue cracks (by sectioning)

-Lowest time Nozzle 4018: 37 starts / 19,931 seconds (Starts/Seconds at sectioning. Cracks initiated earlier)

-High stress at stubout causing LCF cracks

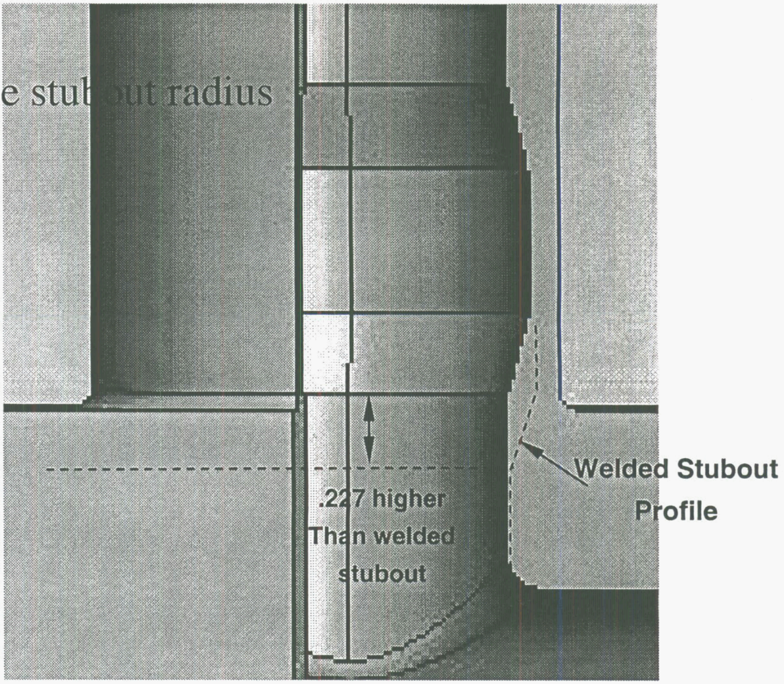
-Weld repairs and/or wide welds extended into the stubout radius

-Embedded linear defects in some welds

-Embedded non linear defects at welds

-Weld surface defects

- **Revised Design:**
- **Integral stubout holds thicker section through radius at platform.**
  - Transition point moved upward by .227
  - Cross section area increased at fillet radius
- **Risk of developing fatigue cracks in fillet radius is reduced for integral stubout configuration**
- **Integral extension retains ID change to meet steerhorn wall thickness**



Conclusion: Better design practice, attention to details needed as design modification