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MANAGEMENT OF SSME HARDWARE LIFE UTILIZATION

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ABSTRACT

Statistical and probabilistic reliability methodologies are developed for the determination of hardware life limits for the Space Shuttle Main Engine (SSME). Both methodologies require that a mathematical reliability model of the engine (system) performance be developed as a function of the reliabiiities of the components and parts. The system reliability model should be developed from the Failure Modes and Effects Analysis/Critical Items List. The statistical reliability methodology establishes hardware life limits directly from the failure distributions of the components and parts obtained from statistically-designed testing. The probabilistic reliability methodology establishes hardware life limits from a decision analysis methodology which incorporates the component/part reliabilities obtained from a probabilistic structural analysis, a calibrated maintenance program, inspection techniques, and fabrication procedures. Probabilistic structural analysis is recommended as a tool to prioritize upgrading of the components and parts.

The Weibull probability distribution is presently being investigated by NASA/MSFC to characterize the failure distribution of the SSME hardware from a limited data base of failures. Methods are outlined to derive a file of values of the shape parameter β of the Weibull distribution (i.e., "β-bank") from failure data obtained for hardware on the SSME and other pump-propelled rocket engines, from material specimen testing, from probabilistic structural analysis, and from expert judgment.

Other recommendations include the development of concise definitions and identification measures of the mechanical failure modes of the hardware in the failure data collection process to facilitate statistical failure data analysis, the calibration of failure distributions derived from probabilistic structural analyses with the failure distributions derived statistically from testing, and the development of a decision analysis methodology to determine hardware life limits when limited failure data is available.

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1.0 INTRODUCTION

During the Mercury, Gemini and Apollo-Saturn programs, NASA developed rocket propulsion systems with high reliability since most were expendable and maintenance could not be performed. Since the 1970's, however, NASA has been challenged with the development of the reusable Space Shuttle Main Engine (SSME) to be designed for 55 Shuttle Orbiter launches, which is 27,000 seconds of operating life. In launch, the three Orbiter SSMEs operate in parallel with the Solid Rocket Boosters (SRBs) for approximately 2 minutes until SRB separation. The SSMEs then continue to burn for a total of about 8 minutes from launch until the Orbiter is near the desired orbital velocity.

The SSME is a high performance, liquid propellant rocket engine with variable thrust. The SSMEs use liquid oxygen and liquid hydrogen propellants, which are stored in the External Tank attached to the Orbiter, and operate at a mixture ratio (LOX/LH_2) of 6:1. Each SSME uses a staged combustion cycle to power the turbopumps with high combustion chamber pressure. First, the staged combustion cycle consists of partial propellant combustion in the preburners at high pressure and relatively low temperature. The propellants are then totally combusted at a high chamber pressure of approximately 3000 psia and a high temperature in the main combustion chamber (MCC) before expanding through the nozzle which has an area ratio of 77.5:1.

Each SSME produces 470,000 lbs. of thrust at rated power level (RPL) and is throttleable from 65 percent RPL to 109 percent, which is full power level (FPL) and 512,000 lbs. of thrust. The SSMEs are designed, fabricated, and maintained by Rockwell International/Rocketdyne Division (RI/RD) for NASA/Marshall Space Flight Center (MSFC). Further descriptions and performance of the SSMEs can be found in Schwinghamer (1976), Johnson and Colbo (1981), Klatt and Wheelock (1982), McCarty and Wood (1983), and Ryan et al., (1983). To date, the SSMEs have collectively acquired approximately 38,000 seconds of operation in 25 launches and a total of 270,000 seconds of combined test and launch time.

2.0 PROBLEM STATEMENT

The reusability requirement with minimum maintenance for quick turn-around time, the high operating temperatures and pressures, and the limited Congressional funding for the Space Shuttle program provide the major engineering challenges for the design, fabrication, and maintenance of a highly reliable SSME. For reliability and maintainability, the SSME can be considered as a system composed of a number of components and parts as shown in Figure 1. The terms "system", "components", and "parts" will be used throughout this paper and are defined as follows:

System: Group of components integrated to perform specific operational function(s).

EXAMPLE: SSME

Component: (Subsystem) Collection of parts which represents a self-contained entity of a complete system and perform a function necessary to the operation of that system.

EXAMPLES: High Pressure Fuel Turbopump (HPFTP)
Main Combustion Chamber (MCC)
Main Fuel Valve (MFV)

Part: Least subdivision of a component which cannot be disassembled without destroying it.

EXAMPLE: HPFTP: Blades, Impellers, Seals, Bearings, Welds, etc.

RI/RD (1984) illustrates the SSME engine, component, and part configurations and gives the acronyms for the hardware used in this paper. A number of components such as the four turbopumps (LPFTP, HPFTP, LPOTP, and HPOTP), valves, ducts, instrumentation, igniters, nozzles, and controllers have been designed as line replaceable units (LRUs) to facilitate field maintenance, automatic checkout, and internal inspection capabilities. A number of the SSME components/parts are life-limited due to low-cycle (LC)/thermal fatigue, high-cycle fatigue (HCF), and cyclic creep. One of the major SSME challenges to date is the quantification of reliable life limits for the SSME hardware.

Reliable life limits for engine parts are established by the aircraft industry from sufficient testing of the components and parts. The aircraft industry develops an engine using the "bottom-up" approach (e.g., Hill, 1977; Gibson, 1985). Extensive testing and redesign is done at the component/part level during the developmental phase of the engine to verify component/part reliability. From adequate testing of the parts and components, the probability distribution of the time (or number of cycles) to failure of each life-limited hardware is developed. The hardware life limit is then determined from the failure distribution to achieve a given reliability level. With this approach, "surprise" failures and redesign problems are minimized during engine level testing and the operational phase. The reliability of the components, parts, and hence, the engine, is well-understood.

The SSME, however, has been developed using the "top-down" approach. The SSME has been designed, fabricated and launched with relatively little developmental testing of the materials, components, and parts. Because of Congressional budgetary restraints, virtually all testing has been/is being conducted at the engine (system) level. This approach for engine development has caused several significant engineering problems in quantifying life utilization of the SSME hardware:

1. Because component/part level testing has not been conducted on the SSME, the reliability of the SSME hardware and the life limits cannot be quantified statistically from the failure data. For most life-limited hardware, none to only a few failures have been observed. Generally, no life-limited component or part is used in flight if it has accumulated time greater than 50% of the fleet leader time of that hardware. What procedure should be used to establish reliable utilization of life-limited SSME hardware?

2. During engine level testing and flight, 26 significant SSME failures have occurred due to a variety of different component/part failures (Vance, 1986). Fifteen of these failures occurred prior to the first launch of the SSMEs on the Shuttle Orbiter Columbia on April 12, 1981. Preliminary Flight Certification (PFC) and Full Power Level Certification (FPLC) are based on accumulating 10,000 seconds on each of two engines for a 10-flight capacity to provide a safety factor of 2. Is engine testing sufficient to prevent the random occurrence of future SSME failures?

3. The SSME has been designed using the factor of safety (FS) approach with the following values for the FS (RI/RD, 1974):

   - 1.5 for ultimate, pressure only
   - 1.4 for ultimate, combined loads
   - 1.1 for yield
   - 4.0 for LCF
   - 10.0 for HCF
   - 10.0 for creep

   The FS concept, however, does not measure the reliability or failure probability and does not quantify the uncertainty associated with the SSME design parameters. The uncertainty associated with the SSME design parameters can be divided into statistical and nonstatistical uncertainties as follows:

- Statistical uncertainty (can be quantified from data)
  - Operating environment
    - Thermal environment
    - Pressure
    - Other design loads
  - Material properties
    - Ultimate, tensile strength
    - Compressive strength
    - S-N fatigue curves
    - Fracture-related properties
  - Dimensions (tolerances)
  - Inspection procedures
- Nonstatistical uncertainty (associated with the assumptions and thermal/stress/fatigue models used in the structural analyses)

How can the above uncertainties be incorporated into a methodology to reliably establish life limits for the SSME hardware?

3.0 OBJECTIVE

This paper proposes that SSME hardware life utilization should be established from a reliability methodology rather than from a factor of safety approach. From a reliability approach, the SSME hardware life limits should be determined from the reliabilities of the parts and components, R_p and R_c, respectively. Two reliability methodologies are presented in this paper:

1. A statistical reliability methodology (Quantitative reliabilities are calculated)
2. A probabilistic reliability methodology (Qualitative reliabilities are calculated)

Figures 2 and 3 outline the statistical and probabilistic reliability methodologies, respectively. Both reliability approaches require that a mathematical reliability model of the engine (system) be developed as a function of the reliabilities of the parts and components. The two methodologies differ in the procedure which is used to develop the reliabilities of the components and parts and to establish hardware life limits.

The advantages and disadvantages of both methodologies are outlined in Table 1. The application of each methodology to establish SSME hardware life limits depends on the available data and on the objective of the reliability analysis. If the objective is to quantify the hardware life limits to maintain a specified hardware reliability, then the statistical approach should be used. On the other hand, if limited failure data is available, then a probabilistic reliability methodology should be utilized as a tool to establish hardware life limits from a cost-benefit analysis which considers the design parameters uncertainties, maintenance program, inspection techniques, and fabrication procedures.

In the statistical reliability methodology outlined in Figure 2, the SSME hardware life limits are determined from the apportioned reliabilities R_p and R_c required to achieve the desired SSME target reliability R_E. The required reliabilities R_p and R_c are verified during the developmental phase of the engine from statistically-designed testing. From sufficient testing at the part and component levels, the probability distribution of the time (or number of cycles) to failure of each life-limited part or component is developed. The hardware life limit is then established from the failure distribution corresponding to the desired reliability for that hardware. Hence this methodology gives a meaningful, quantitative assessment of the reliabilities of the parts, components, and hence, the SSME.

A probabilistic reliability methodology qualitatively, rather than quantitatively, assesses the reliabilities of the parts, components, and engine. The reliabilities of the SSME hardware are determined qualitatively from probabilistic structural analyses of the failure phenomenon which incorporates the uncertainty in the design parameters listed in Section 2. The reliability numbers generated from this method do not have quantitative meaning except for hardware where the theoretical failure distribution is benchmarked by the failure distribution developed from testing. In lieu of reliabilities quantified from testing, probabilistic assessement of the part/component reliabilities does give the relative reliabilities of the SSME hardware given the uncertainty in the respective design parameters. Consequently, the probabilistic structural analysis becomes one of several tools needed for a decision analysis process to quantify SSME hardware life limits as discussed in Section 6.

This paper addresses the following aspects of these two methodologies:

- SSME system reliability
- SSME component/part reliabilities
  - Statistical component/part reliabilities
  - Probabilistic component/part reliabilities
- Decision analysis methodology

4.0 SSME SYSTEM RELIABILITY

The performance of the SSME should be represented by a mathematical reliability model of the engine which subdivides the SSME into lower levels of components and parts, including identification of the interfaces/interactions among the components and parts which affect the engine reliability. System or SSME reliability, R_E, is apportioned down to the level of component and part reliabilities, R_C and R_P, respectively.

For the SSME, the logical starting point to develop the system performance model is the Failure Modes and Effects Analysis/Critical Items List (FMEA/CIL) document prepared by RI/RD (1984). This document identifies the potential hardware failures, their effects on engine and vehicle performance, and their ranking according to a criticality category. A Criticality Category 1 failure, the most serious, results in loss of life or vehicle (including loss or injury to the public). The mathematical reliability model of engine performance should be initially developed for all Criticality Category 1 failures identified in the FMEA/CIL for each mission operational phase: propellant conditioning, engine start, mainstage, cutoff, and post-cutoff. However, further development of the FMEA/CIL report would be required since the mechanical failure modes, causes of failure, and failure rates (failure distributions) of the SSME hardware leading to Criticality Category 1 failures has not been adequately developed in this document. The mechanical failure modes of the SSME parts of each component should be separated into a failure mode matrix of age-related and non-age-related failure modes as shown in Table 2.

A system reliability model of the SSME is proposed to facilitate hardware life utilization as follows:

- To provide, in a logical and illustrative manner, a thorough understanding of the complex interrelationships of all failure modes which could initiate SSME failure.
- To provide a methodology to identify the sensitivity of SSME performance to different failure modes and designs.
- To provide a mathematical tool to apportion and determine the reliabilities of the components/parts from which the hardware life can be determined.
- To prioritize upgrading of the component/part reliabilities.

Mathematical reliability models of a system include event trees, fault trees (or conversely, success trees), and reliability block diagrams. Conceptual, partial fault tree and reliability block diagrams which model SSME system performance are shown in Figures 4 and 5, respectively. The fault tree would be the logical continuation of the FMEA/CIL study and should be developed initially for all Criticality Category 1 failures as assessed in the FMEA/CIL.

Fault tree analysis is a powerful tool to understand a complex system such as the SSME. In 1961, fault tree analysis was originated by H.A. Watson of Bell Telephone Laboratories to evaluate the safety of the Minuteman Launch Control System. Fault tree analysis is a deductive methodology to determine the "basic events" (faults or failure modes) which could propagate to result in the undesired "top event", the failure of the SSME. Basic events, such as turbine blade failure, which could lead to a Criticality Category 1 failure, are represented by circles in Figure 4. Basic events have failure probabilities (distributions) assigned to them and hence represent the component/part failure probabilities (or conversely, reliabilities). Quantitative analysis of the fault tree calculates the probability of the top event occurring from failure information of the basic events. In addition, quantitative fault tree analysis can be used to determine the required reliabilities of the components and parts from the target SSME reliability R_E, which can be used to assess the hardware life limits of the SSME. Assessment of the reliabilities of the components and parts is discussed below.

5.0 SSME COMPONENT/PART RELIABILITIES

The most feasible approach to establish the reliability of a mechanical component is to break it down into the individual parts which can fail. The effect of each operational and physical uncertainty on these parts can then be determined to establish the mechanical failure mode(s) of each part. The component reliability is then a function of the reliabilities of the individual parts. In general terms, a basic mechanical failure mode can be defined as the physical process(es) which occur or combine their effects to alter the size, shape, or material properties of SSME hardware to make it incapable of satisfactorily performing its intended functions. Examples of mechanical failure modes include LCF, HCF, wear, cyclic creep, buckling, etc. If the mechanical failure modes, failure rates, and hence, reliabilities, of the parts are known, then the component reliability can be determined (Raze, Nelson, and Simard, 1986).

As an illustrative example, consider that a valve assembly may fail due to only two failure modes: seal leakage (caused by wear) and a cracked connector/housing (caused by fatigue). If R_s represents the reliability of the seal and R_h represents the reliability of the housing, then the reliability of the valve, R_v is given as:

$$R_v = R_s \times R_h \qquad (1)$$

Because the SSME has little mechanical redundancy, generally the reliability of the parts should be greater than the reliability of the components, which in turn should be more reliable than the engine.

The cumulative Weibull probability distribution (Weibull, 1951) has been utilized by the aircraft engine industry (e.g., Abernethy et al., 1983b) to characterize the probability distribution of the time (or number of cycles) to failure of a number of mechanical failure modes of engine hardware. Table 3 presents preliminary documentation of the use of the Weibull probability distribution to characterize the failure distributions of engine hardware and more generally, of mechanical failure modes such as LCF, HCF, wear, etc. The Weibull distribution is presently being implemented at NASA/MSFC to develop the failure distributions of SSME hardware from a limited data base of failures (Leath, 1986). Because reliability literature contains numerous references on the theory of the Weibull distribution, the establishment of confidence intervals, etc., only the engineering significance of the Weibull distribution will be discussed below.

The cumulative two-parameter Weibull probability function, $F_T(t)$, of the random variable T representing the life (in time or number of cycles) to failure of an engine component or part is given as:

$$F_T(t) = 1 - \exp[-(\frac{t}{\eta})^{\beta}] \qquad (2)$$

where

β = Weibull shape parameter
η = Weibull scale parameter (characteristic life)

When the failure data is graphed on Weibull probability plot paper, the shape parameter β is the slope of the straight line fitted to the data and represents the failure rate of the hardware. In general, the Weibull shape parameter (or slope) β for the different parts comprising a given component will not be equal. Therefore, the component, or valve, reliability distribution R_V (or conversely, the failure distribution) in equation (1) will not be a Weibull distribution, i.e., the distribution expressing R_V will not plot as a straight line on Weibull paper. The importance of the Weibull shape parameter β in characterizing component/part reliability is addressed below.

The mean, or expected value, E(T), of the Weibull distribution is given as:

$$E(T) = \eta\ \Gamma[1 + \frac{1}{\beta}] \qquad (3)$$

where $\Gamma[\ ]$ is the complete Gamma function. The coefficient of variation, γ, of the Weibull distribution is given as:

$$\gamma = \left[\frac{\Gamma[1 + 2/\beta]}{\Gamma^2[1 + 1/\beta]} - 1\right]^{1/2} \qquad (4)$$

Note that γ is dependent only on the Weibull shape parameter β and is independent of η. The relationship between β and γ in Equation (4) is graphed in Figure 6. As the value of β increases, γ decreases. Therefore, overestimation of β implies a smaller value of γ or "more certainty" in the failure mode process. If the coefficient of variation of a given failure mode is known, then β can be derived from equation (4).

For a hardware life limit t_D corresponding to a cumulative probability of failure $F_T(t)$ equal to p_F, Equation (2) can be solved for t_D as follows:

$$t_D = \eta \left[\ln \frac{1}{(1 - p_F)}\right]^{1/\beta} \qquad (5)$$

Then the factor of safety (FS) for the mean life E[T] of the Weibull distribution can be solved from Equations (3) and (5) as:

$$\text{Factor of Safety} = FS = \frac{E(T)}{t_D} \qquad (6)$$

The FS will be a function of only β (or γ) and p_F. The relationship between p_F, FS, and β (or γ) is graphed in Figure 7. The following trends noted in Figure 7 illustrate the sensitivity of p_F and FS to the estimate of β when performing Weibull analysis:

- For a given β, p_F decreases as FS increases. (A higher FS gives a lower p_F).
- For a given FS, p_F decreases as β increases. (Overestimation of β gives an unconservative estimate (too low) estimate of p_F).

For example, if the Weibull distribution for a LCF failure mode of a specific SSME hardware has a shape parameter β of 3, then the design lives selected to limit p_F to 0.01 and 0.001 would correspond to values of the FS of about 4 and 9, respectively.

In order to maintain a given p_F (or target reliability) of a specific hardware, the effect of β on the design life t_D is illustrated in Figure 8. Consider the case of overestimation β for values of p_F less than 0.632. For example, for a p_F of 0.001, for a value of β equal to 2, the ratio of t_D/η is equal to 0.1. However, if β is overestimated to be 2.5, then t_D/η would be equal to 0.25, which would imply a design life of 2-1/2 times greater than the actual value. Consequently, an accurate estimate of the Weibull shape parameter β is important to realistically quantify the reliability of a component or part. For values of p_F less than 0.632, it is conservative therefore to use an underestimated (smaller) value of β.

Methods to develop a file of values of the Weibull shape parameter β to assess component/part reliabilities for the SSME hardware are outlined in Table 4. The first method determines values of β, and hence, hardware reliabilities, from failure data of the SSME or other pump-propelled liquid rocket engines. The second method establishes value of β from data obtained from material specimen testing. The third method determines values of β theoretically from probabilistic structural analyses of the failure phenomenon of the hardware. Finally, the fourth method uses values of β determined from expert judgment. For example, for some components it may be conservative to use a value of β equal to one, which implies that the failure distribution follows an exponential distribution and the failure rate is constant. The first and third methodologies are discussed below.

5.1 STATISTICAL COMPONENT/PART RELIABILITIES

If considerable testing is performed at the component/part level, then the probability distribution of the time (or number of cycles) to failure of a component or part, and hence β, can be determined directly from statistical analysis of the failure data (method 1 in Table 4). The component or part can then be utilized for an operating life corresponding to the required level of reliability for that particular hardware as illustrated in Figure 2. This approach enables meaningful, absolute reliability values to be utilized in a quantitative reliability methodology.

As failures of SSME hardware are observed in testing or flight, a file of values of the Weibull shape parameter β ("β-bank") for different observed failure modes, materials, and parts should be developed from the failure data. To provide consistency between the failure data and the structural analysis of a given failure mode, the mechanical failure modes (wear, fatigue, etc.) leading to SSME Criticality Category 1 failures should be identified in matrix form as in Table 2. Descriptive measures (inspection procedures) and verification methods of each failure mode should be incorporated into the failure data collection process to facilitate correct statistical analysis of the failure data. Much of the scatter observed in failure data plotted on Weibull paper is due to the mixing of the different mechanical failure modes. Consequently, the data for the different failure modes of a given hardware must be properly separated by physical inspection and classification before the statistical analysis of the failure data can be performed.

Therefore, the statistical treatment of the SSME failure data should involve the following steps:

- Develop a concise definition of each failure mode.
- Develop a descriptive measure of each failure mode for maintenance and inspection purposes.
- Monitor the estimates of η, β, and the desired B-lives as the number of failures increases.
- Monitor the reliability growth as the number of failures increases.
- Document and verify the Weibull analysis computer programs and theory.
- Document the appropriateness/procedure of performing Weibayes/Weibest analysis per Abernethy, et al., (1983). For example, what are appropriate values of β?

In addition, to complement the limited failure data on SSME hardware, values of β should be established from similar hardware on other pump-propelled rocket engines as recommended in method 1b in Table 4. Per MacGregor (1982), RI/RD has obtained about 85,000 Unsatisfactory Condition Reports (UCRs) over the past 30 years from the development of eight different pump-propelled rocket engines (including the SSME), the delivery of about 2500 engines, and the launch of over 1000 flight vehicles. From consideration of failures which have occurred only during the operational (mature) phase of these engines, RI/RD has identified at least 13 common failure modes as listed in Table 5. It is recommended that these failure modes be further investigated to develop a file of β values to complement the values of β developed from the limited SSME failure data. It is also recommended that RI/RD's data base of UCRs be investigated to derive values of β for failure modes in addition to those identified by MacGregor (1982).

The use of failure data from other pump-propelled rocket engines must also address the possibility of variation of the value of β (the failure rate) from engine-to-engine. Such variations may be due to hardware design differences, overall engine design variations, and variability in operating environments. For failure modes of similar hardware on different engines where sufficient failure data is available, the hypothesis of engine-to-engine variability should be tested. However, the use of historical failure data from similar hardware of other engines may lead to more reasonable hardware life assessments than assuming, for example, a constant failure rate for all hardware. In addition, the values of β derived from the historical data may also be incorporated in the Bayesian analysis of hardware reliabilities being implemented by JPL (1986).

5.2 PROBABILISTIC COMPONENT/PART RELIABILITIES

Development of the component and part reliabilities from a probabilistic structural analysis (method 3 in Table 4) involves the following steps:

- Identify all the design parameters which have uncertainty associated with them.
- Collect data on the variabilities of the design parameters.
- Model the probability distributions of the design parameters.
- Perform the probabilistic structural analysis by propagating these distributions through the mathematical model of the failure phenomena.
- Model the probability (e.g. Weibull) distribution of hardware life.

The reliability of a given hardware is a function of the N random design variables representing the variabilities in the material, load, and structural parameters. Let $\bar{X} = (X_1, X_2, \ldots, X_N)$ be a vector of design variable of a given hardware. The performance function $g(\bar{X})$ of the hardware for a given failure mode can be expressed as

$$g(\bar{X}) = g(X_1, X_2, \ldots, X_N) \tag{7}$$

The limit state, or the boundary of the failure domain, of the hardware may then be defined as

$$g(\bar{X}) = 0 \tag{8}$$

Hence,

$$g(\bar{X}) > 0 \text{ is the "safe state"} \tag{9}$$

$$g(\bar{X}) \leq 0 \text{ is the "failure state"} \tag{10}$$

A typical form of equation (10) is given by

$$g(\bar{X}) = L(\bar{X}) - R(\bar{X}) \leq 0 \tag{11}$$

where $L(\bar{X})$ is the load (or stress) parameter and $R(\bar{X})$ is the capacity (or strength) parameter. The probability of failure p_F of the hardware is then defined as

$$p_F = P[g(\bar{X}) \leq 0] \tag{12}$$

Let $f_{\bar{X}}(\bar{x})$ be the joint probability function of the random design variables X_i

$$f_{\bar{X}}(\bar{x}) = f_{X_1,\ldots,X_N}(x_1,\ldots,x_N) \qquad (13)$$

Then equation (12) can be written as

$$p_F = \int_{g(\bar{X}) \leq 0} f_{\bar{X}}(\bar{x})\, d\bar{x} \qquad (14)$$

Depending on the complexity of the failure mode and the data available on the random design variables, the probability of failure (or conversely, the reliability) in equation (14) may be calculated by one of three probabilistic structural analysis methods:

- Full distributional approach
- Second moment method
- Numerical techniques, such as Monte Carlo simulation

Computation of the probability of failure from equation (14) is called the "full distributional" approach since it requires the joint probability density function of the random design variables. If the integral in equation (14) is computed exactly, then the computed probability of failure is exact. The exact integration, however, is possible only for limited cases such as certain stress-strength interference problems per equation (11) (e.g. Haugen, 1968; Ang and Tang, 1984; Witt, 1985). The second moment method is an approximate method which does not require the joint probability density function of the design variables but requires only the first two moments of each variable (e.g. Ang and Tang, 1984).

A number of SSME components/parts are life-limited due to LCF, HCF, and cyclic creep. For these failure modes, the relationship between the design parameters associated with uncertainty and the hardware life are defined only by a computer program, e.t., local strain, fatigue life prediction, finite element stress model, etc. Consequently, it would be difficult to obtain a closed-form solution for the full distribution of hardware life. More feasibly, the probabilistic structural analysis must be based on a deterministic methodology, by considering the input design variables to be random rather than deterministic and propagating the random variables through the structural analysis via numerical techniques.

Monte Carlo simulation is the most widely-used numerical technique to construct the failure distribution. While Monte Carlo simulation can be used to solve virtually any reliability problem, a major disadvantage of this methodology has been the expense required to carry-out the necessary computations. Johnson, Maxwell, and Allred (1975), Johnson and Maxwell (1976), and Maxwell and Johnson, (1977) limit the number of simulations required for a complete structural analysis algorithm by developing an interpolation function which represents the dependent failure mode parameter (such as stress or life) as an explicit linear or nonlinear function of the design parameters. Presently for selected SSME hardware, Monte Carlo simulation is being implemented by the Jet Propulsion Laboratory (JPL) (1986) with the complete structural analysis procedures to derive the probability distributions of the Weibull parameters (β, η).

For the SSME, probabilistic structural analysis of the components/parts should be used as follows:

- To acquire a better understanding of the effects of uncertainties of the material properties, thermal environment, etc. on the determination of hardware life limits.
- To qualitatively assess component/part reliabilities when failure data is not available. The qualitative reliabilities are then used to prioritize upgrading the hardware in a decision analysis methodology to establish hardware life limits.
- To calibrate structural analysis procedures with the failure data. The objective is for the probabilistic structural analysis of a given failure mode to predict the same Weibull distribution of hardware life as statistically derived from the failure data.

6.0 DECISION ANALYSIS METHODOLOGY

Because testing at the component/part levels has not been conducted, the determination of hardware life limits for the SSME becomes a decision analysis problem. The decision analysis process should be a cost-benefit analysis which establishes hardware life limits from the following sources:

- The validity of hardware life limits realized from the probabilistic structural analysis
- The inherent reliability being achieved by the maintenance program, inspection procedures, fabrication procedures, and quality control

Until the component/part reliabilities generated from a probabilistic structural analysis are verified with reliabilities generated from failure data, the reliability of the SSME hardware, and hence, the life limits, will have to be qualified by a maintenance program calibrated to prevent functional failures from occurring.

The relative part/component reliabilities, determined from the probabilistic structural analysis and aggregated through the system performance model, can be used to prioritize which hardware should be upgraded. The upgrading of a particular hardware should consider the following alternatives and the expected costs/benefits:

- Conduct testing
  - To improve information on material properties
  - To improve information on the operating environment
  - To improve information on component/part reliabilities
- Modify the design
- Improve maintenance/inspection procedures
- Improve fabrication procedures

7.0 RECOMMENDATIONS

In summary, the following recommendations should be implemented for the management of SSME hardware life utilization:

- Identify and define descriptive measures of the mechanical failure modes of all SSME hardware for use in maintenance, inspection, and statistical failure data analysis.
- Develop a mathematical reliability model of the SSME (e.g. fault tree analysis) from the FMEA/CIL Criticality Category 1 failures.
- Develop a file of values of the Weibull shape parameter β to model the failure distributions of SSME hardware.
- Calibrate failure distributions (Weibull parameters) developed from probabilistic structural analysis with failure distributions statistically derived from testing.
- Develop a decision analysis methodology to determine hardware life limits when failure data is not available which incorporates the following:
  - Expected costs
  - Probabilistic structural analysis
  - Maintenance/inspection procedures
  - Fabrication procedures

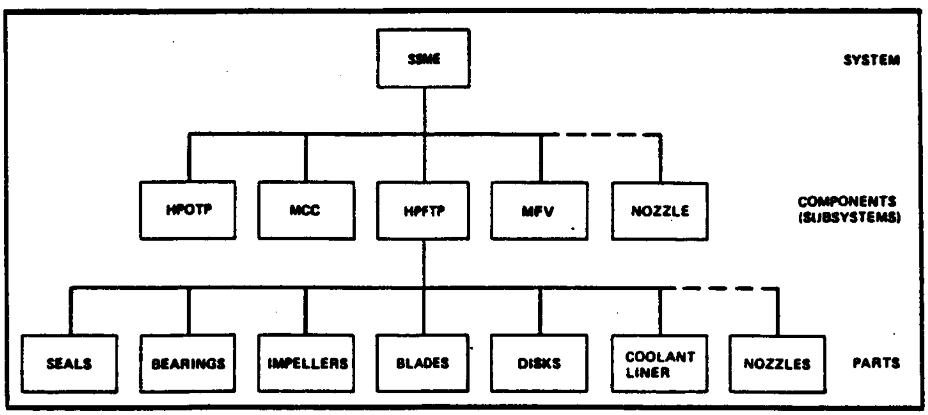

Figure 1. Relationship between parts, components, and system of SSME.

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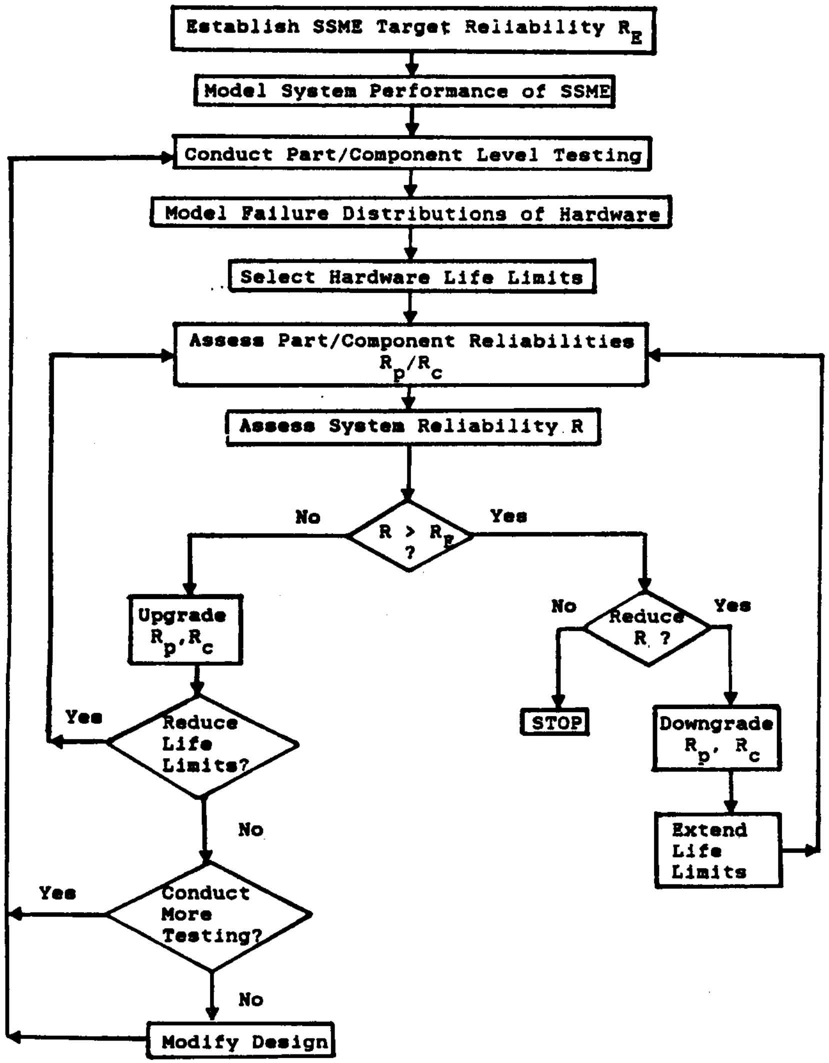

Figure 2. Statistical Reliability Methodology for SSME Hardware Life Utilization

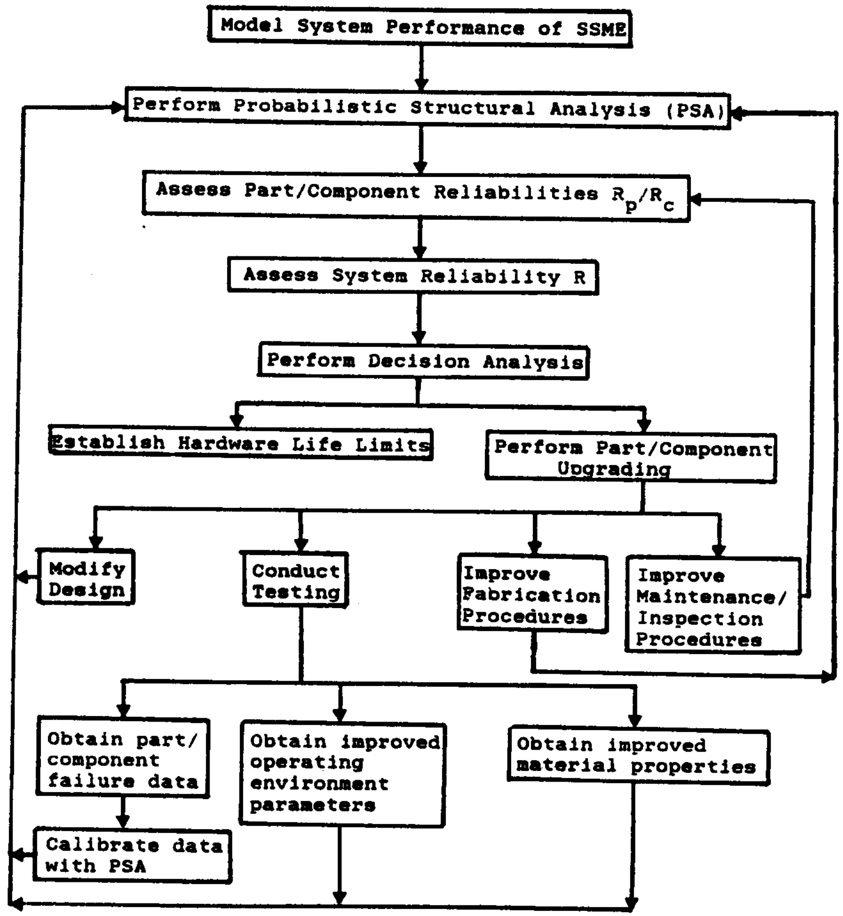

Figure 3. Probabilistic Reliability Methodology for SSME Hardware Life Utilization

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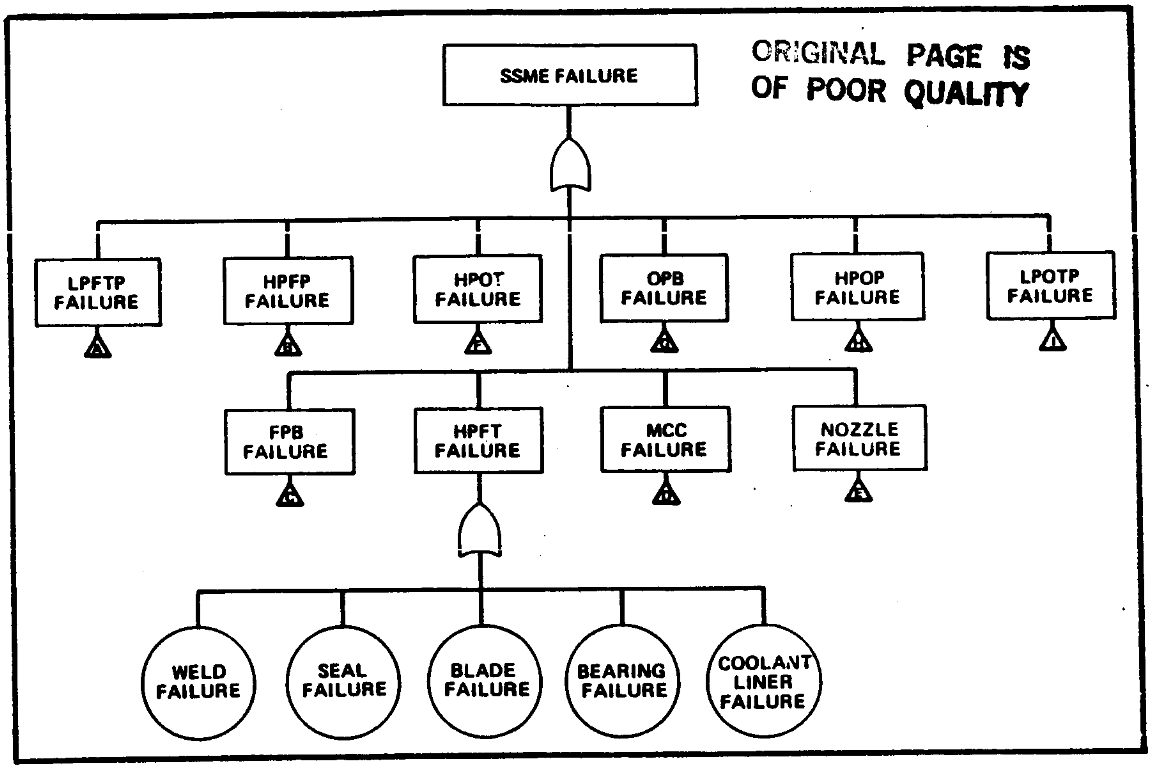

Figure 4. Partial conceptual fault tree of SSME. (Ducts, valves, controller, etc. not shown. Transfer events not developed.)

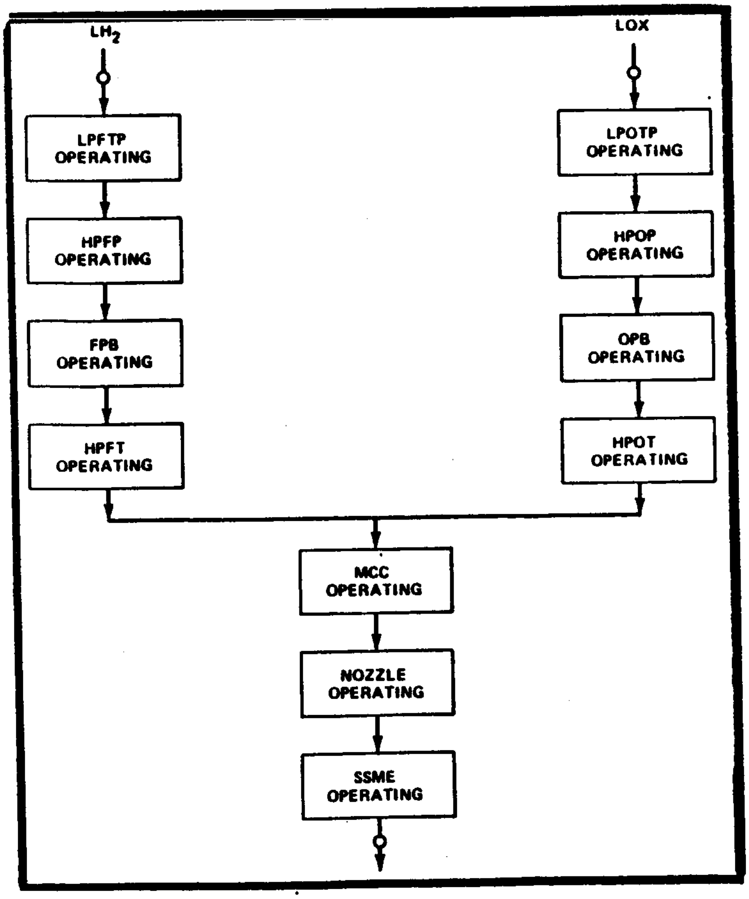

Figure 5. Partial conceptual reliability block diagram of SSME.

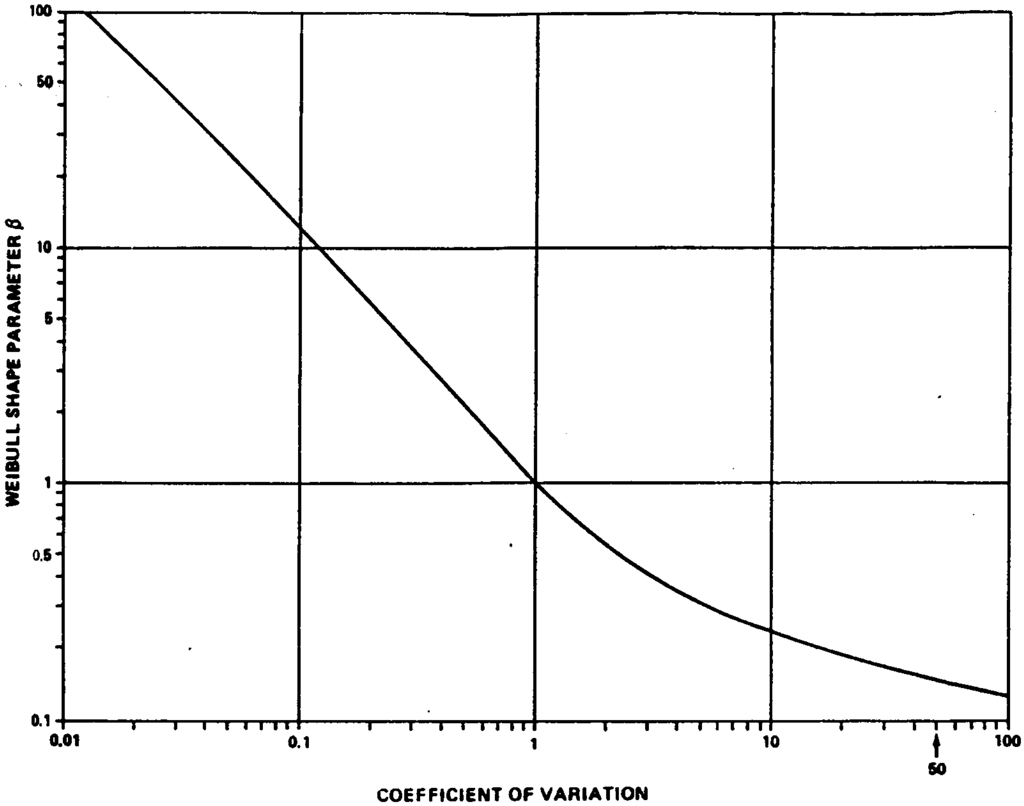

Figure 6. Coefficient of Variation vs. Shape Parameter β for the Weibull Distribution

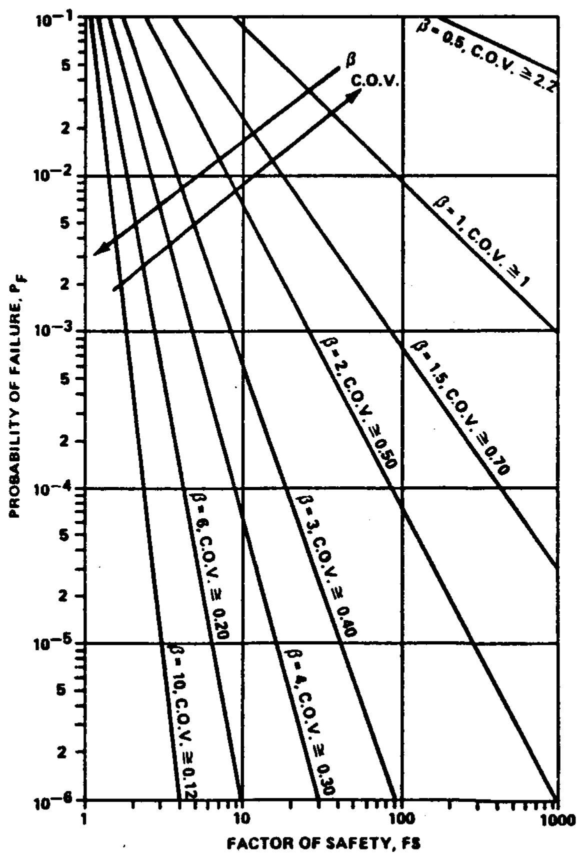

Figure 7. Factor of Safety vs. Probability of Failure as a Function of Shape Parameter β for the Weibull Distribution

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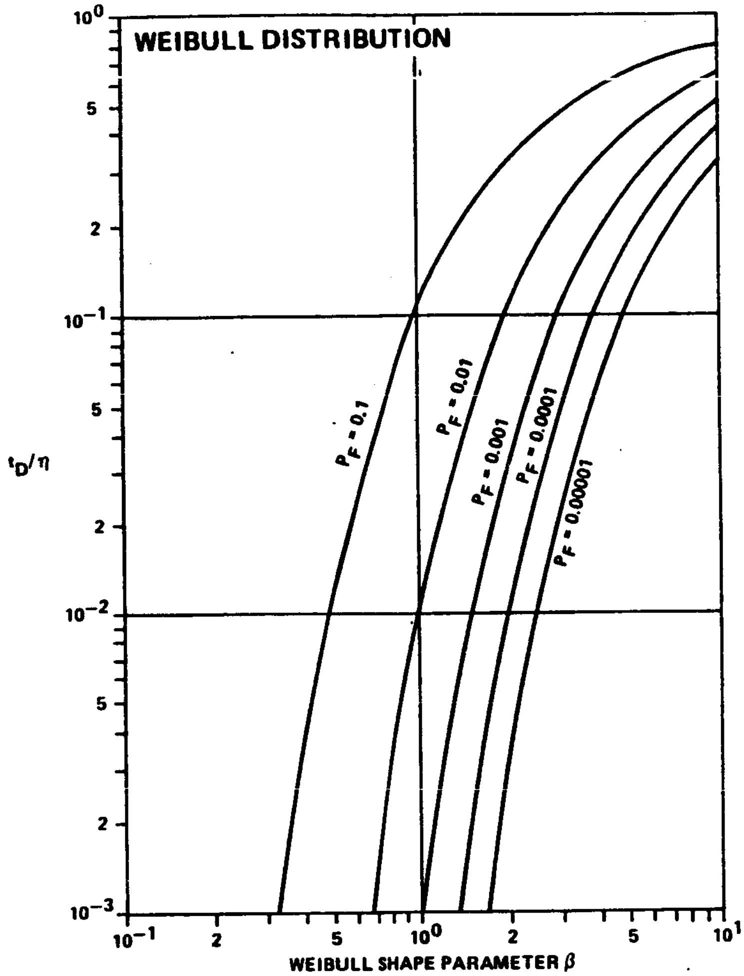

Figure 8. Shape Parameter β vs. Ratio of Design Life T_D to Characteristic Life η as a Function of the Probability of Failure p_F for the Weibull Distribution

7. Conclusions

For the controller failure data Weibull Models fits well. The MTBF assuming censored Weibull Model is 1,448 hours. If one uses simple Exponential Model, MTBF is 881. It is advisable to use censored models which take into account the time for the units which did not fail. The B1 life using Weibull Model is 197.5 hours.

For SSME blade failures using grouped Weibull Model MTBF obtained is 27.69 hours. The variances of the estimators are also obtained for the parameters in MTBF. The B1 life is 2.16. The drawback of the method is that to find the estimators one needs to solve two simultaneous nonlinear equations. Alternatively the randomly placed model can be used. For this method MTBF is 17.32 hours and B1 life is 1.5 hours. This method depends on seed numbers used in the random number generators so it is better to make number of runs with different seed points and average the results.

Other models like Gamma Model may give the better fit for controller failure data. The maximum likelihood estimating equations involve incomplete gamma functions solving these equations need sophisticated programming techniques. These problems need further investigation.

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TABLE 3

APPLICATIONS OF WEIBULL DISTRIBUTION FOR FAILURE MODE ANALYSIS
(PRELIMINARY LIST)

Application	Reference
■ Bearing failures in a fighter engine augmentor turbopump: Weibull shape parameter β of 4.615 (final value)	Abernethy, Medlin, and Ringhiser (1983)
■ General classification of Weibull failure modes:	Abernethy, Medlin, and Ringhiser (1983); Abernethy, Breneman, Medlin, and Reinman (1983)

Failure Mode	β
Infant Mortality	<1
Inadequate Burn-in Green Run Misassembly Some Quality Problems Electronics	
Random Failures	1.0
Independent of Time Maintenance Errors Electronics Mixture of Problems	
Early Wearout	3.0
Surprise LCF	
Rapid, Old-age Wearout	6.0
Bearings Corrosion	

■ RB-211 Engine Module ... Blundell and Beard (1985)

RB-211 Engine Module	Weibull Shape Parameter β
I.P. Compressor	0.7, 3.08
Intermediate Case	3.068
H.P. Compressor and Turbine	2.206
I.P. and L.P. Turbine	1.355, 3.5
High-Speed External Gearbox	2.85

TABLE 3 (CONT'D)

APPLICATION	REFERENCE
■ Titanium-6-A1-4V alloy engine discs, LCF failures at bolt holes, values of Weibull shape parameter β of 2.0 and 3.2	Mahorter, London, Fowler and Salvino (1985); Mahorter, Fowler, and Salvino (1985)
■ Wearout of augmentor hydraulic fuel pumps on fighter aircraft: Weibull shape parameter β of 2.6. Housing cracks of augmentor hydraulic fuel pump on fighter aircraft: Weibull shape parameter β of 2.9	Medlin and Elsaesser (1983)
■ Probability distribution associated with Weibull shape parameter β:	Salzman and Gauger (1986)

Distribution Type	Weibull Shape Parameter β
Exponential	1.0
Rayleigh	2.0
Lognormal	2.5 - 3.0
Normal	3.0 - 4.0
Small Extreme Value	> 10.0

APPLICATION	REFERENCE
■ Weibull distribution used for LCF crack initiation life of gas turbine engine disc	Sattar and Sundt (1975)
■ Air Turbine Starter:	Trimble and Schmidt (1983)

Failure Mode	Weibull Shape Parameter β
Ball Bearing Fatigue	2.0
Roller Bearing Fatigue	1.5
Bearing Infant Mortality	0.5
Gear Fatigue	2.5
Seal Random Failures	1.0
Seal Infant Mortality	0.5
Clutch Random Failures	1.0

APPLICATION	REFERENCE
■ Application of Weibull probability distribution to model fatigue data.	Wirsching (1981); Fatigue Reliability: Development of Criteria for Design (1982)

TABLE 4

METHODS TO DEVELOP WEIBULL SHAPE PARAMETER β FILE FOR SSME HARDWARE

1. From test/flight data of engine hardware

   a. SSME

   b. Other liquid rocket engines which are pump-propelled (Assumption: Similar operations and similar component/part configurations should have similar values of β).

      - J-2 engine in Saturn Ib and V vehicles (153)[1]
      - H-1 engine in Saturn Ib vehicle (294)
      - F-1 engine in Saturn V vehicle (85)
      - RS-27 engine in Delta vehicle (69)
      - Thor engine in Thor vehicle (524)
      - Atlas engine in Atlas, Atlas-Centaur vehicles (1110)

2. From test data on material specimens of engine hardware

3. From probabilistic structural analysis

4. From expert judgment

[1]Approximate number of engines developed per MacGregor (1982).

TABLE 5

OCCURRENCE OF FAILURE MODES IN PUMP-PROPELLED LIQUID ROCKET ENGINES[1]

FAILURE MODE DESCRIPTION	ENGINE SYSTEM							TOTAL MODE
	SSME	J-2	H-1	F-1	RS-27	THOR	ATLAS	
COOLANT PASSAGE LEAKAGE	34		38	6		76	105	259
JOINT LEAKAGE:								
A. HOT GAS	5	9	61	22	28	27	79	231
B. PROP. & LUBE HYDR.	12		68	43	40	219	148	530
HIGH TORQUE, T/P	20					11	10	41
CRACKED TURBINE BLADES	9	7	27					43
CRACK—CONVOLUTIONS BELLOWS	5					8	12	25
LOOSE ELECTRICAL CONNECTORS	6							6
BEARING DAMAGE	4	1	12			6	2	25
TUBE FRACTURE		17						17
TURBOPUMP LEAKAGE		13	28	2	12	19	65	139
VALVE FAILS TO PERFORM:								
A. MOISTURE, ICE		13					2	15
B. CONTAM/FRICTION		6	26	10				42
INTERNAL VALVE LEAKAGE:								
A. CONTAMINATION		58	29		8	50	16	161
B. COMPRESSION OF SPRING				9				9
C. VIBRATION SEAT				6	2	7	3	18
D. TRAPPED PRESSURE					11	4		15
REGULATOR DISCREPANCIES					5	33	44	82
CONTAMINATED HYDR. CONTR. ASSY							26	26
TOTAL ENGINE	95	127	280	98	106	460	512	1687

[1]PER MACGREGOR (1982)

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