Selection of Critical Failure Modes for Service Life Overtesting

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An empirical technique for identifying critical failure modes of a solid-propellant rocket motor is presented. The technique was utilized in the Minuteman Long-Range Service Life Analysis (LRSLA) program, where the critical failure modes were selected for overtest. The technique provides for a numeric ranking of the failure potential of all possible failure modes. The failure potential ranking is achieved by identifying and assessing numerically the contributing factors. By assessing such factors as age sensitivity of material properties, evidence of age degradation, initial margin of safety, and effect of component failure mode on system performance, failure modes are ranked least critical to most critical. The technique is verified by reassessment of the margin of safety for each failure mode using data inputs from the dissected overtest motor and material property test program.

Introduction

THERE has been considerable effort expended by numerous agencies[1-4] toward developing predictive techniques for estimating service life of solid-propulsion subsystems. These techniques primarily include test programs that monitor changes with age of materials or components believed to be age-sensitive. These trends then are extrapolated to analytically derived failure limits to estimate service life.

This paper describes an improved procedure, the failure mode analysis approach,[5-7] designed to remove the arbitrariness of selecting the age-sensitive failure modes that should be tracked in an ongoing surveillance program. In addition, this procedure identifies in a systematic manner those failure modes for which the failure limits should be validated by means of full-scale motor overtests. The overtest concept consists of increasing the operational loads in a realistic manner until failure occurs and by comparing the experimental to analytically predicted failure modes and failure limits. This paper presents the detailed steps involved in this failure-mode-analysis approach using the Minuteman Stage I loaded motor case an an example.

Overall Failure Mode Analysis

The selection of critical failure modes for overtesting constitutes the initial phase of an overtest program. As indicated in the flow diagram (Fig. 1), this initial phase is divided into two parts: 1) the identification of all critical failure modes, and 2) the selection of the critical failure modes for overtesting. The first part utilizes past experience on known failure modes and failure limits for the nonreplacable loaded motor case, in addition to a review of motor drawings, specifications, and aging data from existing aging and surveillance programs, to arrive at all potential age-related failure modes. These potential failure modes are assessed in a failure mode and limit tree, which relates the component and material failure modes to motor performance failure modes and identifies available data on safety margins and age sensitivity of each failure mode. Each age-sensitive failure mode then is rated according to its criticality to system performance and age sensitivity, and an overall failure potential factor is assigned. A failure mode having a low failure potential factor is classified as a critical failure mode.

The second part of this effort deals with a more thorough analysis using analytical models and best material properties available to arrive at a best estimate of the safety margin for each failure mode. Conservative analytical models are utilized in identifying key parameters and failure limits for each failure mode in accomplishing this task. Based upon the calculated safety margin, the failure modes are reduced further to those with a sufficiently small safety margin to make these failure modes candidates for overtesting. Following the overtest program, validated analytical models and dissected full-scale motor properties are utilized to arrive at final safety margin calculations and reassessment of margins of safety for failure modes not overtested.

Discussion

Failure Mode and Limit Tree

The failure mode and limit tree documents the systematic procedure by which component and material failure modes, both those that have occurred and those that are postulated to occur due to material degradation with age, are identified and assessed further. Each failure mode is related to the critical property, which, if degraded due to age, can cause the failure to occur. An estimated failure limit for the critical property is recorded which may be a specification value or an existing calculated value based on a design analysis. The aging experience from existing surveillance programs is documented to indicate if a significant aging trend exists in the critical

Table 1 Example of failure mode and limit tree

<table>
<tr><td colspan="6">AGE SENSITIVE ITEM/INTERFACE = PROPELLANT/LINER SYSTEM</td></tr>
<tr><td colspan="6">COMPONENT/MATERIAL FAILURE MODES</td></tr>
<tr><td>IDENTIFICATION</td><td>CRITICAL PROPERTY</td><td>ESTIMATED FAILURE LIMIT</td><td>AGING EXPERIENCE</td><td>MARGIN OF SAFETY</td><td>EFFECT ON SYSTEM PERFORMANCE</td></tr>
<tr><td>BOND FAILURE OF LINER/ PROPELLANT (UF-2121/TP-H1011)</td><td>BOND SHEAR STRENGTH</td><td>BOND STRENGTH 8.5 PSI</td><td>BOND STRENGTH INCREASING AT 7.4 PSI/YR. ALTHOUGH THE SAFETY MARGIN APPEARS TO BE INCREASING, THE CONCLUSION MAY NOT BE SIGNIFICANT.</td><td>INCREASING</td><td>COULD CAUSE EXCESS BURN AREA AND ABNORMAL P/T CURVE.</td></tr>
<tr><td colspan="6">MOTOR PERFORMANCE FAILURE MODES</td></tr>
<tr><td colspan="3">IDENTIFICATION</td><td colspan="3">FAILURE LIMITS</td></tr>
<tr><td colspan="3">1. ABNORMAL PRESSURE/TIME CURVE</td><td colspan="3">3 SIGMA EXPERIENCE BAND ON THRUST, ISP, ACTION TIME.
EXCEED THRUST DECAY PROFILE BAND.</td></tr>
<tr><td colspan="3">2. CASE BURNTHROUGH, CASE BURST</td><td colspan="3">CATASTROPHIC FAILURE IN SEVERAL MODES.</td></tr>
<tr><td colspan="3">3. ABNORMAL IGNITION</td><td colspan="3">MAXIMUM IGNITION DELAY = 0.200 SEC.
MAXIMUM IGNITION PRESSURE = 920 PSI.</td></tr>
</table>

Presented as Paper 76-717 at the AIAA/SAE 12th Propulsion Conference, Palo Alto, Calif., July 26-29, 1976; submitted Aug. 10, 1976; revision received Dec. 27, 1976.

Index categories: Reliability, Maintainability, and Logistics Support; Solid and Hybrid Rocket Engines.

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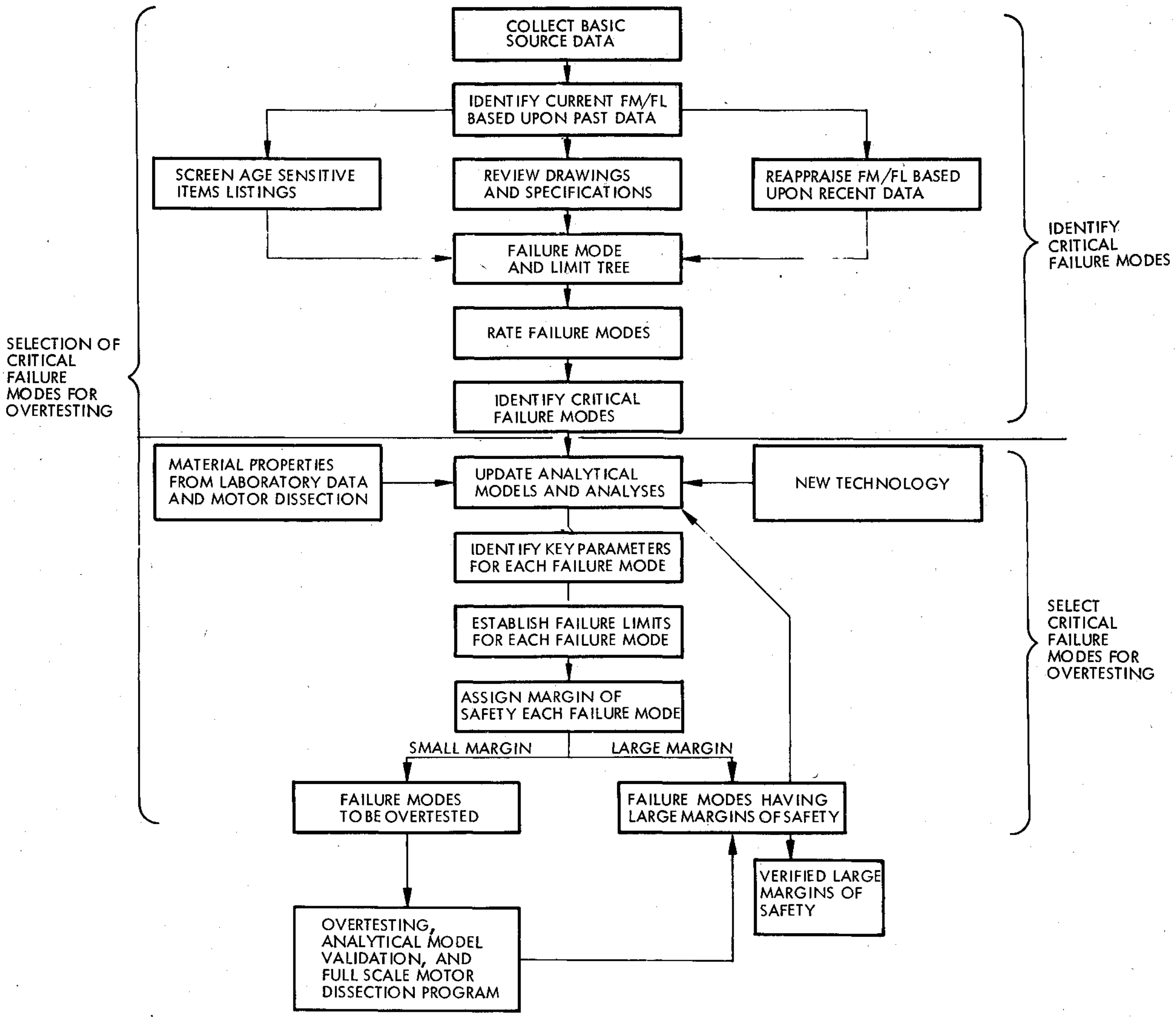

Fig. 1 Flow diagram: overall failure mode analysis.

property. The safety margins at unaged and aged conditions are based on worst-case capability vs failure-limit comparison and the aging experience. The final entry is the effect of the material or component failure on overall motor performance. The associated motor performance failure modes and failure limits also are identified. Concurrently, known motor failure modes are reviewed to verify that no age-sensitive component failure modes have been omitted. In filling out this matrix, an extensive effort is required in review of drawings, specifications, design criteria, test reports, failure reports, aging and surveillance data, structural analysis reports, field/recycle reports, and engineering changes, which occurred during the motor production. This systematic approach minimizes the possibility of ignoring significant data.

Table 2 Definition of rating factors

AGE-SENSITIVITY FACTOR (ASF)	AGE DEGRADATION
1	DEFINITE LIKELIHOOD OF DEGRADATION
2	LIKELIHOOD UNCERTAIN
3	NO LIKELIHOOD OF DEGRADATION
CRITICALITY FACTOR (CF)	EFFECT OF COMPONENT FAILURE MODE ON SYSTEM PERFORMANCE
1	SIGNIFICANT EFFECT OR LOW MARGIN OF SAFETY
2	INDETERMINATE EFFECT
3	INSIGNIFICANT EFFECT
	FAILURE POTENTIAL FACTOR (FPF) = ASF X CF (SIX POSSIBLE PRODUCT LEVELS 1, 2, 3, 4, 6 AND 9)

In Table 1, the entries for some of the Stage I propellant/linear area failure modes in the motor case have been filled in as an example.

Rating Factors for Failure Modes (Stage I)

Each age-sensitive failure mode identified in the failure mode and limit tree is evaluated by a rating system, which considers two factors, the age-sensitivity factor (ASF) and the criticality factor (CF), defined in Table 2. The age-sensitivity factor is an expression of the experience derived from existing surveillance programs or other special programs that provide an indication of change in properties or performance with age. It is a numerical rating of the degree and significance of age degradation. A low factor is assigned when there is any evidence of age degradation toward a failure limit, resulting in a decreasing margin of safety with age. An intermediate factor is assigned when there is no evidence of statistically significant (95%) degradation, and a high factor is assigned where there is proof of change in properties away

Table 3 Example of rating factors for one Stage I failure mode

PROBABLE FAILURE MODES (AND EFFECTS)	AGE SENSITIVITY FACTOR (ASF)	RATIONALE FOR ASF	CRITICALITY FACTOR (CF)	RATIONALE FOR CF	FAILURE POTENTIAL FACTOR (FPF)
BOND FAILURE LINER (UF 2121) PROPELLANT (TP-H1011)	2	STRENGTH INCREASING BUT TEST PROCEDURE MAY NOT BE VALID.	1	KNOWN FAILURE HISTORY. BOND FAILURE CAN CAUSE OVER PRESSURE OR BURN THROUGH.	2

from the failure limit, resulting in an increasing margin of safety with age.

The criticality factor is an expression of the effect of material or component failure mode on system performance and utilizes historical data on failures in full-scale motor tests. A low factor defines a high probability that a system failure will result from a material or component failure, whereas the higher factors reflect reduced probabilities of system failure. A CF = 2 is assigned to all failure modes where the criticality is uncertain.

In summary, failure potential factors (FPF's) ranging from 1 to 9 define the range of concern about a failure mode, going from greatest to least, respectively. This rating was performed by a group comprising various engineering disciplines and is based on best engineering judgment. As an example, the rating factors and the associated rationale for some of the Stage I propellant/liner area failure modes are presented in Table 3.

Summary of Failure Mode Ratings

Following the assignment of failure potential ratings to all material and component failure modes for the loaded-motor case, the failure modes are divided into two groups: 1) the ones with FPF's of 4 or less are identified as critical failure modes and reserved for further evaluation as candidates for overtesting; and 2) the ones with FPF's greater than 4 are defined as not critical and removed from further consideration at this time. Since an FPF rating of 4 can be obtained on a failure mode having a factor of 2 for both ASF and CF ratings, thus reflecting uncertainty of having a problem, the resulting list is considered a conservative estimate of potential failure modes. The use of 4 as a limiting value insures that no failure modes of uncertain criticality or age sensitivity are omitted. This initial screening results in a substantial reduction in failure modes of immediate concern. For example, out of 42 total rated failure modes for the Stage I loaded-motor case, only 14 were rated FPF 4 or less. This, in turn, results in reduced cost of an overtest program.

Stage I Critical Failure Modes

The critical failure modes for the Stage I loaded-motor case with failure potential factors of 4 or less are shown in Fig. 2. The failure modes encompass failures at both motor firing or long-time storage conditions. There are two major categories among the critical failure modes, viz., those that are considered as structural failure modes and those that are nonstructural or ballistic performance oriented.

Final Selection of Stage I Structural Failure Modes for Overtesting

The Stage I critical failure modes that are structural in nature were evaluated further by means of detailed structural models[6] developed for greater in-depth structural evaluations of these failure modes. Each failure mode was analyzed for the maximum operational conditions, and worst-case failure limits were established. In addition, the failure limits were compared to their respective capabilities for each critical parameter, and margins of safety were calculated. Combining the recalculated margins of safety with the available aging trend data resulted in a recommendation of whether or not to overtest this failure mode. In general, any failure mode having a margin of safety of <0.5 was recommended for overtesting. Some of the failure modes not recommended for overtesting-to-failure were tested "piggyback" later in the overtest program. This approach again significantly reduced the number of failure modes to be overtested and resulted in a cost-effective full-scale motor overtest program. In the case of the Stage I loaded-motor case, five of the eleven structural failure modes were recommended for overtesting, whereas three of the remaining failure modes were tested 'piggyback' in the actual overtests.

Final Selection of Stage I Nonstructural Failure Modes for Overtesting

Only three Stage I critical failure modes were nonstructural in nature. These were all related to degradation of the inhibitor coating, which is applied to the propellant surface in certain areas to control pressure rise rate. Degradation could lead to bond failures and result in inhibitor ejection during motor ignition and the exposure of additional propellant surfaces, which could cause motor overpressure. Since there was evidence of age degradation on only two of the three inhibitor materials, it was recommended that a static firing be performed of a motor with the degraded inhibitor removed to assess the criticality of this material degradation to system performance. If satisfactory performance could be achieved, this failure mode would be removed from the critical list and set aside as of no concern. This was an example of the overtest philosophy that allows for bypassing the need for establishing realistic failure limits and aging trends if a potential failure mode can be proven to be noncritical to system performance. Ballistic models were established to calculate motor chamber pressures and silo overpressures resulting from the increased propellant surface at ignition. These models would be validated by a motor firing, thus verifying the predictive model relating amount of inhibitor to chamber pressure and silo overpressure. More statistical validation was not considered necessary because of severity of the overtest.

Evaluation of Failure Mode Rating Technique

Following the completion of full-scale motor overtests, validation of analytical models, dissection of these motors, and material property testing from these motors, the margins of safety for each failure mode originally designated as

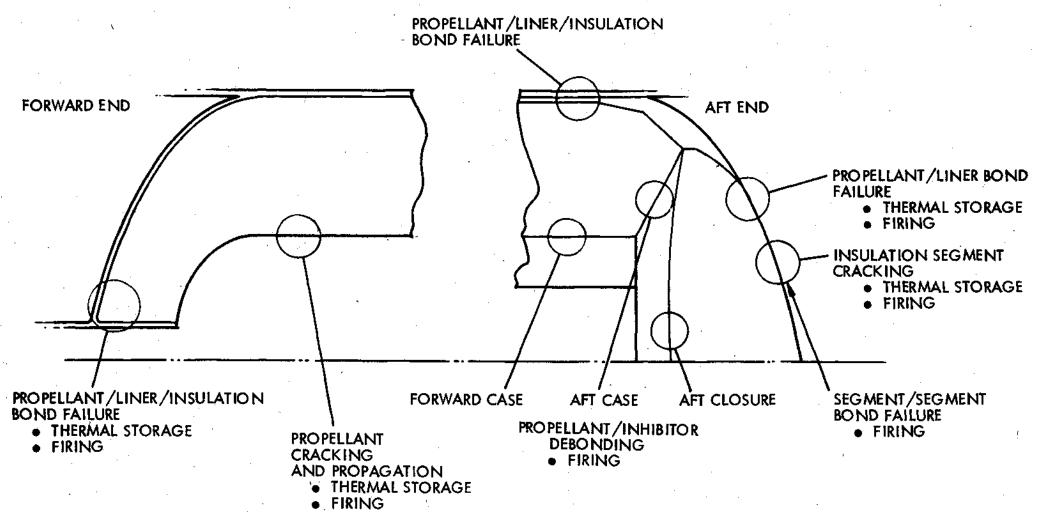

Fig. 2 Stage I motor critical failure modes (FPF = 4 or less).

critical during the failure mode rating phase were re-evaluated. The single failure mode that ended up being the governing failure mode for the service life of the Stage I motor was one of the failure modes originally rated as a PFP = 2, i.e., the propellant/liner/insulation bond failure in the forward dome under long-term-storage conditions. Other failure modes were assigned various margins of safety not necessarily in the order of the failure potential factor, but there were no failure modes identified in the overtest program which were not included in the final list of critical failure modes. In this sense, the failure mode rating approach is considered to have been successful in limiting the final number of failure modes of concern, without eliminating any critical failure modes or missing unexpected failure modes.

Conclusions

The failure mode rating procedures utilized in this program were successful in identifying potentially critical failure modes for both Stage I and III loaded-motor cases, including the service-life-governing failure mode. Although the initial failure mode screening procedure utilized only preliminary data on margins of safety and system criticality, the criteria for retention of failure modes for further evaluation were sufficiently conservative to include all failure modes with low margin of safety. The reduction in the number of failure modes to be overtested results in considerable cost savings to the program, since full-scale motor overtests are minimized. The procedures presented in this paper are sufficiently general to be applicable to other propulsion systems or nonpropulsion process evaluations.

Acknowledgment

This work was performed under contract by Ogden Air Logistics Command, Hill Air Force Base, Utah.

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