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A COMPARISON OF HIGH CYCLE FATIGUE METHODOLOGIES

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Science and Engineering Directorate

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To evaluate alternate turbopump development (ATD) high cycle fatigue (HCF) methodology, a comparison was made with the space shuttle main engine (SSME) methodology. This report documents the comparison and evaluates ATD's HCF system.

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TECHNICAL MEMORANDUM

A COMPARISON OF HIGH CYCLE FATIGUE METHODOLOGIES

I. INTRODUCTION

Marshall Space Flight Center (MSFC) has historically been involved in space flight hardware design, margin of safety calculations for strength, fatigue life assessments, and more recently fracture control. Although fracture mechanics considerations determine life assuming a defect of some magnitude already exists in hardware, assessments for fatigue attempt to predict the initiation of such a defect in previously unflawed components. While in most cases fracture control precludes a fatigue generated indication, there are hardware and conditions which make evaluation of fatigue life mandatory. Some of these include pressure systems where a leak is highly undesirable (shuttle external tank), flow systems in which particles could be dangerously ingested (space shuttle main engine (SSME) oxidizer pump), rotating hardware that could change natural frequencies and/or balance (turbopump turbine blades), and structure that has been noted as fail-safe through the logic of redundant load paths (spacelab orthogrid struts).

This paper deals strictly with the high cycle fatigue (HCF) aspects of hardware failure and the philosophies used on the SSME hardware, the alternate turbopump development (ATD) hardware, and the life requirements deemed necessary by MSFC.

II. BACKGROUND

The concern over HCF methodology began in June of 1990 when the precursor critical design review (PCDR) was initiated for the ATD program. The ultimate goal of this review was to verify both the fuel and the oxidizer turbopumps for SSME engine level testing at the Stennis Space Center (SSC). Obviously, placing any newly designed component on a multimillion dollar engine/test stand requires careful evaluation of all structural issues. As a part of the PCDR activity, a review item discrepancy (RID) was submitted concerning the ATD HCF technique. The procedure outlined in the submitted verification data was clearly outside the experience base of both MSFC and the SSME contractor. Because of the criticality of this issue, the MSFC Durability Analysis Branch was given the action to evaluate this approach, compare it to the current SSME way of life assessment, and make sure it complied with the MSFC HCF requirements. This report documents that effort so that all parties involved, including future MSFC engineers, will have a written record of the resolution of this important issue.

III DISCUSSION

A. ATD Methodology

Appendix A is a flowchart supplied by the ATD contractor which documents the HCF procedure. The method utilizes a modified Goodman diagram. Material endurance limit (σ_{End}) is based on 10^8 cycles and -3σ lower bound criteria. The mean stress is defined as follows:

$$\sigma_{Mean} = \sigma_{Max}/K_T \quad \text{if} \quad \sigma_{Max}/K_T < F_{TY} \tag{1}$$

$$\sigma_{Mean} = F_{TY} \quad \text{if} \quad \sigma_{Max}/K_T > F_{TY} \quad \text{and is a local stress ,} \tag{2}$$

where

σ_{Mean} = nominal mean stress

σ_{Max} = peak concentrated stress

K_T = stress concentration factor

F_{TY} = yield strength.

Based on the stress concentration factor, the endurance limit is adjusted down. Appendix B contains the chart used to determine this knock down factor (*F*). A K_T of 1.5 is assumed when the actual K_T is less than 1.5; therefore, the endurance limit will always be reduced by at least 22.5 percent. This adjusted endurance limit (σ'_{End}) is used on the Goodman diagram to determine the alternating stress capability.

$$\sigma'_{End} = (F)(\sigma_{End}) \tag{3}$$

σ_{Alt} = allowable concentrated alternating stress.

The following Goodman diagram (fig. 1) shows how the alternating stress capability is determined based on mean stress and the adjusted endurance limit.

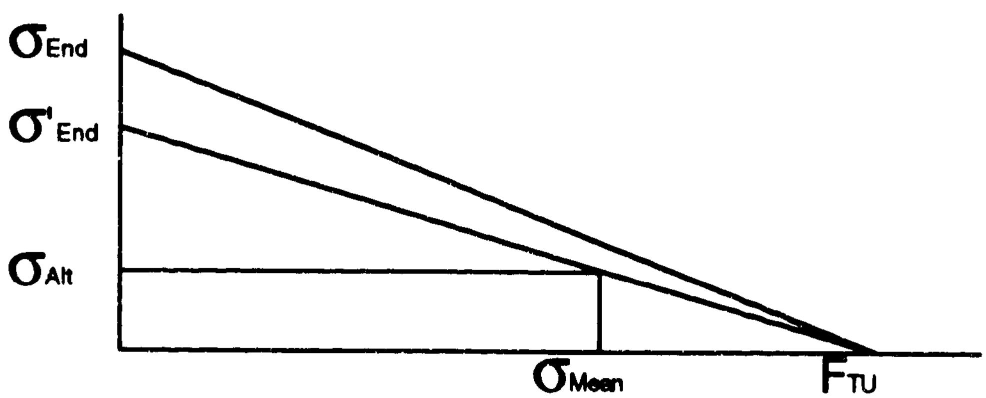


Figure 1. ATD Goodman diagram.

If the predicted dynamic stresses are below this capability, the part is quoted as having infinite HCF life. If the capability falls below the predicted value, then the required finite HCF cycles will be determined (using a safety factor of 4). From the material S-N curve, an endurance limit is found. This value is reduced by 15 percent in compliance with MSFC requirements.

B. SSME Methodology

The SSME program also uses Goodman's linear relationship to determine alternating stress capability (section 5.1.4, vol. 2, ref. 1). The mean stress is adjusted when elastic stress exceeds yield. This approach assumes an elastic perfectly plastic stress strain diagram. The equivalent mean stress is defined as follows:

$$\sigma_{Mean} = \sigma_{Max} \quad \text{if} \quad \sigma_{Alt} + \sigma_{Max} < F_{TY} \tag{4}$$

$$\sigma_{Mean} = F_{TY} - \sigma_{Alt} \quad \text{if} \quad \sigma_{Alt} + \sigma_{Max} > F_{TY} \quad \text{and} \quad \sigma_{Alt} < F_{TY} \tag{5}$$

$$\sigma_{Mean} = 0 \quad \text{if} \quad \sigma_{Alt} > F_{TY} \tag{6}$$

The material endurance limit (σ_{End}) is based on 10^7 cycles. This example shows how the equivalent mean stress is used in the Goodman diagram (fig. 2).

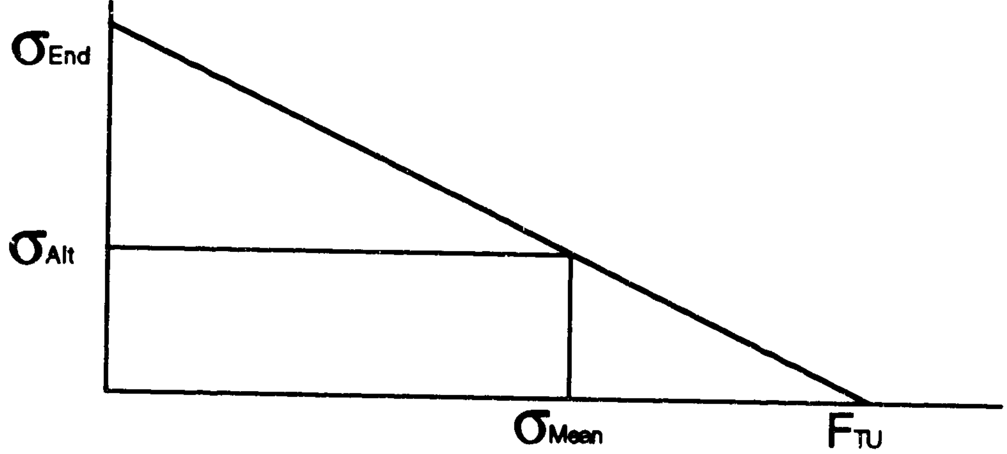


Figure 2. SSME Goodman diagram.

IV. ANALYSIS

The allowable alternating stress can be defined by equations for both methods. These two governing equations can then be equated, defining a line on a graph. The graph represents all possible design conditions. The line divides the graph into two regions, which represent the areas where one method is more conservative than the other. This is the approach used in the comparison. Both criteria use Goodman's linear relationship:

$$\sigma_{Eq\ Alt} = \frac{\sigma_{Alt}}{1 - (\sigma_{Mean} / F_{TU})} \tag{7}$$

If $\sigma_{Eq\ Alt} < \sigma_{End}$ then part has infinite life. If $\sigma_{Eq\ Alt} > \sigma_{End}$ then part has finite life

If the endurance limit (σ_{End}) is substituted for equivalent alternating stress, alternating stress capability (σ_{Alt}) can be determined for infinite life;

$$\sigma_{End} = \frac{\sigma_{Alt}}{1-(\sigma_{Mean} / F_{TU})} \quad , \tag{8}$$

therefore,

$$\sigma_{Alt} = \sigma_{End} \ (1-\sigma_{Mean} / F_{TU}) \ . \tag{9}$$

The method that predicts the lower alternating stress capability is the more conservative. As shown in section III, mean stress is defined differently for ATD and SSME. A separate equation is written for each system. The regions listed define which method is applicable.

<u>For ATD</u>

$$\sigma_{Mean} = \sigma_{Max}/K_T \quad \text{if} \quad \sigma_{Max}/K_T < F_{TY} \quad \text{(region A1)} \tag{1}$$

$$\sigma_{Mean} = F_{TY} \quad \text{if} \quad \sigma_{Max}/K_T > F_{TY} \quad \text{and is a local stress (region A2)} \tag{2}$$

<u>For SSME</u>

$$\sigma_{Mean} = \sigma_{Max} \quad \text{if} \quad \sigma_{Alt}+\sigma_{Max} < F_{TY} \quad \text{(region S1)} \tag{4}$$

$$\sigma_{Mean} = F_{TY}-\sigma_{Alt} \quad \text{if} \quad \sigma_{Alt}+\sigma_{Max} > F_{TY} \quad \text{and} \quad \sigma_{Alt} < F_{TY} \quad \text{(region S2)} \tag{5}$$

$$\sigma_{Mean} = 0 \quad \text{if} \quad \sigma_{Alt} > F_{TY} \quad \text{(region S3)} \tag{6}$$

The corresponding equations which predict concentrated alternating stress capability are (σ_{EP} denotes ATD material endurance limit, σ_{ER} denotes SSME material endurance limit):

<u>Region A1</u>

$$\sigma_{Alt} = \sigma_{EP} \ (1-\sigma_{Nominal}/F_{TU}) \ . \tag{10}$$

<u>Region A2</u>

$$\sigma_{Alt} = \sigma_{EP} \ (1-F_{TY} / F_{TU}) \ . \tag{11}$$

<u>Region S1</u>

$$\sigma_{Alt} = \sigma_{ER} \ (1-\sigma_{Max} / F_{TU}) \ . \tag{12}$$

<u>Region S2</u>

$$\sigma_{Alt} = \sigma_{ER} \ (1-(F_{TY}-\sigma_{Alt})/F_{TU}) \ . \tag{13}$$

<u>Region S3</u>

$$\sigma_{Alt} = \sigma_{ER} \ . \tag{14}$$

For this comparison, region S3 will not be included. Due to overlap in the ATD and SSME regions, three equations are written which define the method that is more conservative. Figure 3 shows this overlap as a function of mean stress.

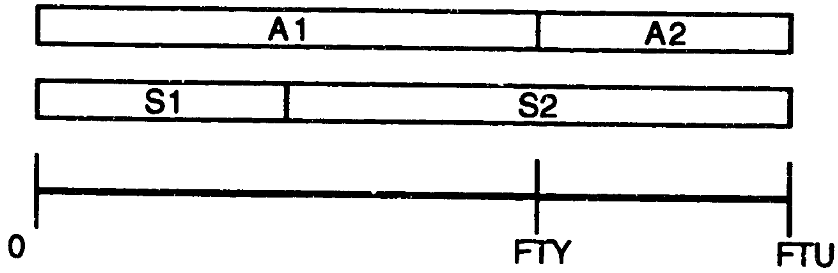


Figure 3. Location of region with mean stress.

The three governing equations are:

<u>For A1 and S1</u>

$$\sigma_{EP}\,(1-\sigma_{Nominal}/F_{TU}) = \sigma_{ER}\,(1-\sigma_{Max}\,/F_{TU}) \ . \qquad (15)$$

<u>For A1 and S2</u>

$$\sigma_{EP}\,(1-\sigma_{Nominal}/F_{TU}) = \sigma_{ER}\,(1-(F_{TY}-\sigma_{Alt})/F_{TU}) \ . \qquad (16)$$

<u>For A2 and S2</u>

$$\sigma_{EP}\,(1-F_{TY}/F_{TU}) = \sigma_{ER}\,(1-(F_{TY}-\sigma_{Alt})/F_{TU}) \ . \qquad (17)$$

Two different examples will be compared. The first is a generic case. This involves assumptions for the material characteristics. The second example is a specific case, the high pressure oxygen turbopump (HPOTP) inducer blade. Material data for both methods are available for INCO 718 .

A. General Case

For this generalized comparison, some assumptions were required: (1) The material yield strength (F_{TY}) was set at 75 percent of the ultimate strength (F_{TU}). This is an average value for all materials used on the ATD program. (2) The ATD endurance limit was set at 90 percent of the SSME value. ATD assumes the endurance limit occurs at 10^8 cycles as compared to 10^7 for SSME. Also, the ATD material data are subject to A-basis criteria, whereas SSME uses an S-basis approach.

Figure 4 shows the results of the generalized analysis. The graph represents the operating domain for most engine hardware. The geometric stress concentration factor is plotted on the abscissa. Mean stress as a percentage of ultimate strength is on the ordinate. The shaded region represents conditions where the SSME method is more conservative. ATD is more conservative in the unshaded area. Equation (15) is used to determine curve A. Curve B is based on the SSME region two criteria (equation (5)). Curve C is generated from equation (16). Line D is material yield strength from ATD's region 2 criteria (equation (2)). By solving equation (17), ATD's method is always more conservative between lines D and E. Line E represents the upper bound of the operating domain, the material ultimate strength.

Figure 4 shows that ATD's method is conservative at more locations in the operating range. This conclusion is based on the relative size of the two areas.

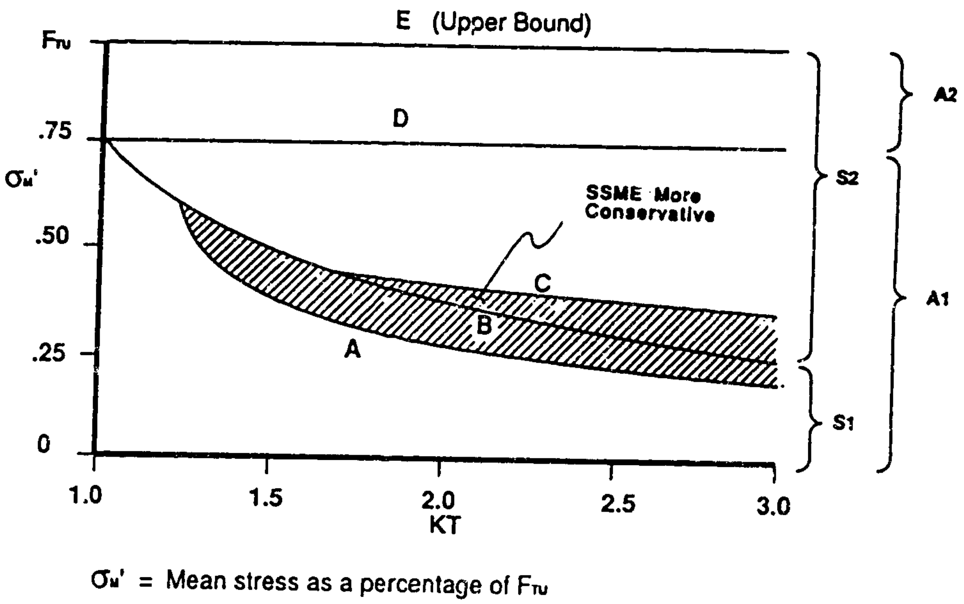


Figure 4. Generic case comparison.

B. Specific Case

The ATD HPOTP inducer (INCO 718) was chosen for the specific case. INCO 718 was selected because it is one of the few materials on which data are available in both material manuals.[2 3] The following table shows data at –270 °F.

	ATD (PWA1010)	SSME
Endurance Limit	35 ksi	46 ksi
Yield Strength	175 ksi	179 ksi
Ultimate Strength	212 ksi	212 ksi

These property values show that the two materials are comparable. Figure 5 shows the results of the specific case. The graph plots stress concentration versus mean stress. The unshaded region represents conditions where ATD's method is more conservative. SSME is more conservative in the shaded area.

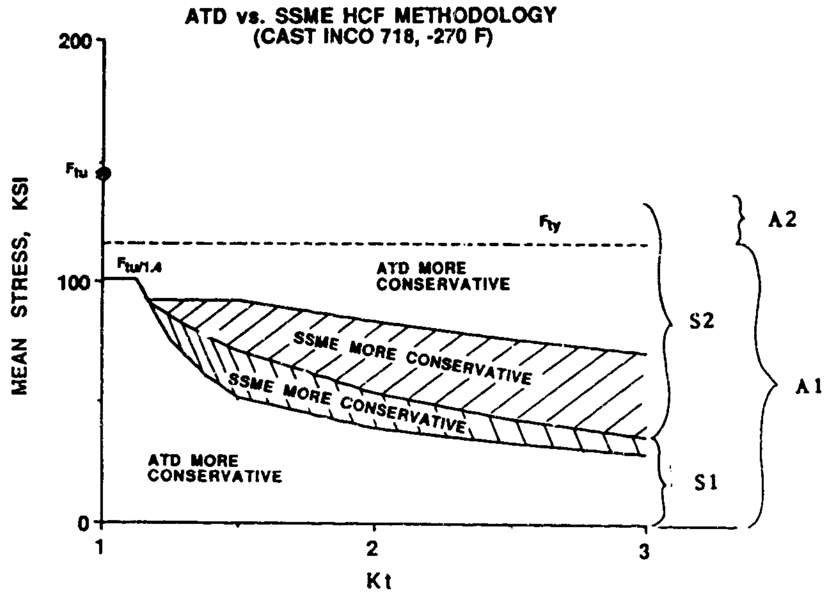


Figure 5. INCO 718 case comparison.

Figure 6 represents the magnitude of the difference between the two methodologies. The ratio of the SSME and ATD predicted capabilities is plotted versus mean stress. A ratio less than 1.0 means that SSME predicts a lower alternating stress capability. Above 1.0, ATD's value is lower. The results show that, as a worst case, ATD would predict the alternating stress capability 30-percent higher than SSME; whereas at the high mean stress levels, SSME would predict a dynamic capability three times the ATD value.

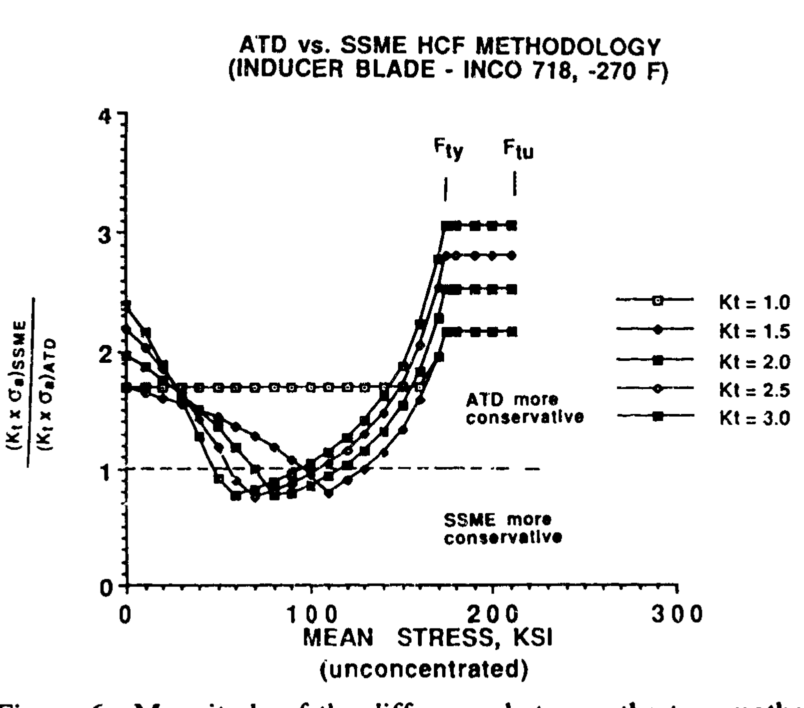


Figure 6. Magnitude of the difference between the two methods.

V. RESULTS

In general, the data show that the ATD HCF methodology is more conservative. For INCO 718, at worst, ATD would over-predict SSME's alternating capability value by 30 percent. Based on these findings, the ATD method is acceptable.

As a result of this comparison, several other related concerns have surfaced:

1. Both methods truncate the S-N curve. SSME assumes the materials endurance limit is 10^7 cycles, and ATD uses 10^8. For most nickel based materials, the cyclic capability is lower beyond these assumed endurance limits.

2. ATD's method for determining stress concentration factors is questionable. The predicted alternating stress capability is a function of K_T. These values are determined by comparing the peak stress to a calculated nominal stress. Determining the nominal stress in a cross section is not an exact procedure.

3. ATD should assure that the K_F curve is conservative for each particular situation, otherwise use K_T. Notch sensitivity is not applicable for all geometries.

4. The SSME shake-down method is not applicable for all situations. For smooth cross sections or rotating components, the mean stress will not "shake-down."

VI. CONCLUSIONS

The ATD HCF methodology is generally more conservative. Areas do exist where one method is more conservative than the other. However, ATD's approach is acceptable even in areas of less conservatism. The ATD HCF procedure meets the MSFC fatigue analysis requirements.

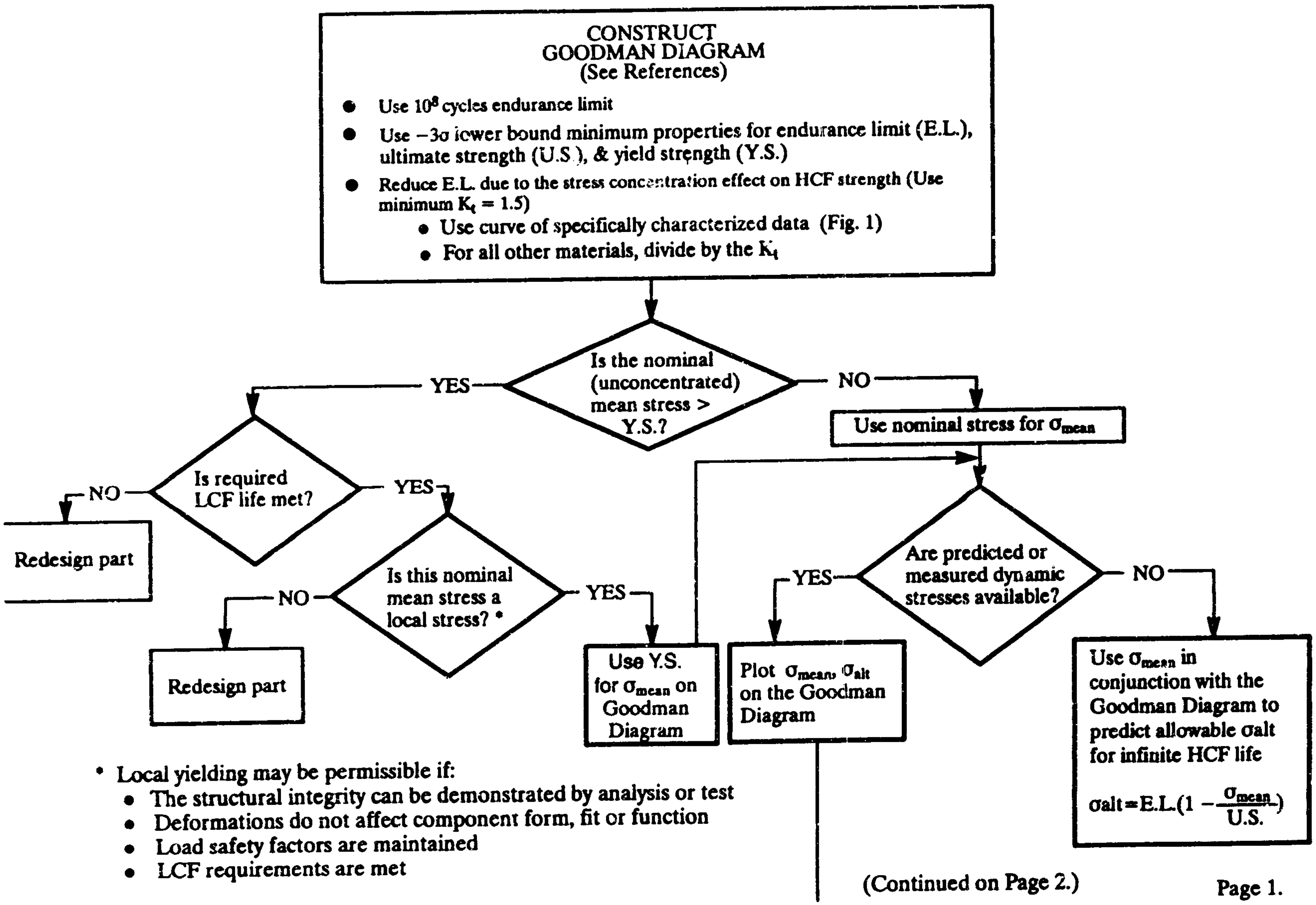
REFERENCES

1. Rocketdyne Structural Analysis Department Manual, April 11, 1988.
2. ATD Materials Manual, December 11, 1991.
3. Rocketdyne Material Properties Manual, 4th Edition 1986.

APPENDIX A

ATD HCF PROCEDURE FLOWCHART

TURBOPUMP HCF ASSESSMENT



* Local yielding may be permissible if:
  - The structural integrity can be demonstrated by analysis or test
  - Deformations do not affect component form, fit or function
  - Load safety factors are maintained
  - LCF requirements are met

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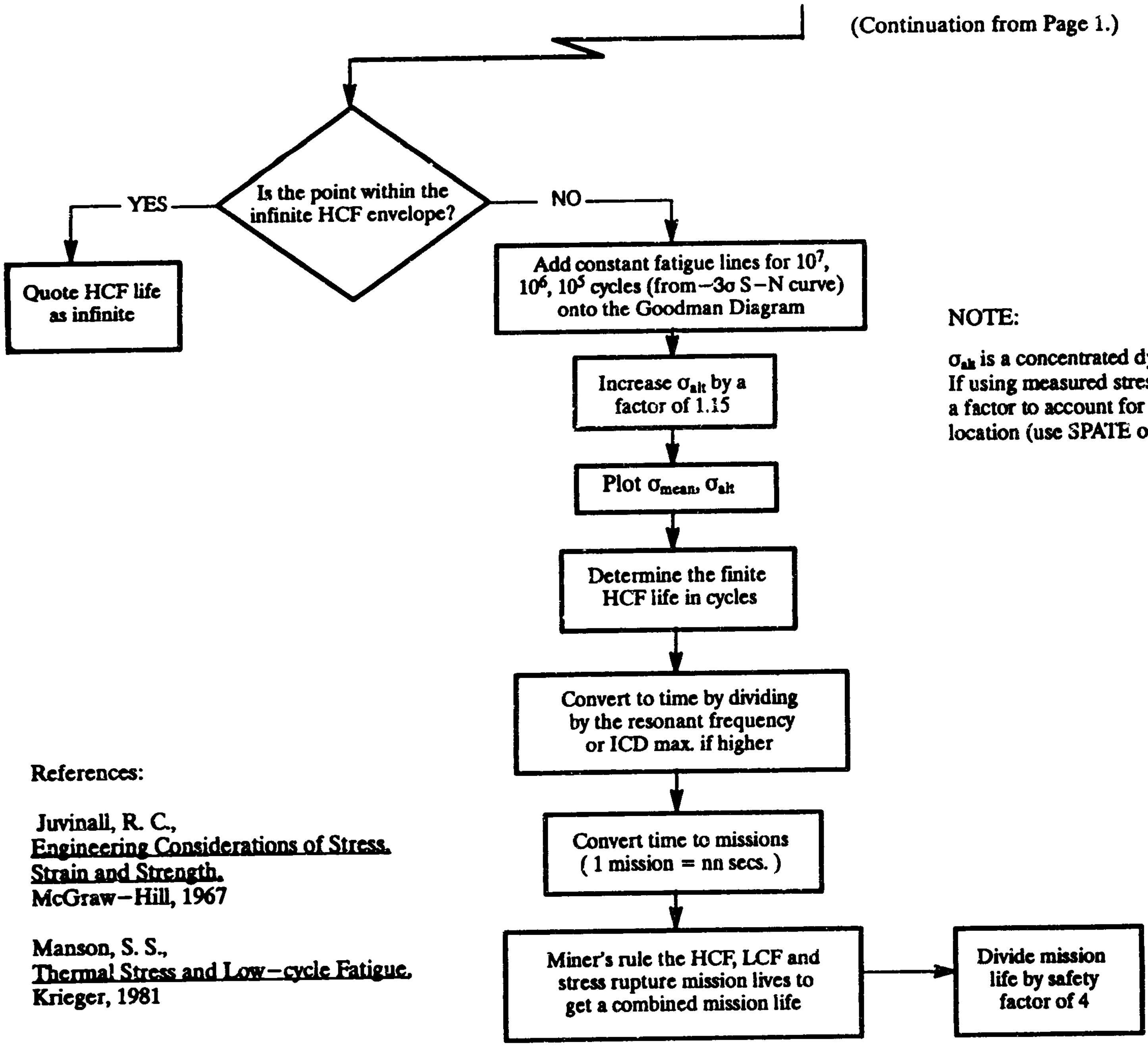
(Continuation from Page 1.)



NOTE:

σ_{alt} is a concentrated dynamic stress.
If using measured stress, there may be a factor to account for gage size and location (use SPATE or other lab test).

References:

Juvinall, R. C.,
Engineering Considerations of Stress, Strain and Strength,
McGraw−Hill, 1967

Manson, S. S.,
Thermal Stress and Low−cycle Fatigue,
Krieger, 1981

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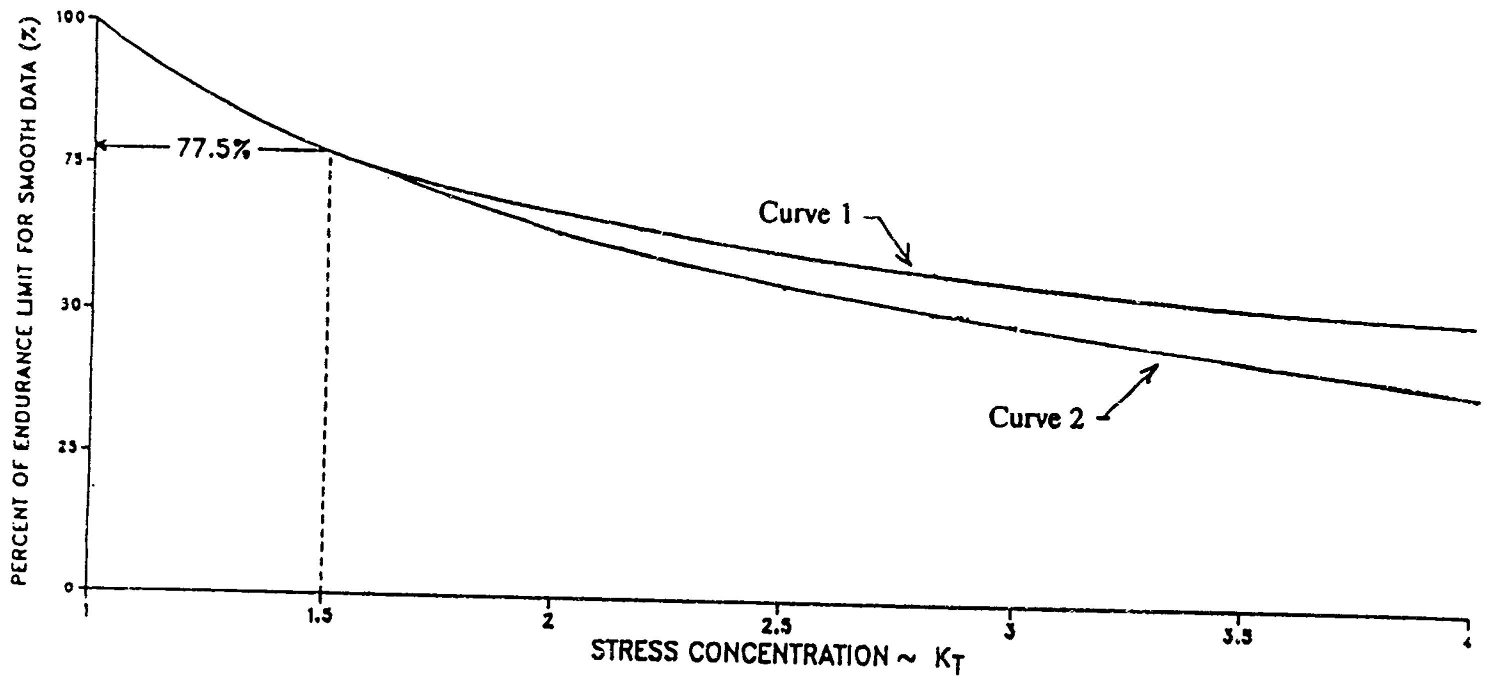
APPENDIX B

ATD ENDURANCE LIMIT ADJUSTMENT FACTOR

STRESS CONCENTRATION EFFECT ON HCF STRENGTH

Specifically Characterized Data



Curve 1 applicable to:

PWA 1010 PWA 1005 PWA 1074

PWA 1490 PWA 1007 PWA 658

PWA 649+ PWA 1016 PWA 1227+

PWA 659

Curve 2 applicable to:

PWA 1202

PWA 1240

PWA 1192, 80°GH2

PWA 1029

Note: Special curves exist for PWA 1480

Figure 1

APPROVAL

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By D.A. Herda

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

J.C. BLAIR
Director, Structures and Dynamics Laboratory

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