An Improved Approach for Flight Readiness Certification—Methodology for Failure Risk Assessment and Application Examples

Volume II: Software Documentation

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June 1, 1992

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The research described in this publication was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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Preface

This report presents the methodology for evaluating flight readiness developed by the Jet Propulsion Laboratory (JPL) under NASA RTOP 553-02-01 sponsored by the Office of Space Flight (OSF), NASA Headquarters. This methodology was developed as a part of the Certification Process Assessment task initiated by OSF due to concern about criteria for certifying flight readiness of the Space Shuttle propulsion system.

An early phase of this work included an extensive review of certification and failure risk assessment approaches used by the aerospace industry and government agencies. Based on the findings of this review, further work was focused on defining, developing, and demonstrating an improved technical approach for failure risk assessment that can incorporate information from both test experience and engineering analysis to obtain a quantitative failure risk estimate. This approach, called Probabilistic Failure Assessment (PFA), is of particular value when information relevant to failure prediction, including test experience and knowledge of parameters used in engineering analyses of failure phenomena, is expensive or difficult to acquire. Under such constraints, a quantitative evaluation of failure risk based on the information available from both engineering analysis and operating experience is needed to make effective risk management decisions and utilize financial resources efficiently.

The PFA methodology is applicable to failure modes that can be characterized by analytical or empirical modeling of failure phenomena and is especially useful when models or information used in analysis are uncertain or approximate. PFA can be applied at any time in the design, development, or operational phases of a program to quantitatively estimate failure risk based on the information available at the time of the risk assessment and can be used to evaluate and rank alternative measures to control risk, thereby enabling the more effective allocation of limited financial resources.

The work documented in this report was carried out by a multidisciplinary team of JPL technical personnel, which was managed by N. R. Moore. This team was composed of individuals with expertise in statistics, systems modeling, and engineering analysis. D. H. Ebbeler formulated and structured the statistical methodology and directed its implementation. L. E. Newlin formulated and implemented probabilistic engineering models and implemented the statistical methodology. S. Sutharshana

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1 See [3] of Section 1.0 references.
formulated probabilistic engineering analysis methods and models. M. Creager\textsuperscript{2} made major contributions to defining and formulating the probabilistic modeling approach and engineering analysis procedures used in this work. Present or former JPL personnel who made substantial contributions in early phases of this work include D. L. Schwartz, W. E. Edmiston, and L. J. Grondalski. D. Goode and J. Ramsay typeset the manuscript, including graphics, using computerized desktop publishing methods, and E. Reinig edited the manuscript.

In developing the PFA methodology, the JPL team interacted with aerospace system manufacturers, the Marshall Space Flight Center, and the Lewis Research Center. Individuals of these organizations generously shared information and spent significant amounts of time with the JPL team. In particular, Rocketdyne, Canoga Park, California, and Pratt & Whitney, West Palm Beach, Florida, collaborated in performing the application examples given herein. In addition, technical comments on certification approaches and failure modeling were provided by the above-listed organizations and by General Electric, Cincinnati, Ohio; the Federal Aviation Administration; and the Wright-Patterson Air Force Base.

The PFA methodology, examples of its application to spaceflight components, and computer software used to implement PFA are documented in the three volumes of this report. Volume I documents the PFA methodology and the application examples, including the rationale for PFA and the analysis procedures used in the examples. Volume II contains user's guides and flowcharts for the computer software used to implement PFA in the application examples. Volume III presents the structure and listings of the computer programs.

\textsuperscript{2} Currently of Structural Integrity Engineering, Chatsworth, CA.
Acknowledgments

The authors wish to acknowledge the guidance and encouragement provided by D. L. Winterhalter of the Office of Space Flight, NASA Headquarters, whose support made this work possible. The authors appreciate the encouragement of R. Bardos, J. Mulcahy, and other individuals of OSF. The review and comments on this work provided by R. Weinstock of Vitro, Washington, D. C. contributed substantially to its successful completion.

The application examples of this report were performed in collaboration with Rocketdyne, Canoga Park, California, and Pratt & Whitney, West Palm Beach, Florida. Several individuals at each organization contributed generously to this work, including E. P. Fox and C. G. Annis of Pratt & Whitney, and K. J. O'Hara and D. O'Connor of Rocketdyne. The authors worked particularly closely with E. P. Fox of Pratt & Whitney and K. J. O'Hara of Rocketdyne; their considerable contributions are gratefully acknowledged.

Present or former personnel of the NASA Marshall Space Flight Center, whose cooperation was instrumental in successfully performing this work, include J. Lombardo, J. S. Richards, G. W. Smith, L. D. Salter, H. P. Stinson, and J. Townsend.

The authors appreciate the technical comments provided by L. Beitch and A. Coles of the General Electric Co., Cincinnati, Ohio, on flight readiness certification approaches and fatigue life modeling. The effort of G. R. Halford of the NASA Lewis Research Center in providing information on materials fatigue life modeling is appreciated.

Throughout the course of this work constructive guidance was provided by the Liquid Rocket Engine Certification Subcommittee of Aerospace Division Committee G-11, Society of Automotive Engineers. The membership of this subcommittee included: W. E. Campbell, Aerojet; K. J. O'Hara, Rocketdyne; E. P. Fox, Pratt & Whitney; J. S. Richards and H. P. Stinson, NASA-MSFC; R. L. Doeblier, Aerospace Corp.; and N. R. Moore, JPL.

Finally, the authors wish to acknowledge the review of the technical approach of this work provided by the late R. P. Feynman of the California Institute of Technology.

The authors express their gratitude to all those individuals who contributed to this work and regret that a complete listing is not feasible.
Abstract

An improved methodology for quantitatively evaluating failure risk of spaceflight systems to assess flight readiness and identify risk control measures is presented. This methodology, called Probabilistic Failure Assessment (PFA), combines operating experience from tests and flights with engineering analysis to estimate failure risk. The PFA methodology is of particular value when information on which to base an assessment of failure risk, including test experience and knowledge of parameters used in engineering analyses of failure phenomena, is expensive or difficult to acquire.

The PFA methodology is a prescribed statistical structure in which engineering analysis models that characterize failure phenomena are used conjointly with uncertainties about analysis parameters and/or modeling accuracy to estimate failure probability distributions for specific failure modes. These distributions can then be modified, by means of statistical procedures of the PFA methodology, to reflect any test or flight experience. Conventional engineering analysis models currently employed for design or failure prediction are used in this methodology.

The PFA methodology can be applied at any time in the design, development, or operational phases of a program to quantitatively estimate failure risk based on the information available at the time failure risk is assessed. Sensitivity analyses conducted as a part of PFA can be used to evaluate and rank such alternative measures to control risk as design changes, testing, or inspections, thereby enabling limited program resources to be allocated more effectively.

PFA is generally applicable to failure modes that can be characterized by analytical or empirical models of failure phenomena and is especially useful when models or information used in analysis are uncertain or approximate. Such failure modes include, but are not limited to, fatigue, flaw propagation, rupture, degradation and wear, and malfunction of mechanical or electrical systems.

It is often not feasible to acquire enough test experience to establish high reliability at high confidence for spaceflight systems. Moreover, the results of conventionally performed engineering analyses of failure modes can be subject to serious misinterpretation when uncertain or approximate information is used to establish analysis parameters and calibrate the accuracy of analysis models. Under these conditions, a quantitative evaluation of failure risk based on the information available from both test or flight experience and engineering analysis is needed to make effective risk management decisions.
This report describes the PFA methodology and presents examples of its application. Conventional approaches to failure risk evaluation for spaceflight systems are discussed, and the rationale for the approach taken in the PFA methodology is presented. The statistical methods, engineering models, and computer software used in fatigue failure mode applications are thoroughly documented.
# Table of Contents

**VOLUME I – Methodology and Applications**

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preface</td>
<td>iii</td>
</tr>
<tr>
<td>Acknowledgments</td>
<td>v</td>
</tr>
<tr>
<td>Abstract</td>
<td>vi</td>
</tr>
<tr>
<td>Table of Contents</td>
<td>ix</td>
</tr>
<tr>
<td>List of Figures</td>
<td>xxvll</td>
</tr>
<tr>
<td>List of Tables</td>
<td>xxvlll</td>
</tr>
</tbody>
</table>

## 1.0 Introduction

1.1 Flight Readiness Assessment
   - 1.1.1 The Flight Readiness Assessment Problem | 1-3
   - 1.1.2 Conventional Approaches to Flight Readiness Assessment
     - 1.1.2.1 Testing to Establish Flight Readiness | 1-5
     - 1.1.2.2 Deterministic Engineering Analysis | 1-9
   - 1.2 An Improved Approach to Flight Readiness Assessment | 1-11
     - 1.2.1 Failure Risk Assessment | 1-11
     - 1.2.2 The Probabilistic Failure Assessment Methodology | 1-12
     - 1.2.3 Probabilistic Failure Modeling | 1-14
     - 1.2.4 Driver Characterization | 1-15
     - 1.2.5 Computational Methods | 1-17
   - 1.3 Implementing the PFA Methodology | 1-19
   - 1.4 Report Organization | 1-21

## 2.0 Methodology

2.1 Statistical Analysis
   - 2.1.1 Failure Simulation Statistics
     - Reference | 2-3
   - 2.1.2 Materials Fatigue Life Characterization
     - 2.1.2.1 Stress/Life Characterization of Fatigue Failure of Materials
       - References | 2-6
     - 2.1.2.2 Strain/Life Characterization of Fatigue Failure of Materials | 2-18
     - 2.1.2.3 Process Variation in Materials | 2-19
   - 2.1.3 Driver Characterization | 2-22

References | 1-24

Appendix 1.A The Limitations of Testing for Reliability Demonstration | 1-27
Appendix 1.B List of Acronyms | 1-31

References | 2-18

Appendix 1.A The Limitations of Testing for Reliability Demonstration | 1-27
Appendix 1.B List of Acronyms | 1-31
2.1.3.1 Driver Probability Distributions ................................................. 2-22
  Uniform Distribution ................................................................. 2-23
  Normal Distribution ................................................................. 2-23
  Beta Distribution ................................................................. 2-25
2.1.3.2 Load Scale Factors ............................................................. 2-27
  Reference ....................................................................................... 2-29
2.1.4 Composite Stresses in High Cycle Fatigue Analysis ......................... 2-29
  Reference ....................................................................................... 2-31
2.1.5 Duty Cycle Effects in Reliability Estimation .................................. 2-32
2.1.6 Modeling Spatially Symmetric Components .................................. 2-33
2.2 Engineering Analysis .................................................................... 2-39
  2.2.1 High Cycle Fatigue Failure Modeling ........................................ 2-39
    2.2.1.1 Introduction ......................................................................... 2-39
    2.2.1.2 Load Description and Stress Analysis ......................... 2-40
      Vibration Environment Characterization .................................. 2-40
      Finite Element Stress Analyses ................................................. 2-41
    2.2.1.3 Duct Stress Analysis ......................................................... 2-42
      Ovality Effect ............................................................................. 2-45
      Torus Effect .............................................................................. 2-48
      Stress Summation ..................................................................... 2-48
    2.2.1.4 Damage Calculations ......................................................... 2-51
      Rainflow Cycle Counting ........................................................... 2-51
      Mean Stress Effects ................................................................... 2-52
    2.2.1.5 Component Analyses ......................................................... 2-55
      References ................................................................................. 2-57
  2.2.2 Low Cycle Fatigue Failure Modeling ......................................... 2-59
    2.2.2.1 Introduction ......................................................................... 2-59
    2.2.2.2 ATD-HPFTP Second Stage Turbine Disk LCF Analysis ........ 2-61
      Component Description ............................................................... 2-61
      Low Cycle Fatigue Failure Modeling Approach ......................... 2-61
      Driver Transformation .................................................................. 2-64
      Mission Stress History for the ATD Disk .................................... 2-68
      Modeling Multiple Critical Locations ........................................... 2-69
      Probabilistic Failure Model Implementation .................................. 2-69
  2.3 Analysis Procedures ..................................................................... 2-73
    2.3.1 Introduction ............................................................................. 2-73
    2.3.2 Driver Characterization .......................................................... 2-75
    2.3.3 Preliminary Deterministic Analysis ....................................... 2-77
    2.3.4 Driver Transformation .......................................................... 2-77
    2.3.5 Probabilistic Failure Model Formulation .................................. 2-78
    2.3.6 Materials Characterization ..................................................... 2-79
Weld Offset Stress Concentration Accuracy Factors 3-42
3.A.2.4 Materials Characterization 3-43
3.A.2.5 Time History Definition 3-44
3.A.2.6 Significant Load Identification 3-46
3.A.2.7 Probability of Failure Curve Parameter Estimation 3-46
3.A.2.8 Driver Sensitivity Analysis 3-51
3.A.2.9 Probability of Failure Curve Standardization 3-52
3.A.3 ATD-HPFTP Second Stage Turbine Disk LCF Analysis Details 3-52
3.A.3.1 Selecting the Component, Failure Mode, and Critical Location 3-52
3.A.3.2 Preliminary Deterministic Analysis 3-52
3.A.3.3 Driver Characterization 3-53
3.A.3.4 Materials Characterization 3-53
3.A.3.5 Time History Definition 3-54
3.A.3.6 Probability of Failure Curve Parameter Estimation 3-54
3.A.3.7 Driver Sensitivity Analysis 3-56
3.A.3.8 Probability of Failure Curve Standardization 3-57

Appendix 3.B Input And Output Files 3-59
3.B.1 HPOTP Main Discharge Duct HCF Analysis Files 3-59
   Input File - DCTHCD 3-59
   Output File - DCTHCO 3-61
   Output File - LOWLIF 3-65
   Output File - DUMP 3-69
3.B.2 LPFTP Turbine Drive Duct HCF Analysis Files 3-70
   Input File - DCTHCD 3-71
   Output File - DCTHCO 3-73
   Output File - LOWLIF 3-77
   Output File - DUMP 3-82
3.B.3 HPOTP Heat Exchanger Coil HCF Analysis Files 3-83
   Input File - HEXHCD 3-83
   Output File - HEXHCO 3-85
   Output File - LOWLIF 3-89
   Output File - DUMP 3-93
3.B.4 ATD-HPFTP Second Stage Turbine Disk LCF Analysis Files 3-94
   Input File - TRBPWD 3-95
   Output File - TRBPWO 3-96
   Output File - LOWLIF 3-98
   Output File - DUMP 3-102

VOLUME II - Software Documentation

4.0 Statistical Analysis Software 4-1
  4.1 Materials Characterization Software 4-3
    4.1.1 Introduction 4-3
4.2.2 BFIT Program ........................................ 4-73
   4.2.2.1 LLS Routine ................................ 4-73
4.2.3 ABTFIT Program ..................................... 4-76
   4.2.3.1 ABT Routine .................................. 4-80
   4.2.3.2 JABT Routine ................................ 4-80
4.2.4 LZERO Program ..................................... 4-80
   4.2.4.1 Routine GAMMA ................................ 4-83
   4.2.4.2 Routine DLGAM ................................ 4-83
   4.2.4.3 Routine MUELLR .............................. 4-83
   4.2.4.4 Routine FCT ................................... 4-83
   4.2.4.5 Routine TRMNAT .............................. 4-83

4.3 Bayesian Statistical Procedure Software ................. 4-85
   4.3.1 Introduction .................................... 4-85
   4.3.2 BAYES Program .................................. 4-85

4.4 Random Number Generation Software ...................... 4-87
   4.4.1 Introduction .................................... 4-87
   4.4.2 RANDOM Routine ................................ 4-87
   4.4.3 NORMGN Routine ................................. 4-87
   4.4.4 GAM Routine .................................... 4-87
   4.4.5 BETAGN Routine ................................ 4-87
   4.4.6 WEIBGN Routine ................................ 4-88

4.5 Reference Time History Generation Software ............. 4-89
   4.5.1 Introduction .................................... 4-89
   4.5.2 NBSIN Program .................................. 4-89

References .................................................................. 4-95

5.0 Fatigue Analysis Software ................................ 5-1

5.1 High Cycle Fatigue Analysis Software .................... 5-3
   5.1.1 Introduction ..................................... 5-3
   5.1.2 DCTHCF Program .................................. 5-4
      5.1.2.1 Main Routine ................................ 5-4
      5.1.2.2 ELWELD Routine ............................. 5-8
      5.1.2.3 M2L1 Routine ................................ 5-8
      5.1.2.4 CALCS Routine .............................. 5-11
      5.1.2.5 NARBN1 Routine ............................. 5-11
      5.1.2.6 RAINF1 Routine ............................. 5-11
      5.1.2.7 PGETSM Routine ............................ 5-21
   5.1.3 HEXHCF Program .................................. 5-21
      5.1.3.1 Main Routine ................................ 5-21
      5.1.3.2 THWELD Routine ............................. 5-26
      5.1.3.3 M4L1 Routine ................................ 5-28
<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1.10</td>
<td>Description of Input Data Files</td>
<td>6-45</td>
</tr>
<tr>
<td>6.1.10.1</td>
<td>Input File HEXHCD</td>
<td>6-45</td>
</tr>
<tr>
<td></td>
<td>Analysis Parameters Block</td>
<td>6-49</td>
</tr>
<tr>
<td></td>
<td>Driver Information Block</td>
<td>6-51</td>
</tr>
<tr>
<td></td>
<td>Load and Geometry block</td>
<td>6-58</td>
</tr>
<tr>
<td></td>
<td>Materials Information Block</td>
<td>6-62</td>
</tr>
<tr>
<td>6.1.10.2</td>
<td>Input File RELATD</td>
<td>6-65</td>
</tr>
<tr>
<td>6.1.10.3</td>
<td>Reference Time History Files</td>
<td>6-67</td>
</tr>
<tr>
<td>6.1.11</td>
<td>Options and Capabilities</td>
<td>6-67</td>
</tr>
<tr>
<td>6.1.12</td>
<td>Code Execution Example</td>
<td>6-68</td>
</tr>
<tr>
<td></td>
<td>Input File - HEXHCD</td>
<td>6-70</td>
</tr>
<tr>
<td></td>
<td>Input File - RELATD</td>
<td>6-72</td>
</tr>
<tr>
<td></td>
<td>Input File - NBM                       3</td>
<td>6-72</td>
</tr>
<tr>
<td></td>
<td>Input File - SIN1</td>
<td>6-72</td>
</tr>
<tr>
<td></td>
<td>Input File - AERO1</td>
<td>6-72</td>
</tr>
<tr>
<td></td>
<td>Output File - HEXHCO</td>
<td>6-73</td>
</tr>
<tr>
<td></td>
<td>Output File - RELHCO</td>
<td>6-77</td>
</tr>
<tr>
<td></td>
<td>Output File - DUMP</td>
<td>6-77</td>
</tr>
<tr>
<td></td>
<td>Output File - IOUTPR</td>
<td>6-78</td>
</tr>
<tr>
<td></td>
<td>Output File - LOWLIF</td>
<td>6-78</td>
</tr>
<tr>
<td>6.1.13</td>
<td>Error Messages and Possible Remedies</td>
<td>6-78</td>
</tr>
<tr>
<td>6.1.14</td>
<td>Summary of Input/Output Files</td>
<td>6-83</td>
</tr>
<tr>
<td></td>
<td>Input Files</td>
<td>6-83</td>
</tr>
<tr>
<td></td>
<td>Output Files</td>
<td>6-83</td>
</tr>
<tr>
<td>6.2</td>
<td>Low Cycle Fatigue Analysis User's Guide</td>
<td>6-85</td>
</tr>
<tr>
<td>6.2.1</td>
<td>TRBPWA Program</td>
<td>6-85</td>
</tr>
<tr>
<td>6.2.2</td>
<td>How To Use Program TRBPWA</td>
<td>6-85</td>
</tr>
<tr>
<td>6.2.3</td>
<td>Description of Input Data Files</td>
<td>6-86</td>
</tr>
<tr>
<td>6.2.3.1</td>
<td>Input File TRBPWD</td>
<td>6-86</td>
</tr>
<tr>
<td></td>
<td>Analysis Parameters Block</td>
<td>6-89</td>
</tr>
<tr>
<td></td>
<td>Driver Information Block</td>
<td>6-91</td>
</tr>
<tr>
<td></td>
<td>Load and Geometry Block</td>
<td>6-93</td>
</tr>
<tr>
<td></td>
<td>Materials Information Block</td>
<td>6-94</td>
</tr>
<tr>
<td>6.2.3.2</td>
<td>Input File RELATD</td>
<td>6-97</td>
</tr>
<tr>
<td>6.2.4</td>
<td>Options and Capabilities</td>
<td>6-99</td>
</tr>
<tr>
<td>6.2.5</td>
<td>Code Execution Example</td>
<td>6-100</td>
</tr>
<tr>
<td></td>
<td>Input File - TRBPWD</td>
<td>6-101</td>
</tr>
<tr>
<td></td>
<td>Input File - RELATD</td>
<td>6-102</td>
</tr>
<tr>
<td></td>
<td>Output File - TRBPWO</td>
<td>6-102</td>
</tr>
<tr>
<td></td>
<td>Output File - RELATO</td>
<td>6-104</td>
</tr>
<tr>
<td></td>
<td>Output File - DUMP</td>
<td>6-104</td>
</tr>
<tr>
<td></td>
<td>Output File - IOUTPR</td>
<td>6-105</td>
</tr>
</tbody>
</table>
Output File - LOWLIF ........................................... 6-106
6.2.6 Error Messages and Possible Remedies ................ 6-110
6.2.7 Summary of Input/Output Files .......................... 6-114
   Input Files ................................................. 6-114
   Output Files ............................................... 6-114

  6.3.1 MATCHR Program ........................................ 6-117
  6.3.2 How To Use the Stress Formulation Option of Program MATCHR 6-117
  6.3.3 Description of the Stress Formulation Input Data Files 6-118
     6.3.3.1 Input File SPECFD ................................ 6-118
       Analysis Parameters Block ............................... 6-118
       Materials Information Block ............................ 6-123
     6.3.3.2 Input File RELATD ................................ 6-127
  6.3.4 Options and Capabilities of the Stress Formulation .......... 6-128
  6.3.5 Code Execution Example for the Stress Formulation ........ 6-129
     Input File - SPECFD ...................................... 6-129
     Input File - RELATD ..................................... 6-130
     Output File - SPECFO .................................... 6-130
     Output File - RELATO .................................... 6-131
     Output File - DUMP ...................................... 6-132
     Output File - IOUTPR .................................... 6-133
  6.3.6 How To Use the Strain Formulation Option of Program MATCHR 6-133
  6.3.7 Description of the Strain Formulation Input Data Files ..... 6-134
     6.3.7.1 Input File SPECFD ................................ 6-134
       Analysis Parameters Block ............................... 6-137
       Materials Information Block ............................ 6-138
     6.3.7.2 Input File RELATD ................................ 6-142
  6.3.8 Options and Capabilities of the Strain Formulation ......... 6-143
  6.3.9 Code Execution Example for the Strain Formulation ........ 6-144
     Input File - SPECFD ...................................... 6-144
     Input File - RELATD ..................................... 6-145
     Output File - SPECFO .................................... 6-145
     Output File - RELATO .................................... 6-146
     Output File - DUMP ...................................... 6-146
     Output File - IOUTPR .................................... 6-149
  6.3.10 Error Messages and Possible Remedies .................. 6-150
  6.3.11 Summary of Input/Output Files .......................... 6-156
     Input Files ................................................. 6-156
     Output Files ............................................... 6-156

6.4 Prior Distribution Parameter Estimation User's Guide ........ 6-159
  6.4.1 BFIT Program ........................................... 6-159
6.4.2 How To Use Program BFIT .................................................. 6-159
6.4.3 Description of the Input Data Files ................................. 6-159
  6.4.3.1 Input File BFITD .................................................. 6-160
  6.4.3.2 Input File LOWLIF .................................................. 6-161
6.4.4 Options and Capabilities .............................................. 6-161
6.4.5 Code Execution Example ............................................... 6-161
  Input File - BFITD .................................................. 6-162
  Input File - LOWLIF .................................................. 6-162
  Output File - BFITO .................................................. 6-166
  Output File - IOUTPR .................................................. 6-166
6.4.6 Summary of Input/Output Files ...................................... 6-166
  Input Files .............................................. 6-166
  Output Files ............................................. 6-167
6.4.7 ABTFIT Program ....................................................... 6-167
6.4.8 How to Use Program ABTFIT ........................................... 6-167
6.4.9 Description of the Input Data Files ................................ 6-167
  6.4.9.1 Input File PARAMS .............................................. 6-168
  6.4.9.2 Input File LOWLIF .............................................. 6-169
6.4.10 Options and Capabilities ........................................... 6-169
6.4.11 Code Execution Example ............................................ 6-170
  Input File - PARAMS ............................................. 6-170
  Input File - LOWLIF ............................................. 6-171
  Output File - ABTOUT ............................................. 6-175
  Output File - BAYESD ............................................. 6-175
  Output File - IOUTPR ............................................. 6-175
6.4.12 Summary of Input/Output Files ................................... 6-176
  Input Files .............................................. 6-176
  Output Files ............................................. 6-176
6.4.13 LZERO Program ....................................................... 6-176
6.4.14 How to Use Program LZERO .......................................... 6-177
6.4.15 Description of the Input Data Files .............................. 6-177
  6.4.15.1 Input File BAYESD ............................................. 6-178
  6.4.15.2 Input File LDAT ............................................. 6-178
6.4.16 Options and Capabilities ........................................... 6-179
6.4.17 Code Execution Example ............................................ 6-179
  Input File - BAYESD ............................................. 6-179
  Input File - LDAT ............................................. 6-179
  Output File - LOUT ............................................. 6-180
6.4.18 Summary of Input/Output Files ................................... 6-180
  Input Files .............................................. 6-180
  Output Files ............................................. 6-180
6.5 Bayesian Statistical Procedure User's Guide ....................... 6-181
6.5.1 BAYES Program .................................................. 6-181
6.5.2 How To Use Program BAYES .................................... 6-181
6.5.3 Description of the Input Data File
   6.5.3.1 Input File BAYESD ........................................... 6-182
       Prior Failure Distribution Parameters Block ............... 6-183
       Operating Experience Block ............................... 6-183
6.5.4 Options and Capabilities ...................................... 6-183
6.5.5 Code Execution Example
   Input File - BAYESD .............................................. 6-184
   Output File - BAYESO ............................................ 6-184
   Output File - UBAYES ............................................ 6-185
6.5.6 Summary of Input/Output Files
   Input Files .......................................................... 6-185
   Output Files ........................................................ 6-186

   6.6.1 NBSIN Program ................................................. 6-187
   6.6.2 How To Use Program NBSIN ................................. 6-187
   6.6.3 Description of the Input Data File
      6.6.3.1 Input File NBSIN ........................................ 6-189
       Generation Parameters Block ............................... 6-189
       Narrow-band Process Information Block .................. 6-191
       Sinusoidal Process Block .................................. 6-192
   6.6.4 Options and Capabilities .................................... 6-192
   6.6.5 Code Execution Example
      Input File - NBSIN ............................................. 6-192
      Output File - IOUTPR .......................................... 6-193
      Output File - AXIAL .......................................... 6-193
      Output File - MOMENT ........................................ 6-194
      Output File - SIN ............................................. 6-194
   6.6.6 Summary of Input/Output Files
      Input Files ........................................................ 6-194
      Output Files ........................................................ 6-194

VOLUME III – Structure and Listing of Programs

7.0 Structure and Listing of Programs ................................ 7-1
   7.1 High Cycle Fatigue Failure Programs ........................ 7-3
      7.1.1 DCTHCF Program ............................................ 7-3
         7.1.1.1 Program Tree Structure ................................ 7-3
         7.1.1.2 List of Subprograms ................................... 7-3
         7.1.1.3 Description of Variables ............................ 7-9
         7.1.1.4 Program DCTHCF Listing
                  Program DCTHCF Listing Temporal Order, Uniform Distribution ... 7-28
Program DCTHCF Listing Temporal Order, Truncated Normal Distribution ........................................... 7-30

7.1.2 HEXHCF Program .................................................. 7-121
7.1.2.1 Program Tree Structure ......................................... 7-121
7.1.2.2 List of Subprograms ............................................ 7-121
7.1.2.3 Description of Variables ........................................ 7-127
7.1.2.4 Program HEXHCF Listing ........................................ 7-145
   Program HEXHCF Listing Temporal Order, Uniform Distribution . 7-147
   Program HEXHCF Listing Temporal Order, Truncated Normal Distribution ........................................... 7-147

7.2 Low Cycle Fatigue Failure Program .................................. 7-241
7.2.1 TRBPWA Program .................................................. 7-241
7.2.1.1 Program Tree Structure ......................................... 7-241
7.2.1.2 List of Subprograms ............................................ 7-241
7.2.1.3 Description of Variables ........................................ 7-247
7.2.1.4 Program TRBPWA Listing ........................................ 7-255
   Program TRBPWA Listing Temporal Order, Uniform Distribution . 7-256
   Program TRBPWA Listing Temporal Order, Truncated Normal Distribution ........................................... 7-257

7.3 Materials Characterization Program .................................. 7-325
7.3.1 MATCHR Program .................................................. 7-325
7.3.1.1 Program Tree Structure ......................................... 7-325
7.3.1.2 List of Subprograms ............................................ 7-325
7.3.1.3 Description of Variables ........................................ 7-335
7.3.1.4 Program MATCHR Listing ........................................ 7-359
   Program MATCHR Listing Temporal Order, Stress Formulation, Uniform Distribution ................................. 7-361
   Program MATCHR Listing Temporal Order, Stress Formulation, Truncated Normal Distribution ........................ 7-362
   Program MATCHR Listing Temporal Order, Strain Formulation, Uniform Distribution ................................. 7-363
   Program MATCHR Listing Temporal Order, Strain Formulation, Truncated Normal Distribution ........................ 7-365

7.4 Prior Distribution Parameter Estimation Program ...................... 7-451
7.4.1 BFIT Program ..................................................... 7-451
7.4.1.1 List of Subprograms ............................................ 7-451
7.4.1.2 Description of Variables ........................................ 7-451
7.4.1.3 Program BFIT Listing ............................................ 7-452
7.4.2 ABTFIT Program ................................................... 7-455
7.4.2.1 Program Tree Structure ......................................... 7-455
7.4.2.2 List of Subprograms ............................................ 7-455
7.4.2.3 Description of Variables ........................................ 7-456
7.4.2.4 Program ABTFIT Listing ....................................... 7-457
7.4.3 LZERO Program .................................................. 7-461
   7.4.3.1 Program Tree Structure ..................................... 7-461
   7.4.3.2 List of Subprograms ......................................... 7-461
   7.4.3.3 Description of Variables .................................. 7-462
   7.4.3.4 Program LZERO Listing ..................................... 7-463

7.5 Bayesian Statistical Procedure Program ................................ 7-471
   7.5.1 BAYES Program ................................................ 7-471
      7.5.1.1 Description of Variables ................................ 7-471
      7.5.1.2 Program BAYES Listing .................................. 7-473

7.6 Random Number Generation Subprograms ................................ 7-477
   7.6.1 RANDOM Subprogram .......................................... 7-477
      7.6.1.1 Description of Variables ................................ 7-477
      7.6.1.2 Subprogram RANDOM Listing ............................ 7-478
   7.6.2 NORMGN Subprogram .......................................... 7-479
      7.6.2.1 Description of Variables ................................ 7-479
      7.6.2.2 Subprogram NORMGN Listing ............................ 7-479
   7.6.3 BETAGN Subprogram .......................................... 7-480
      7.6.3.1 Description of Variables ................................ 7-480
      7.6.3.2 Subprogram BETAGN Listing ............................ 7-481
   7.6.4 GAM Subprogram ............................................. 7-482
      7.6.4.1 Description of Variables ................................ 7-482
      7.6.4.2 Subprogram GAM Listing ................................ 7-482
   7.6.5 WEIBGN Subprogram .......................................... 7-483
      7.6.5.1 Description of Variables ................................ 7-483
      7.6.5.2 Subprogram WEIBGN Listing ............................ 7-483
   7.6.6 PRYRV Subprogram .......................................... 7-484
      7.6.6.1 Description of Variables ................................ 7-484
      7.6.6.2 Subprogram PRYRV Listing ............................ 7-485

7.7 Reference Time History Generation Program .......................... 7-487
   7.7.1 NBSIN Program ............................................. 7-487
      7.7.1.1 Program Tree Structure ................................ 7-487
      7.7.1.2 List of Subprograms ................................... 7-487
      7.7.1.3 Description of Variables ................................ 7-488
      7.7.1.4 Program NBSIN Listing ................................ 7-491
List of Figures

Figure 1-1  Reliability Demonstrated by Zero-Failure Operating Experience for \(N = 2\) at 95% Confidence ........................................ 1-7
Figure 1-2  Information Sources for Failure Risk Assessment ........................................ 1-11
Figure 1-3  The Probabilistic Failure Assessment Methodology ........................................ 1-13
Figure 1-4  The Probabilistic Failure Modeling Procedure ........................................ 1-14
Figure 1-5  Options for Controlling Failure Risk ........................................ 1-19
Figure 1-6  Reliability Demonstrated By Nonfailure Operating Experience for the Powerhead Assembly ........................................ 1-29
Figure 1-7  Reliability Demonstrated By Nonfailure Operating Experience for the HPOTP Main Discharge Duct ........................................ 1-29
Figure 1-8  Reliability Demonstrated By Nonfailure Operating Experience for the LPFTP Turbine Drive Duct ........................................ 1-30
Figure 1-9  Reliability Demonstrated By Nonfailure Operating Experience for the HPOTP Heat Exchanger ........................................ 1-30
Figure 2-1  Component Failure Mode Monte Carlo Simulation Structure ........................................ 2-3
Figure 2-2  S/N Curves ........................................ 2-18
Figure 2-3  Uniform Distribution ........................................ 2-24
Figure 2-4  Normal Distribution ........................................ 2-24
Figure 2-5  Beta Distributions with \(p = 0.5\) and Different Values of \(\theta\) ........................................ 2-25
Figure 2-6  Beta Distributions with \(p = 0.7\) and Different Values of \(\theta\) ........................................ 2-26
Figure 2-7  Procedure for Specifying Beta Distribution ........................................ 2-26
Figure 2-8  Load Scale Factors ........................................ 2-27
Figure 2-9  Superposition of Narrow-Band Gaussian and Sinusoidal Stress-Time Histories ........................................ 2-30
Figure 2-10 Cumulative Distribution for a Situation with a Lot of Small Damage Effects ........................................ 2-34
Figure 2-11 Cumulative Distribution for a Situation with a Rare Large Damage Effect ........................................ 2-34
Figure 2-12 Component with 10-element Symmetry ........................................ 2-35
Figure 2-13 High Cycle Fatigue Failure Modeling Approach ........................................ 2-39
Figure 2-14 Duct Structural Analysis Procedure ........................................ 2-41
Figure 2-15 Geometry of an Elbow Duct ........................................ 2-43
Figure 2-16 Schematic of Duct Stress Analysis ........................................ 2-50
Figure 2-17 Procedure for Rainflow Counting ........................................ 2-52
Figure 2-18 Mean Stress Calculation Assuming an Elastic Perfectly Plastic Stress-Strain Curve ........................................ 2-53
Figure 2-19 Mean Stress Calculation Using Neuber’s Rule ........................................ 2-54
Figure 2-20 Calculation Procedure for the High Cycle Fatigue Failure Simulation ........................................ 2-56
Figure 2-21 Low Cycle Fatigue Failure Modeling Approach ........................................ 2-59
Figure 2-22 Calculation Procedure for the Low Cycle Fatigue Failure Simulation ........................................ 2-60
Figure 2-23 Axial Cross Section of the ATD-HPFTP Turbine Showing the Monolithic Disk ........................................ 2-62
Figure 2-24 Stylized Radial Cross Section of a Turbine Disk ........................................ 2-62
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-25</td>
<td>Reference Stress Method for ATD Disk LCF Life</td>
<td>2-63</td>
</tr>
<tr>
<td>2-26</td>
<td>Radial Cross Section of the Disk Blade Attachment Area</td>
<td>2-67</td>
</tr>
<tr>
<td>2-27</td>
<td>Axial Cross Section of the Disk Illustrating $K_d$, the Stress Factor</td>
<td>2-67</td>
</tr>
<tr>
<td>2-28</td>
<td>Illustration of the Stress-Time History for the ATD Disk</td>
<td>2-68</td>
</tr>
<tr>
<td>2-29</td>
<td>Structure of the Probabilistic Failure Model for the ATD-HPFTP</td>
<td>2-70</td>
</tr>
<tr>
<td>2-30</td>
<td>Structure of the LCF Failure Simulation for the ATD-HPTFP</td>
<td>2-72</td>
</tr>
<tr>
<td>2-31</td>
<td>Overall Procedure for Fatigue Failure Modes</td>
<td>2-74</td>
</tr>
<tr>
<td>2-32</td>
<td>Procedure for Significant Load Identification</td>
<td>2-81</td>
</tr>
<tr>
<td>2-33</td>
<td>Preprocessing</td>
<td>2-85</td>
</tr>
<tr>
<td>2-34</td>
<td>Cycle Identification</td>
<td>2-86</td>
</tr>
<tr>
<td>3-1</td>
<td>Location of the HPOTP Main Discharge Duct</td>
<td>3-3</td>
</tr>
<tr>
<td>3-2</td>
<td>Detail of HPOTP Main Discharge Duct Near Weld 6</td>
<td>3-4</td>
</tr>
<tr>
<td>3-3</td>
<td>Inconel 718 Weld Data</td>
<td>3-4</td>
</tr>
<tr>
<td>3-4</td>
<td>Location of the LPFTP Turbine Drive Duct</td>
<td>3-5</td>
</tr>
<tr>
<td>3-5</td>
<td>Detail of the LPFTP Turbine Drive Duct Near Weld 32</td>
<td>3-6</td>
</tr>
<tr>
<td>3-6</td>
<td>Incoloy 903 Weld Data</td>
<td>3-6</td>
</tr>
<tr>
<td>3-7</td>
<td>Finite Element Discretization of HPOTP Main Discharge Duct Forces Extracted from Node 24</td>
<td>3-11</td>
</tr>
<tr>
<td>3-8</td>
<td>HPOTP Main Discharge Duct Impact of Weld Offset on Failure Life Distribution</td>
<td>3-13</td>
</tr>
<tr>
<td>3-9</td>
<td>HPOTP Main Discharge Duct Failure Life Distribution and Driver Sensitivities</td>
<td>3-14</td>
</tr>
<tr>
<td>3-10</td>
<td>HPOTP Main Discharge Duct Risk Equivalent Life Limiting Procedure</td>
<td>3-15</td>
</tr>
<tr>
<td>3-11</td>
<td>Finite Element Discretization of LPFTP Turbine Drive Duct Forces Extracted from Node 61</td>
<td>3-16</td>
</tr>
<tr>
<td>3-12</td>
<td>LPFTP Turbine Drive Duct Impact of Weld Offset on Failure Life Distribution</td>
<td>3-18</td>
</tr>
<tr>
<td>3-13</td>
<td>LPFTP Turbine Drive Duct Failure Life Distribution and Driver Sensitivities</td>
<td>3-19</td>
</tr>
<tr>
<td>3-14</td>
<td>HPOTP Heat Exchanger</td>
<td>3-21</td>
</tr>
<tr>
<td>3-15</td>
<td>Detail of the HPOTP Heat Exchanger Coll Near Weld 3</td>
<td>3-22</td>
</tr>
<tr>
<td>3-16</td>
<td>316L and 321 Stainless Steel Parent Material Test Data</td>
<td>3-23</td>
</tr>
<tr>
<td>3-17</td>
<td>321 Weld Data Used as Proxy</td>
<td>3-23</td>
</tr>
<tr>
<td>3-18</td>
<td>Stress Concentration Factor $K_T$ Distribution</td>
<td>3-25</td>
</tr>
<tr>
<td>3-19</td>
<td>Finite Element Discretization of HPOTP Heat Exchanger Coll-Forces Extracted from Node 27</td>
<td>3-27</td>
</tr>
<tr>
<td>3-20</td>
<td>HPOTP Heat Exchanger Impact of Weld Offset on Failure Life Distribution</td>
<td>3-29</td>
</tr>
<tr>
<td>3-21</td>
<td>HPOTP Heat Exchanger Failure Life Distribution and Driver Sensitivities</td>
<td>3-30</td>
</tr>
<tr>
<td>3-22</td>
<td>Axial Cross Section of the ATD-HPFTP Turbine Showing the Monolithic Disk</td>
<td>3-32</td>
</tr>
<tr>
<td>3-23</td>
<td>Stylized Radial Cross Section of a Turbine Disk</td>
<td>3-32</td>
</tr>
<tr>
<td>3-24</td>
<td>Axial Cross Section of the Disk</td>
<td>3-33</td>
</tr>
</tbody>
</table>

xxiv
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-28</td>
<td>Flowchart for Subprogram GAMMA</td>
<td>4-84</td>
</tr>
<tr>
<td>4-29</td>
<td>Flowchart for the Bayesian Statistical Procedure Program BAYES</td>
<td>4-86</td>
</tr>
<tr>
<td>4-30</td>
<td>Flowchart for the Time History Generation Program NBSIN</td>
<td>4-90</td>
</tr>
<tr>
<td>5-1</td>
<td>Structure of the Probabilistic Failure Model for the Elbow Ducts with Welds</td>
<td>5-5</td>
</tr>
<tr>
<td>5-2</td>
<td>Main Flowchart for the Duct Analysis Program DCTHCF</td>
<td>5-6</td>
</tr>
<tr>
<td>5-3</td>
<td>Flowchart for the Subprogram ELWELD</td>
<td>5-9</td>
</tr>
<tr>
<td>5-4</td>
<td>Flowchart for the Subprogram M2L1</td>
<td>5-10</td>
</tr>
<tr>
<td>5-5</td>
<td>Flowchart for the Subprogram CALCS</td>
<td>5-12</td>
</tr>
<tr>
<td>5-6</td>
<td>Flowchart for the Subprogram NARBIN1</td>
<td>5-13</td>
</tr>
<tr>
<td>5-7</td>
<td>Flowchart for Subprogram RAINF1</td>
<td>5-15</td>
</tr>
<tr>
<td>5-8</td>
<td>Flowchart for Subprogram PGETSM</td>
<td>5-22</td>
</tr>
<tr>
<td>5-9</td>
<td>Structure of the Probabilistic Failure Model for Straight Ducts with Welds and Temperature Differences</td>
<td>5-23</td>
</tr>
<tr>
<td>5-10</td>
<td>Main Flowchart for the HEX Coil Analysis Program HEXHCF</td>
<td>5-24</td>
</tr>
<tr>
<td>5-11</td>
<td>Flowchart for Subprogram THWELD</td>
<td>5-27</td>
</tr>
<tr>
<td>5-12</td>
<td>Flowchart for Subprogram M4L1</td>
<td>5-29</td>
</tr>
<tr>
<td>5-13</td>
<td>Flowchart for the Subprogram NARBN2</td>
<td>5-30</td>
</tr>
<tr>
<td>5-14</td>
<td>Flowchart for Subprogram RAINF2</td>
<td>5-32</td>
</tr>
<tr>
<td>5-15</td>
<td>Flowchart for Subprogram NEUBER</td>
<td>5-39</td>
</tr>
<tr>
<td>5-16</td>
<td>Structure of the Probabilistic Failure Model for the ATD-HPFTP Second Stage Turbine Disk</td>
<td>5-42</td>
</tr>
<tr>
<td>5-17</td>
<td>Main Flowchart for the ATD Disk LCF Analysis Program TRBPWA</td>
<td>5-43</td>
</tr>
<tr>
<td>5-18</td>
<td>Flowchart of Driver Transformation</td>
<td>5-47</td>
</tr>
<tr>
<td>5-19</td>
<td>Program Flowchart Symbols</td>
<td>5-49</td>
</tr>
<tr>
<td>5-20</td>
<td>Flowchart for Subprogram INSORT</td>
<td>5-51</td>
</tr>
<tr>
<td>6-1</td>
<td>Format for File DCTHCD</td>
<td>6-5</td>
</tr>
<tr>
<td>6-2</td>
<td>Format for File RELATD</td>
<td>6-9</td>
</tr>
<tr>
<td>6-3</td>
<td>Data Blocks for Input File</td>
<td>6-9</td>
</tr>
<tr>
<td>6-4</td>
<td>Detail of the HPOTP Main Discharge Duct, Near Weld 6</td>
<td>6-28</td>
</tr>
<tr>
<td>6-5</td>
<td>Format for File HEXHCD</td>
<td>6-46</td>
</tr>
<tr>
<td>6-6</td>
<td>Detail of the HPOTP Heat Exchanger Coil Small Tube Outlet Near Weld 3</td>
<td>6-68</td>
</tr>
<tr>
<td>6-7</td>
<td>Format for File TRBPWD</td>
<td>6-87</td>
</tr>
<tr>
<td>6-8</td>
<td>Format for File SPECFD</td>
<td>6-119</td>
</tr>
<tr>
<td>6-9</td>
<td>Format for File RELATD</td>
<td>6-121</td>
</tr>
<tr>
<td>6-10</td>
<td>Data Blocks for Input File</td>
<td>6-121</td>
</tr>
<tr>
<td>6-11</td>
<td>Format for File SPECFD</td>
<td>6-135</td>
</tr>
<tr>
<td>6-12</td>
<td>Format for File RELATD</td>
<td>6-136</td>
</tr>
<tr>
<td>6-13</td>
<td>Format for File BFITD</td>
<td>6-160</td>
</tr>
<tr>
<td>6-14</td>
<td>Format for File LOWLIF</td>
<td>6-160</td>
</tr>
<tr>
<td>6-15</td>
<td>Format for File PARAMS</td>
<td>6-168</td>
</tr>
</tbody>
</table>
## List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 1-1</td>
<td>Index of Topics Contained in the Report</td>
<td>1-22</td>
</tr>
<tr>
<td>Table 1-2</td>
<td>Index of Software Documentation Contained in the Report</td>
<td>1-23</td>
</tr>
<tr>
<td>Table 2-1</td>
<td>The Required Values of $k$ and the Computed Coverage for Sample Sizes of $N$</td>
<td>2-29</td>
</tr>
<tr>
<td>Table 2-2</td>
<td>Summary of Load Sources, Critical Locations and Significant Force Components</td>
<td>2-58</td>
</tr>
<tr>
<td>Table 2-3</td>
<td>Driver Distributions for the ATD-HPFTP Second Stage Turbine Disk</td>
<td>2-72</td>
</tr>
<tr>
<td>Table 3-1</td>
<td>Driver Distributions for the HPOTP Main Discharge Duct</td>
<td>3-8</td>
</tr>
<tr>
<td>Table 3-2</td>
<td>Driver Distributions for the LPFTP Turbine Drive Duct</td>
<td>3-9</td>
</tr>
<tr>
<td>Table 3-3</td>
<td>HPOTP Main Discharge Duct Beam-End Forces Near Weld 6</td>
<td>3-12</td>
</tr>
<tr>
<td>Table 3-4</td>
<td>LPFTP Turbine Drive Duct Beam-End Forces Near Weld 32</td>
<td>3-17</td>
</tr>
<tr>
<td>Table 3-5</td>
<td>Driver Distributions for the HPOTP Heat Exchanger Coll</td>
<td>3-24</td>
</tr>
<tr>
<td>Table 3-6</td>
<td>HPOTP Heat Exchanger Coil Beam-End Forces Near Weld 3</td>
<td>3-28</td>
</tr>
<tr>
<td>Table 3-7</td>
<td>Driver Distributions for the Turbine Disk</td>
<td>3-34</td>
</tr>
<tr>
<td>Table 3-8</td>
<td>Scanning Circumference for Critical Angle Causing Minimum Life</td>
<td>3-40</td>
</tr>
<tr>
<td>Table 3-9</td>
<td>Weld Offset Measurements</td>
<td>3-41</td>
</tr>
<tr>
<td>Table 3-10</td>
<td>Wall Temperature and Internal Pressure at Weld 3 From Engine Balance Model</td>
<td>3-43</td>
</tr>
<tr>
<td>Table 3-11</td>
<td>321 SS Welded S/N Data</td>
<td>3-44</td>
</tr>
<tr>
<td>Table 3-12</td>
<td>Summary of Materials Characterization Study of 321 Weld Data</td>
<td>3-44</td>
</tr>
<tr>
<td>Table 3-13</td>
<td>Lives for Different Random Number Seeds and History Length</td>
<td>3-45</td>
</tr>
<tr>
<td>Table 3-14</td>
<td>Von Mises Stress and Damage Indices Due to Each Load Component</td>
<td>3-47</td>
</tr>
<tr>
<td>Table 3-15</td>
<td>Load Components Rank Ordered by Damage Indices for Contributing Stress Components</td>
<td>3-48</td>
</tr>
<tr>
<td>Table 3-16</td>
<td>Significant Load Identification Checks</td>
<td>3-48</td>
</tr>
<tr>
<td>Table 3-17</td>
<td>Probability of Failure Curve Parameter Estimates for 6%, 10% and 20% Weld Offset</td>
<td>3-50</td>
</tr>
<tr>
<td>Table 3-18</td>
<td>Driver Sensitivity Analysis for 10% Weld Offset</td>
<td>3-51</td>
</tr>
<tr>
<td>Table 3-19</td>
<td>Inconel 100 Notched S/N Data</td>
<td>3-53</td>
</tr>
<tr>
<td>Table 3-20</td>
<td>Summary of Materials Characterization Study of IN100 Notched Data</td>
<td>3-54</td>
</tr>
<tr>
<td>Table 3-21</td>
<td>Driver Sensitivity Analysis for the Turbine Disk</td>
<td>3-57</td>
</tr>
<tr>
<td>Table 4-1</td>
<td>The Seven Cases Considered by Subprogram FNDRNG</td>
<td>4-35</td>
</tr>
<tr>
<td>Table 4-2</td>
<td>The Four Cases Considered by Subprogram NORRNG</td>
<td>4-42</td>
</tr>
<tr>
<td>Table 7-1</td>
<td>List of Subprograms For Program DCTHCF</td>
<td>7-3</td>
</tr>
<tr>
<td>Table 7-2</td>
<td>List of Variables for Program DCTHCF</td>
<td>7-9</td>
</tr>
<tr>
<td>Table 7-3</td>
<td>List of Subprograms for Program HEXHCF</td>
<td>7-121</td>
</tr>
<tr>
<td>Table 7-4</td>
<td>List of Variables for Program HEXHCF</td>
<td>7-127</td>
</tr>
<tr>
<td>Table 7-5</td>
<td>List of Subprograms For Program TRBPWA</td>
<td>7-244</td>
</tr>
<tr>
<td>Table 7-6</td>
<td>List of Variables For Program TRBPWA</td>
<td>7-247</td>
</tr>
<tr>
<td>Table 7-7</td>
<td>List of Subprograms for Program MATCHR</td>
<td>7-325</td>
</tr>
</tbody>
</table>
Table 7-8  List of Variables for Program MATCHR ............................................ 7-335
Table 7-9  Routine/Variable Chart ................................................................. 7-352
Table 7-10 List of Subprograms for Program BFIT ........................................ 7-451
Table 7-11 List of Variables for Program BFIT .............................................. 7-451
Table 7-12 List of Subprograms for Program ABTFIT .................................... 7-455
Table 7-13 List of Variables for Program ABTFIT .......................................... 7-456
Table 7-14 List of Subprograms for Program LZERO ...................................... 7-461
Table 7-15 List of Variables for Program LZERO ........................................... 7-462
Table 7-16 List of Variables for Program BAYES ........................................... 7-471
Table 7-17 List of Variables for Subprogram RANDOM ................................... 7-477
Table 7-18 List of Variables for Subprogram NORMGN .................................. 7-479
Table 7-19 List of Variables for Subprogram BETAGN ................................... 7-481
Table 7-20 List of Variables for Subprogram GAM ........................................ 7-482
Table 7-21 List of Variables for Subprogram WEIBGN .................................. 7-483
Table 7-22 List of Variables for Subprogram PRYRV ...................................... 7-485
Table 7-23 List of Subprograms for Program NBSIN ..................................... 7-487
Table 7-24 List of Variables for Program NBSIN .......................................... 7-488
4.0 Statistical Analysis Software
Section 4.1
Materials Characterization Software

4.1.1 Introduction

This section presents a description of the computer program which implements the materials characterization model discussed in Section 2.1.2. MATCHR, the code for simulating the cyclic fatigue behavior of a material, is described here. This code contains both the stress and strain formulations of the materials characterization model in a stand-alone form.\(^1\) Its purpose is to facilitate the characterization of a materials data set for a component before performing the probabilistic failure modeling. The overall layout of the program is described using a master flowchart that refers to other flowcharts which describe the subprograms in greater detail. The random variate generators are described in Section 4.4. The relevant user's guide for running this code is given in Section 6.3, and a list of subprograms, a definition of key variables, and the complete source listing are given in Section 7.3. A glossary of standard flowchart symbols is given for the reader's benefit in Appendix 5.A.

4.1.2 MATCHR Program

The materials characterization model is implemented as the FORTRAN program MATCHR. The flowchart for the MATCHR program is given in Figure 4-1. The program starts by opening the following input and output files:

<table>
<thead>
<tr>
<th>NAME</th>
<th>TYPE</th>
<th>CONTENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPECFD</td>
<td>Input</td>
<td>Simulation parameters and specific material data</td>
</tr>
<tr>
<td>SPECFO</td>
<td>Output</td>
<td>Input data echo</td>
</tr>
<tr>
<td>DUMP</td>
<td>Output</td>
<td>Results of simulation</td>
</tr>
<tr>
<td>IOUTPR</td>
<td>Output</td>
<td>Run information and intermediate calculations</td>
</tr>
</tbody>
</table>

The simulation parameters which specify the run options are read from the SPECFD file. An echo of these parameters is written to IOUTPR. The required number of trials is set according to the type of variation specified. If the truncated Normal variation and its corresponding empirical median curve are specified, then the number of MATCHR iterations can be set to 2000;\(^2\) for all other cases only one MATCHR iteration is needed. The formulation of the materials characterization model is then determined.

---

\(^1\) The materials characterization models contained within the Probabilistic Failure Models are subsets of MATCHR.

\(^2\) The value of 2000 is more than adequate for a simulation size of 200,000 trials to obtain an accurate median value of the materials curve shape parameter. This value can be considerably smaller, depending on the accuracy desired for that median value.
Figure 4-1 Main Flowchart for the Materials Characterization Model Program MATCHR
Figure 4-1 Main Flowchart for the Materials Characterization Model Program MATCHR (Cont'd)
Figure 4-1 Main Flowchart for the Materials Characterization Model Program MATCHR (Cont'd)
DECOMP

STRAIN DECOMPOSITION
INFORMATION AGGREGATION
(See Section 4.1.4)

DO II → 1
TO NTRIAL BY 1

PAREST

PARAMETER ESTIMATION
FOR PLASTIC COMPONENTS
(See Section 4.1.5)

ADJSTM

ENSURE mp < mE AFTER
SELECTION OF mp
(See Section 4.1.7)

PAREST

PARAMETER ESTIMATION
FOR ELASTIC COMPONENTS
(See Section 4.1.5)

Figure 4-1 Main Flowchart for the Materials Characterization
Model Program MATCHR (Cont'd)
Figure 4-1  Main Flowchart for the Materials Characterization Model Program MATCHR (Cont'd)

4 - 8
SORTM

SORT \( m_p \)'s AND \( m_E \)'s
(See Section 4.1.10)

EXPCTD

CALCULATE EMPIRICAL MEDIAN S/N CURVE FOR PLASTIC COMPONENTS
(See Section 4.1.3.12)

EXPCTD

CALCULATE EMPIRICAL MEDIAN S/N CURVE FOR ELASTIC COMPONENTS
(See Section 4.1.3.12)

STOP

Figure 4-1  Main Flowchart for the Materials Characterization Model Program MATCHR (Cont'd)
4.1.2.1 Stress Formulation

The stress/life characterization of fatigue failure of materials begins by reading the value of stress for which a fatigue life is desired. The material data input and information aggregation calculations are performed by subprogram INFAGG described in Section 4.1.3. INFAGG also calculates the median S/N curve when Uniform variation of the shape parameters is specified.

A DO loop is required to obtain a median S/N curve when truncated Normal variation of the shape parameters is specified. The PAREST routine controls the calculations for estimating the parameters for the S/N model. Routine PAREST is described in Section 4.1.5. Materials process variation can be included by calling the NORMGN routine and then transforming the resulting Normal variate to the Lognormal variate $Z$ in Equation 2-48. A call to WEIBGN provides materials intrinsic variability $\varphi$. The random variate routines NORMGN and WEIBGN are described in Sections 4.4.3 and 4.4.6.

When all the S/N model parameters have been selected for the regions with S/N data, the S/N curve can be tied to a tensile point $S_0$ by routine KOMO. The value of stress read from file SPECFD earlier is used by subprogram GTLIFE to calculate a fatigue life using the randomly selected S/N curve. Subprograms KOMO and GTLIFE are described in Sections 4.1.6 and 4.1.8.

If the truncated Normal distribution was used for the materials shape parameter $m$, the empirical median S/N curve will be calculated upon user request. The routine SORTM is called to sort the values of $m$ and the routine EXPCTD calculates the median S/N curve. Sections 4.1.10 and 4.1.3.12 describe the routines SORTM and EXPCTD.

4.1.2.2 Strain Formulation

The strain/life characterization of fatigue failure of materials begins by reading the value of strain for which a fatigue life is desired. The material data input, strain decomposition and information aggregation calculations are performed by subprogram DECOMP described in Section 4.1.4. DECOMP also calculates the median S/N curve when Uniform variation of the shape parameters is specified.

A DO loop is required to obtain a median S/N curve when truncated Normal variation of the shape parameters is specified. The PAREST routine controls the calculations

---

3 The information aggregation calculations are discussed on Pages 2-6 through 2-14.
4 The parameter estimation calculations are discussed on Pages 2-15 through 2-18.
5 Extension of the S/N curve to the left is discussed on Page 2-17.
6 The median S/N curve for the truncated Normal case is discussed on Page 2-15.
for estimating the parameters for the S/N model.\textsuperscript{7} PAREST is called twice, first for the plastic strain components and then for the elastic strain components. In between the calls to PAREST, routine ADJSTM ensures \( m_p < m_E \). Materials process variation can be included by calling the NORMGN routine and then transforming the resulting Normal variate to the Lognormal variate \( Z \) in Equation 2-50. A call to WEIBGN provides \( \varphi \) based on \( \beta_o \) defined as the average of those derived from the plastic and elastic strain component analyses. The materials characterization routines PAREST and ADJSTM are described in Sections 4.1.5 and 4.1.7. The random variate routines NORMGN and WEIBGN are described in Sections 4.4.3 and 4.4.6.

When both of the S/N model parameters have been selected for the plastic and elastic S/N data, the value of strain read from file SPECFD earlier is used by subprogram GTLIF2 to calculate a fatigue life using the randomly selected S/N curve. Subprogram GTLIF2 is described in Section 4.1.9.

If the truncated Normal distribution was specified for the materials shape parameters \( m_p \) and \( m_E \), the empirical median S/N curve will be calculated upon user request.\textsuperscript{8} The routine SORTM is called to sort the values of \( m_p \) and \( m_E \) and the routine EXPCTD calculates the component median curves. Sections 4.1.10 and 4.1.3.12 describe the routines SORTM and EXPCTD.

4.1.3 INFAGG Routine

The flowchart for the INFAGG routine is given in Figure 4-2. The routine controls the calls to the data input and information aggregation calculation routines. INFAGG starts by opening the following input and output files:

\[
\begin{array}{|c|c|c|}
\hline
\text{NAME} & \text{TYPE} & \text{CONTENTS} \\
\hline
\text{RELATD} & \text{Input} & \text{Related material data input} \\
\text{RELATO} & \text{Output} & \text{Related material data echo} \\
\hline
\end{array}
\]

The arrays are then set to their default or initial values by routine INIT. Routine RCE reads the data from files SPECFD and RELATD, transforms (or converts) the stresses to an equivalent stress ratio of \( R = -1.0 \), and echoes the data to files SPECFO and RELATO. Routines INIT and RCE are described in Sections 4.1.3.1 and 4.1.3.2.

The information aggregation begins with linear regression calculations performed by routine SW2SU2 on the combined specific and related data. Then the constraints on the shape parameters \( \{ m_j \} \) implied by the user-provided \( C_o \) constraint are calculated by FINDMC. SW2SU2 and FINDMC are described in Sections 4.1.3.4 and

\textsuperscript{7} The parameter estimation calculations are discussed on Pages 2-15 through 2-18.

\textsuperscript{8} The median S/N curve for the truncated Normal case is discussed on Page 2-15.
START

OPEN FILES RELATED AND RELATED

INIT

INITIALIZE ARRAYS
(See Section 4.1.3.1)

READ FROM SPECFD SPECIFIC S/N DATA $C_{0r}(m_r, \bar{m}_r)$

WRITE TO SPECFD SPECIFIC S/N DATA $C_{0r}(m_r, \bar{m}_r)$

READ DATA

TRANSFORM STRESS DATA
(See Section 4.1.3.3)

PARTITION DATA
(See Section 4.1.3.2)

WRITE TO RELATED S/N DATA

READ FROM RELATED S/N DATA

CONVRT

ECHO DATA

PARTITION DATA

SW2SU2

REGRESS In S ON In N
REGRESS In N ON In S
(See Section 4.1.3.4)

FINDMC

TRANSFORM C CONSTRAINT TO $m$ CONSTRAINTS
(See Section 4.1.3.5)

Figure 4-2 Flowchart for Subprogram INFAGG, Stress Formulation
TRUNCATED NORMAL

UNIFORM

INTRVL

FOR EACH LIFE REGION
FIND $I_o$, INTERVAL ESTIMATE FOR $C$
FIND $J_o$, INTERVAL ESTIMATE FOR $m_j$
(See Section 4.1.3.6)

PROCESS VARIATION?

YES

GTPVAR

CALCULATE $\sigma^2$
(See Section 4.1.3.7)

FNDRNG

COMPUTE POSTERIOR CREDIBILITY RANGE
(See Section 4.1.3.8)

ADDREG

ADD INFORMATION ON REGIONS WITHOUT S/N DATA
(See Section 4.1.3.9)

Figure 4-2 Flowchart for Subprogram INFAGG, Stress Formulation (Cont'd)
CONCAV

IMPOSES S/N CURVE CONCAVITY CONSTRAINT
(See Section 4.1.3.10)

WRITE TO DUMP
PRIOR AND POSTERIOR
CREDIBILITY RANGES
\( \hat{C}, \hat{m}, \sigma^2 \)

MEDIAN

CALCULATE MEDIAN \( m \) VALUES
(See Section 4.1.3.11)

EXPCTD

CALCULATE PARAMETER VALUES
FOR MEDIAN S/N CURVE
(See Section 4.1.3.12)

\[ \pi(m_i) \]
LIFE REGION BOUNDARIES
SPECIFIC S/N DATA

RETURN

Figure 4-2 Flowchart for Subprogram INFAGG, Stress Formulation (Cont’d)
PERFORM BAYESIAN ANALYSIS TO OBTAIN $m_\theta$ & $\sigma_\theta^2$ FOR EACH REGION
(See Section 4.1.3.13)

PROCESS VARIATION?

YES

GTPVAR

CALCULATE $\sigma^2$
(See Section 4.1.3.7)

NORRNG

COMPUTE POSTERIOR CREDIBILITY RANGE
(See Section 4.1.3.14)

ADDRNG

ADD INFORMATION ON REGIONS WITHOUT S/N DATA
(See Section 4.1.3.15)

CONCAV

IMPOSES S/N CURVE CONCAVITY CONSTRAINTS
(See Section 4.1.3.10)

Figure 4-2 Flowchart for Subprogram INFAGG, Stress Formulation (Cont'd)
Figure 4-2  Flowchart for Subprogram INFAGG, Stress Formulation (Cont'd)
4.1.3.5. The remaining routine calls depend upon the choice of distribution for the shape parameters.

The Uniform distribution case begins with the confidence interval calculations performed by INTRVL. By definition, the prior credibility ranges are the confidence intervals. If materials processes variation is specified, GTPVAR calculates \( \sigma^2 \), *Equation 2-49*, the extent of departures from the multiple heat median S/N curve warranted by the available information. The credibility ranges, \( C \) constraint, and the user-provided range information are combined by routine FNDRNG to obtain posterior credibility ranges on the shape parameters \( \pi(m_j) \). The user-supplied \( m \) ranges for the non-data life regions to the right of those with data are added to the array containing the \( \pi(m_j) \) by routine ADDREG. Concavity constraints are applied within subprogram CONCAV. The results of the calculations above are written to file DUMP. Finally, the median S/N curve is calculated. The median \( m \)'s are found by MEDIAN and then used by EXPCTD to obtain the median curve parameters which are written to file DUMP. Routines INTRVL, GTPVAR, FNDRNG, ADDREG, CONCAV, MEDIAN, and EXPCTD are described in Sections 4.1.3.6, 4.1.3.7, 4.1.3.8, 4.1.3.9, 4.1.3.10, 4.1.3.11, and 4.1.3.12, respectively.

The truncated Normal distribution case begins with the Bayesian analysis performed by MUSIG to find the Normal distribution parameters for the \( m \)'s. If materials process variation is requested, GTPVAR calculates \( \sigma^2 \), the extent of departures from the multiple heat median S/N curve warranted by the available information, by using *Equation 2-49*. The \( C \) constraint and the user provided range information are combined by routine NORRNG to obtain posterior credibility ranges on the shape parameters \( \pi(m_j) \). The user-supplied \( m \) ranges and Normal distribution parameters for the non-data life regions to the right of those with data are added to the arrays containing the \( \pi(m_j) \), \( m_* \), and \( \sigma_* ^2 \) by routine ADDRGN. Concavity constraints are applied within subprogram CONCAV. Then results of the calculations above are written to file DUMP. Routines MUSIG, GTPVAR, NORRNG, ADDRGN, and CONCAV are described in Sections 4.1.3.13, 4.1.3.7, 4.1.3.14, 4.1.3.15, and 4.1.3.10.

### 4.1.3.1 Routine INIT

The routine initializes the arrays used in the stress formulation information aggregation routine, INFAGG, to zero.

---

9 Combining information to obtain the posterior credibility ranges on \( m \) is discussed on Page 2-13.

10 No data regions to the right are discussed on Page 2-17.
4.1.3.2 Routine RCE

The flowchart for the RCE routine is given in Figure 4-3. The routine controls the input/output of the specific and related materials data, region information, and exogenous information. RCE begins by reading the data from file SPECFD which contains the specific S/N data, region information and exogenous information, and then RCE echoes the information to file SPECFO. First the general information pertaining to the specific material data set is read, including the material description, yield and ultimate strengths, the total number of S/N data points, and the number of data divisions. A data division is a group of S/N data points having the same stress ratio and belonging to the same life region. The number of data divisions is stored in variable NDIV.

The first data division DO loop reads, transforms, and echoes the specific material S/N data. The transformation is performed when the stress ratio, stored in the variable RATIO, is not equal to minus one. The transformation is to the equivalent stress for a stress ratio of minus one, and is performed by routine CONVRT. Also, the S/N data is partitioned and stored appropriately according to the indicated life region. Routine CONVRT is discussed in Section 4.1.3.3.

When the DO loop is completed, the stress tensile point and region information are read and echoed next. The region information includes the number of life regions and the upper bounds of those regions.

The last information in file SPECFD used by all stress formulation options is the implicit and explicit constraints on the shape parameters \( \{m_j\} \). The implicit constraint is an upper bound, \( C_o \), on the coefficient of variation of fatigue strength, \( C \), for the specific material data set. The explicit constraint consists of a point value or range of values of the shape parameter for each life region of the specific material data set.

When the truncated Normal variation of the shape parameters is specified, RCE reads and echoes the Bayesian prior information for each life region. If the materials process variation is specified, the process variation information is read and echoed. Process variation in materials is discussed in Section 2.1.2.3.

---

11 Extension of the S/N curve to the left is discussed on Page 2-17.
12 The implicit constraint on the materials model shape parameter provided by prior information on the coefficient of variation of fatigue strength is discussed on Pages 2-12 through 2-13.
13 The explicit constraint on the materials model shape parameter provided by prior information on the materials shape parameter is discussed on Page 2-12.
14 Specification of the Bayesian prior distribution for the truncated Normal case is discussed on Page 2-14.
Figure 4-3  Flowchart for Subprogram RCE, Stress Formulation
Figure 4-3 Flowchart for Subprogram RCE, Stress Formulation (Cont'd)
READ AND ECHO RELATED MATERIAL
S/N DATA SET INFORMATION

DO M ← 1
TO NDIV BY 1

READ S/N DATA FOR EACH
DATA DIVISION

RATIO = −1.0

CONVRT

TRANSFORM STRESS DATA
(See Section 4.1.3.3)

ECHO S/N DATA FOR EACH
DATA DIVISION

PARTITION DATA BY REGIONS

RETURN

Figure 4-3 Flowchart for Subprogram RCE, Stress Formulation
(Cont’d)
Next, RCE reads the data from file RELATD which contains the related S/N data and echoes the information to file RELATO. First the number of related data sets is read, stored in variable NSETS, and echoed. The outer data set DO loop is performed for each related data set. The general information pertaining to each related material data set is read, including the material description, yield strength, and ultimate strength, the total number of S/N data points, and the number of data divisions.

The inner data division DO loop reads, transforms, and echoes the related S/N data. The transformation is performed when the stress ratio, stored in variable RATIO, is not equal to minus one. The transformation is to the equivalent stress for a stress ratio of minus one, and is performed by routine CONVRT. Also, the S/N data is partitioned and stored appropriately according to the indicated life region. Routine CONVRT is discussed in Section 4.1.3.3.

4.1.3.3 Routine CONVRT

The flowchart for CONVRT is given in Figure 4-4. Routine CONVRT performs the transformation required to obtain an equivalent maximum stress $\sigma_{emax}$ corresponding to a stress ratio of minus one. An elastic-perfectly-plastic stress versus strain behavior is assumed here for the material. First, the alternating stress $\sigma_{alt}$ is calculated from the maximum stress $\sigma_{max}$ and the stress ratio $R$. This stress is checked against the yield stress $\sigma_y$. Three different cases occur. If the alternating stress is above the yield, then the equivalent maximum stress is the alternating stress. If the alternating stress is below the yield stress and the maximum stress is above the yield stress, then the equivalent maximum stress is given by

$$\sigma_{emax} = \frac{\sigma_{alt}}{1 - \frac{\sigma_y - \sigma_{alt}}{\sigma_u}}$$

If both the alternating stress and the maximum stress are below the yield stress, then the appropriate transformation for the equivalent maximum stress is

$$\sigma_{emax} = \frac{\sigma_{alt}}{1 - \frac{1 + R}{2} \frac{\sigma_{max}}{\sigma_u}}$$

4.1.3.4 Routine SW2SU2

The flowchart for the SW2SU2 routine is given in Figure 4-5. The routine performs the $y$ on $x$ and $x$ on $y$ regressions to obtain the sample variances $S_x^2$, $S_y^2$, and $S_{xy}$, and the residual variances $S_w^2$ and $S_u^2$ for each life region. For the calculations, $x$ is

---

15 Related S/N data is discussed on Page 2-7.
START

DO 1 → 1
TO NUMBER OF POINTS BY 1

CALCULATE THE ALTERNATING STRESS
\[ \sigma_{\text{alt}} = \sigma_{\text{max}} \frac{1 - R}{2} \]

\( \sigma_{\text{alt}} \geq \sigma_{y} \)

TRUE

\( \sigma_{\text{emax}} = \sigma_{\text{alt}} \)

FALSE

\( \sigma_{\text{alt}} < \sigma_{y} \) & \( \sigma_{\text{max}} > \sigma_{y} \)

TRUE

\( \sigma_{\text{emax}} = \frac{\sigma_{\text{alt}}}{1 - \frac{\sigma_{y} - \sigma_{\text{alt}}}{\sigma_{u}}} \)

FALSE

\( \sigma_{\text{emax}} = \frac{\sigma_{\text{alt}}}{1 - \frac{1 + R}{2} \frac{\sigma_{\text{max}}}{\sigma_{u}}} \)

RETURN

Figure 4-4 Flowchart for Subprogram CONVRT, Stress Formulation
START

INITIALIZE ARRAYS

DO L ← 1
TO R BY 1

DO J ← 0
TO P BY 1

CALCULATE $\bar{x}_j$ AND $\bar{y}_j$
IN REGION $L$

DO K ← 1
TO $N_j$ BY 1

Figure 4-5 Flowchart for Subprogram SW2SU2
SUM OVER ALL DATA POINTS IN EACH DATA SET \( j \) FOR REGION \( L \)

\[
N S_x^2 = \sum_{j=0}^{P} \sum_{k=1}^{N_j} (x_{jk} - \bar{x}_j)^2
\]

\[
N S_y^2 = \sum_{j=0}^{P} \sum_{k=1}^{N_j} (y_{jk} - \bar{y}_j)^2
\]

\[
N S_{xy} = \sum_{j=0}^{P} \sum_{k=1}^{N_j} (x_{jk} - \bar{x}_j)(y_{jk} - \bar{y}_j)
\]

SUM OVER EACH DATA SET \( j \) FOR REGION \( L \)

\[
N = \sum_{j=0}^{P} (N_j - 1) - 1
\]

\[
N S_{xy} \geq 0
\]

TRUE

TRMNAT

STOP PROGRAM

FALSE

CALCULATE SAMPLE VARIANCES

\[
S_x^2, S_y^2, S_{xy}
\]

STOP

**Figure 4-5 Flowchart for Subprogram SW2SU2 (Cont’d)**
CALCULATE $d$ AND $b$
(Equations 2-20 and 2-21)

$$d = \frac{S_{xy}}{S_x^2}$$
$$b = \frac{S_{xy}}{S_y^2}$$

DO $J \rightarrow 0$
TO $P$ BY 1

DO $K \rightarrow 1$
TO $N_j$ BY 1

SUM OVER ALL DATA POINTS IN EACH DATA SET $J$ FOR REGION $L$

$$NS_{\hat{w}}^2 = \sum_{i=0}^{P} \sum_{k=1}^{N_j} \hat{w}_{jk}^2$$
$$NS_{\hat{u}}^2 = \sum_{i=0}^{P} \sum_{k=1}^{N_j} \hat{u}_{jk}^2$$

CALCULATE RESIDUAL VARIANCES
$S_{\hat{w}}^2$ and $S_{\hat{u}}^2$

RETURN

Figure 4-5 Flowchart for Subprogram SW2SU2 (Cont'd)
equal to ln S and y is equal to ln N. SW2SU2 starts by initializing the arrays required for the calculations.

Within the outer region DO loop are two sets of nested DO loops, where the region counter \( L = 1, \ldots, R \), and \( R \) is the number of life regions with S/N data.\(^{16}\) In each set of DO loops, the outer loop is for each S/N data set, \( j = 0, \ldots, P \), and the inner DO loop is for each data point in each data set, \( k = 1, \ldots, N_j \). The first step is to calculate the sample means \( \bar{x}_j \) and \( \bar{y}_j \) for each data set in each region. Then the sample variances and degrees of freedom for each region in each data set are calculated as follows:

\[
N S_x^2 = \sum_{j=0}^{P} \sum_{k=1}^{N_i} (x_{jk} - \bar{x}_j)^2
\]

\[
N S_y^2 = \sum_{j=0}^{P} \sum_{k=1}^{N_i} (y_{jk} - \bar{y}_j)^2
\]

\[
N S_{xy} = \sum_{j=0}^{P} \sum_{k=1}^{N_i} (x_{jk} - \bar{x}_j)(y_{jk} - \bar{y}_j)
\]

\[
N = \sum_{j=0}^{P} (N_j - 1) - 1
\]

where \( S_x^2 \), \( S_y^2 \), and \( S_{xy} \) are the sample variance of \( x \), sample variance of \( y \), and sample covariance of \( x \) and \( y \), and \( N \) is the number of degrees of freedom for each life region, respectively. If \( S_{xy} \) is non-negative, the data does not support the analysis assumptions and the program run will be terminated. The sample variances are used to calculate the regression parameters \( d \) and \( b \) of Equations 2-20 and 2-21,

\[
d = \frac{S_{xy}}{S_x^2} \quad \text{and} \quad b = \frac{S_{xy}}{S_y^2}.
\]

The second set of DO loops calculates the residual variances \( S_{e}^2 \) and \( S_{d}^2 \) for each life region given by:

---

\(^{16}\) \( R \) is equal to one for the strain formulation.
\[ NS_w^2 = \sum_{j=0}^{P} \sum_{k=1}^{N_j} \hat{w}_{jk}^2 \]

\[ NS_u^2 = \sum_{j=0}^{P} \sum_{k=1}^{N_j} \hat{u}_{jk}^2 \]

where

\[ \hat{w}_{jk} = (y_{jk} - \bar{y}_j) - d (x_{jk} - \bar{x}_j) \]

\[ \hat{u}_{jk} = (x_{jk} - \bar{x}_j) - b (y_{jk} - \bar{y}_j) \]

from Equations 2-20 and 2-21.

4.1.3.5 Routine FINDMC

The flowchart for FINDMC is given in Figure 4-6. Routine FINDMC performs the calculations to obtain the region-dependent constraint on the shape parameter \((m_c, \bar{m}_c)\) implied by the user-supplied constraint, \(C_o\), on the coefficient of variation of fatigue strength. The routine begins by initializing the arrays that are to contain the results. The remaining calculations are performed for each life region.

If a \(C\) constraint has been specified, there are three solutions to Equation 2-28. If \(S_x^2 = C_o^2\), the solution is a lower bound given by Equation 2-30

\[ m_c > -S_y^2 / (2 S_{xy}) \]

If \(S_x^2 < C_o^2\), then the solution is also bounded from below and given by Equation 2-31

\[ m_c > -S_{xy} - \left[ S_{xy}^2 - S_y^2 (S_x^2 - C_o^2) \right]^{\frac{1}{2}} / S_x^2 - C_o^2 \]

If \(S_x^2 > C_o^2\), then the solution is an interval constraint given by Equation 2-32

\[ m_c < -S_{xy} - \left[ S_{xy}^2 - S_y^2 (S_x^2 - C_o^2) \right]^{\frac{1}{2}} / S_x^2 - C_o^2 \]

\[ \frac{S_x^2 - C_o^2}{S_x^2 - C_o^2} \]

4 - 28
Initialize arrays

Do L = 1 to R by 1

Co² = 0

FALSE

Sx² = Co²

FALSE

Perfom common calculations

Arg1 = Sx² - Co²

Arg2 = (Sxy² - Sxy² * Arg1)²

SX² < Co²

FALSE

mc > -Sxy² / 2 Sxy (Equation 2-30)

TRUE

mc > (-Sxy - Arg2) / Arg1 (Equation 2-31)

TRUE

(-Sxy - Arg2) / Arg1 < mc < (-Sxy + Arg2) / Arg1 (Equation 2-32)

FALSE

NO CONSTRAINT

TRUE

RETURN

Figure 4-6 Flowchart for Subprogram FINDMC, Stress Formulation
4.1.3.6 Routine INTRVL

The flowchart for INTRVL is given in Figure 4-7. Routine INTRVL performs the calculations to obtain the region-dependent point estimates and 95% confidence intervals on the coefficient of variation of fatigue strength $C$ and shape parameter $m$ based upon S/N data only. The routine begins by initializing the arrays that are to contain the results. The remaining calculations are performed for each life region.

The points estimates of $m$ and $C$ are given by Equation 2-22

$$\hat{m} = -d \text{ and } \hat{C} = S_{\hat{C}}.$$ 

The 95% confidence interval on $C$ is given by Equation 2-24

$$I_o = \left[ \hat{C} \left( \frac{N}{\chi_{0.975}^2(N)} \right)^{\frac{1}{2}}, \hat{C} \left( \frac{N}{\chi_{0.025}^2(N)} \right)^{\frac{1}{2}} \right].$$

The 95% confidence interval on $m$ is given by Equation 2-26

$$J_o = \left[ \left( \hat{m} - t_{0.025}(N) \frac{S_{\hat{C}}}{\left( N S_x^2 \right)^{\frac{1}{2}}} \right), \left( \hat{m} + t_{0.025}(N) \frac{S_{\hat{C}}}{\left( N S_x^2 \right)^{\frac{1}{2}}} \right) \right].$$

4.1.3.7 Routine GTPVAR

The flowchart for GTPVAR is given in Figure 4-8. Routine GTPVAR calculates $\sigma^2$, the extent of departures from the multiple heat median S/N curve warranted by the information available by using region-specific parameters defined in Equations 2-49 and 2-50. The routine begins by initializing the arrays that are to be used for intermediate calculations.

The number of data points in region $L$, $N_L$, is calculated in the inner DO loop. Then the total number of points $N$ and $T$, the sum over regions of the "extent of departures," is calculated. Finally $\sigma^2$ is found by dividing $T$ by $N$.

4.1.3.8 Routine FNDRNG

The flowchart for FNDRNG is given in Figure 4-9. Routine FNDRNG performs the calculations to obtain the posterior credibility ranges of the shape parameter $m$ for the Uniform distribution case. These ranges are found by combining the shape parameter constraints in Equations 2-26 and 2-27 with Equation 2-30, 2-31 or 2-32. The routine begins by initializing the arrays that are to contain the results. The remaining calculations are performed for each life region and the posterior credibility ranges are constrained to be non-negative. The seven different cases that must be considered are given in Table 4-1:
1. **INITIALIZE ARRAYS**

2. **DO** $L \rightarrow 1$ TO $R$ BY 1

3. **CALCULATE $\hat{m}$ AND $\hat{C}$**
   
   \[ \hat{m} = -d \text{ AND } \hat{C} = S_0^2 \]

4. **CALCULATE CREDIBILITY INTERVALS**
   
   \[ l_o = \left[ \hat{C} \left( N/\chi^2_{0.025}(N) \right)^{1/2}, \hat{C} \left( N/\chi^2_{0.975}(N) \right)^{1/2} \right] \]

   \[ \text{Arg} = t_{0.025}(N) S_{\hat{m}}/(N S_x^2)^{1/2} \]

   \[ J_o = [\hat{m} - \text{Arg}, \hat{m} + \text{Arg}] \]

**Figure 4-7** Flowchart for Subprogram INTRVL, Uniform Distribution
START

INITIALIZE ARRAYS

DO L ← 1
TO R BY 1

DO J ← 0
TO P BY 1

SUM OVER EACH DATA
SET J FOR REGION L

\[ N_j = \sum_{i=0}^{P} N_j - 1 \]

SUM OVER EACH REGION L

\[ N = \sum_{i=1}^{R} N_i \]
\[ T = \sum_{i=1}^{R} (\lambda_i - 1) C_i^2 \]

\[ \sigma^2 = \frac{T}{N} \]

RETURN

Figure 4-8 Flowchart for Subprogram GTPVAR
START

INITIALIZE ARRAYS

DO L → 1 TO R BY 1

CASE 1

TRUE

\( \pi(m) = J_o \)

FALSE

\( \pi(m) = J_o \cap (m_c, \infty) \)

CASE 2

TRUE

\( \pi(m) = J_o \cap (m_c, \overline{m_c}) \)

FALSE

CASE 3

TRUE

\( \pi(m) = m = \overline{m} \)

CASE 4

FALSE

\( \pi(m) = J_o \cap (m_c, \infty) \)

A

1

B

Figure 4-9 Flowchart for Subprogram FNDRNG, Uniform Distribution
Figure 4-9 Flowchart for Subprogram FNDLRG, Uniform Distribution (Cont'd)
Table 4-1 The Seven Cases Considered by Subprogram FNDRNG

<table>
<thead>
<tr>
<th>Case</th>
<th>((m, \bar{m}))</th>
<th>((m_c, \bar{m}_c))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>2</td>
<td>NA</td>
<td>(m_c &lt; m)</td>
</tr>
<tr>
<td>3</td>
<td>(m = m = \bar{m})</td>
<td>(m_c &lt; m &lt; \bar{m}_c)</td>
</tr>
<tr>
<td>4</td>
<td>(m = m = \bar{m})</td>
<td>NA</td>
</tr>
<tr>
<td>5</td>
<td>(m &lt; m &lt; \bar{m})</td>
<td>(m_c &lt; m)</td>
</tr>
<tr>
<td>6</td>
<td>(m &lt; m &lt; \bar{m})</td>
<td>(m_c &lt; \bar{m}_c)</td>
</tr>
</tbody>
</table>

**Case 1**
There is no user-provided explicit constraint on \(m\) or \(C\) constraint; therefore the posterior credibility range will be given by \(J_o\).

**Case 2**
There is no user-provided explicit constraint on \(m\); however, there is an implicit lower bound provided by the \(C\) constraint. If the intersection exists, the lower bound of \(\pi(m)\) is the maximum of the lower bound of \(J_o\) and \(m_c\), and the upper bound of \(\pi(m)\) is the upper bound of \(J_o\).

**Case 3**
There is no user-provided explicit constraint on \(m\); however, there is an implicit range provided by the \(C\) constraint. If the intersection exists, the lower bound of \(\pi(m)\) is the maximum of the lower bound of \(J_o\) and \(m_c\), and the upper bound of \(\pi(m)\) is the minimum of the upper bound of \(J_o\) and \(\bar{m}_c\).

**Case 4**
The user-provided explicit constraint on \(m\) is a point value. The explicit value has priority; therefore \(\pi(m)\) consists only of this point.

**Case 5**
There is no user-provided \(C\) constraint, but there is an explicit constraint on \(m\). If the intersection exists, the lower bound of \(\pi(m)\) is the maximum of the lower bound of \(J_o\) and \(m\), and the upper bound of \(\pi(m)\) is the minimum of the upper bound of \(J_o\) and \(\bar{m}\).
Case 6
There is both a user-provided explicit range on $m$ and an implicit lower bound provided by the $C$ constraint. If the intersection exists, the lower bound of $\pi(m)$ is the maximum of the lower bound of $J_o$, $m$, and $m_c$, and the upper bound is the minimum of the upper bound of $J_o$, and $\overline{m}$.

Case 7
There is both a user-provided explicit range on $m$ and an implicit range provided by the $C$ constraint. If the intersection exists, the lower bound of $\pi(m)$ is the maximum of the lower bound of $J_o$, $m$, and $m_c$, and the upper bound is the minimum of the upper bound of $J_o$, $m$, and $m_c$.

4.1.3.9 Routine ADDREG
Routine ADDREG adds the user-provided $\pi(m_i)$ ranges for the life regions to the right without data for the Uniform distribution case of the stress formulation. ADDREG also specifies point values for $m$ in the regions without data for the median S/N curve calculation.

4.1.3.10 Routine CONCAV
In order to be consistent with the concavity constraints of the stress formulation of the S/N model, it may be necessary to modify the posterior credibility ranges of the shape parameters. Routine CONCAV ensures that the upper bounds of the posterior credibility ranges are consistent with the concavity constraints by setting the upper bound of the $m$ range in the $i$th region to be the minimum of the upper bounds in regions $i$ and $i + 1$. If the lower bound in region $i$ should be higher than the upper bound in region $i + 1$, the program run is terminated. The rest of the concavity constraints are applied in routine FINDM for the Uniform distribution case and FINDMN in the truncated Normal distribution case. FINDM and FINDMN are discussed in Sections 4.1.5.1 and 4.1.5.2.

4.1.3.11 Routine MEDIAN
The flowchart for the MEDIAN routine is given in Figure 4-10. The subprogram calculates the median $m$ for each life region for the Uniform distribution case of the stress formulation given by Equation 2-34. The routine begins by initializing the array that is to contain the median $m$’s. The remaining calculations are performed for each life region.

---

17 No data regions to the right are discussed on Page 2-17.
18 Concavity constraints are discussed on Pages 2-13 through 2-14.
Figure 4-10 Flowchart for Subprogram MEDIAN, Stress Formulation, Uniform Distribution

\[ E(m_i) = \max \left[ \frac{E(m_{i-1}) + U_i}{2}, \frac{L_i + U_i}{2} \right] \]

\[ E(m_i) = \begin{cases} L_i + U_i & \text{YES} \\ \frac{L_i + U_i}{2} & \text{TRUE} \end{cases} \]
There are three possible cases that must be considered. If the posterior credibility range has a point value, then the median \( m \) will have that point value. If the DO loop counter is on region 1, then the median is given by

\[
E(m_1) = (L_1 + U_1) / 2
\]

otherwise the median \( m \) in region \( I = 2, \ldots, R \) is

\[
E(m_I) = \max \left[ \frac{E(m_{I-1}) + U_I}{2} + \frac{L_I + U_I}{2} \right]
\]

where \( L_I \) and \( U_I \) are the lower and upper bounds, respectively, of the posterior credibility range in region \( I \).

4.1.3.12 Routine EXPCTD

The flowchart for the EXPCTD routine is given in Figure 4-11. The routine controls the calls to the median curve calculations. The routine uses the point estimates for the \( m \)'s to find the \( \{K_j\} \) and \( \beta_0 \) parameters consistent with those \( m \)'s and the specific material data set. The calculations begin by routine TRNSFM transforming the specific material S/N data. The transformation produces the \( \{Z_i\} \) as a function of the S/N data, the \( \{m_i\} \), and the life region boundaries. Then the sample mean and variance of \( Z \) are calculated by routine SMNVAR. KBETA computes the estimates of \( k \) and \( \beta_0 \). Then the \( \{K_j\} \) are calculated by routine FINDK using Equations 2-37 through 2-41. The stress values corresponding to the life region boundaries are obtained from FINDSB. If the tensile point \( S_o \) for the stress formulation is being used, then the S/N curve can be tied to \( S_o \) by routine KOMO. Finally, the results of the calculations are written to file DUMP. Routines TRNSFM, SMNVAR, KBETA, FINDK, FINDSB, and KOMO are described in Sections 4.1.5.3 through 4.1.5.7 and 4.1.6.

4.1.3.13 Routine MUSIG

The flowchart for the MUSIG routine is given in Figure 4-12. The subprogram calculates the parameters of the truncated Normal posterior density of \( m \) for each life region for the truncated Normal distribution case. The routine begins by initializing the arrays that are to contain the point estimates of \( m \) and \( C \) and the parameters \( m_* \) and \( \sigma_*^2 \) for each life region. The remaining calculations are performed for each life region.

---

\[19\] The S/N data transformation is discussed on Page 2-16.

\[20\] Extension of the S/N curve to the left is discussed on Page 2-17.

\[21\] The Bayesian analysis to obtain the parameters of the truncated Normal posterior density is discussed on Page 2-14.
START

TRNSFM
TRANSFORM S/N DATA INTO \[ \{ Z_i \} \]
(See Section 4.1.5.3)

SMNVAR
COMPUTE \( \bar{Z} \) AND \( S_z^2 \)
(See Section 4.1.5.4)

KBETA
COMPUTE ESTIMATES FOR \( k \) AND \( \beta_0 \)
(See Section 4.1.5.5)

FINDK
COMPUTE \( \{ K_i \} \)
(See Section 4.1.5.6)

FINDSB
CALCULATE \( S_{i+1}^{*} \) FOR USE IN LIFE CALCULATION
(See Section 4.1.5.7)

Figure 4-11 Flowchart for Subprogram EXPCTD
Figure 4-11 Flowchart for Subprogram EXPCTD (Cont'd)
1. **Initialize Arrays**

2. **Do L ← 1 to R by 1**

3. **Calculate \( \hat{m} \) and \( \hat{c} \) (Equation 2-22)**
   - \( \hat{m} = -d \) and \( \hat{c} = S_{\hat{c}} \)

4. **\( \delta = 0 \)**
   - **TRUE**
     - \( m_* = \hat{m} \)
   - **FALSE**
     - \( m_* = \frac{\hat{m} N S_x^2 + m_o \delta}{N S_x^2 + \delta} \)

5. **\( \sigma^2 = 0 \)**
   - **TRUE**
     - \( \sigma_*^2 = \frac{S_{\hat{c}}^2}{(N S_x^2 + \delta)} \)
   - **FALSE**
     - \( \sigma_*^2 = \frac{\sigma^2}{(N S_x^2 + \delta)} \)

6. **Return**

*Figure 4-12 Flowchart for Subprogram MUSIG, Truncated Normal Distribution*
First, the point estimates for $m$ and $C$ are calculated using Equation 2-22. The parameter $m_*$ is calculated next. If the user has not specified a value for $\delta$, indicated by $\delta = 0$, then $m_*$ is given by the point estimate $\hat{m}$. When a value for $\delta$ has been provided, then $m_*$ is given by

$$m_* = \frac{\hat{m} N S_x^2 + m_0 \delta}{N S_x^2 + \delta}$$

Finally, the $\sigma_*^2$ is calculated. If the user has not specified a value for $\sigma^2$, indicated by $\sigma^2 = 0$, then $\sigma_*^2$ is given by

$$\sigma_*^2 = S_w^2 / (N S_x^2 + \delta)$$

otherwise $\sigma_*^2$ is given by

$$\sigma_*^2 = \sigma^2 / (N S_x^2 + \delta)$$

4.1.3.14 Routine NORRNG

The flowchart for NORRNG is given in Figure 4-13. Routine NORRNG performs the calculations to obtain the posterior credibility ranges of the shape parameter $m$ for the truncated Normal distribution case. These ranges are found by combining the shape parameter constraints in Equation 2-27 with Equation 2-30, 2-31 or 2-32. The routine begins by initializing the arrays that are to contain the results. The remaining calculations are performed for each life region and the posterior credibility ranges are constrained to be non-negative. The four different cases that must be considered are given in Table 4-2.

<table>
<thead>
<tr>
<th>Case</th>
<th>$(m, \bar{m})$</th>
<th>$(m_0, \bar{m}_c)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>$m = m = \bar{m}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>$m &lt; m &lt; \bar{m}$</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>$m &lt; m &lt; \bar{m}$</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>$m &lt; m &lt; \bar{m}$</td>
</tr>
</tbody>
</table>
Figure 4-13 Flowchart for Subprogram NORRNG, Truncated Normal Distribution
Case 1
The user-provided explicit constraint on $m$ is a point value. The explicit value has priority; therefore $\pi(m)$ consists only of this point.

Case 2
There is no user-provided $C$ constraint, but there is an explicit constraint on $m$; therefore, the posterior credibility range will be given by $(m, m)$.

Case 3
There is both a user-provided explicit range on $m$ and an implicit lower bound provided by the $C$ constraint. If the intersection exists, the lower bound of $\pi(m)$ is the maximum of $\underline{m}$ and $m_c$, and the upper bound is $\overline{m}$.

Case 4
There is both a user-provided explicit range on $m$ and an implicit range provided by the $C$ constraint. If the intersection exists, the lower bound of $\pi(m)$ is the maximum of $\underline{m}$ and $m_c$, and the upper bound is the minimum of $\overline{m}$ and $\overline{m_c}$.

4.1.3.15 Routine ADDRGN
Routine ADDRGN adds the user-provided $\pi(m_i)$ ranges for the life regions to the right without data for the truncated Normal distribution case of the strain formulation. ADDRGN also specifies point values for $m$ in the regions without data for the median S/N curve calculation.

4.1.4 Routine DECOMP
The flowchart for the DECOMP routine is given in Figure 4-14. The routine controls the calls to the data input, strain decomposition, and information aggregation calculation routines. DECOMP starts by opening the following input and output files:

<table>
<thead>
<tr>
<th>NAME</th>
<th>TYPE</th>
<th>CONTENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>RELATD</td>
<td>Input</td>
<td>Related material data input</td>
</tr>
<tr>
<td>RELATO</td>
<td>Output</td>
<td>Related material data echo</td>
</tr>
</tbody>
</table>

The arrays are then set to their default or initial values by routine INITD. Routine RDECHO reads the data from files SPECFD and RELATD and echoes the data to files SPECFO and RELATO. Routines INITD and RDECHO are described in Sections 4.1.4.1 and 4.1.4.2.

The strain decomposition begins with a call to PREP. Routine PREP stores the user-supplied plastic and elastic strain components into arrays with the data structure

---

22 No data regions to the right are discussed on Page 2-17.
START

OPEN FILES RELATED AND RELATED INITD

READ FROM SPECIFIED S/N DATA
\((m_p, \bar{m}_p), (m_E, \bar{m}_E)\)

WRITE TO SPECIFIED S/N DATA
\((m_p, \bar{m}_p), (m_E, \bar{m}_E)\)

INITD

INITIALIZE ARRAYS
(See Section 4.1.4.1)

RDECHO

READ DATA

READ FROM RELATED S/N DATA

WRITE TO RELATED S/N DATA

ECHO DATA
(See Section 4.1.4.2)

PREP

PREPARE DATA FOR DATA STRUCTURE REQUIRED
(See Section 4.1.4.3)

GIVEN PLASTIC COMPONENTS

GIVEN ELASTIC COMPONENTS

SW2SU2

REGRESS In \(S_p\) ON IN \(N\)
REGRESS IN \(N\) ON IN \(S_p\)
(See Section 4.1.3.4)

SW2SU2

REGRESS In \(S_E\) ON IN \(N\)
REGRESS IN \(N\) ON IN \(S_E\)
(See Section 4.1.3.4)

A

B

Figure 4-14 Flowchart for Subprogram DECOMP, Strain Formulation
Figure 4.14 Flowchart for Subprogram DECOMP, Strain Formulation (Cont'd)
Figure 4-14 Flowchart for Subprogram DECOMP, Strain Formulation (Cont'd)
EXPCTD
CALCULATE PARAMETER VALUES FOR MEDIAN PLASTIC S/N CURVE
(See Section 4.1.3.12)

EXPCTD
CALCULATE PARAMETER VALUES FOR MEDIAN ELASTIC S/N CURVE
(See Section 4.1.3.12)

CALCULATE $\beta_o$ FOR MEDIAN S/N CURVE

WRITE TO DUMP $\beta_o$

PROCESS VARIATION?

NO

GTPVAR

CALCULATE $\sigma^2$
(See Section 4.1.3.7)

WRITE TO DUMP $\sigma^2$

$x(m_p), \pi(m_E)$
SPECIFIC PLASTIC COMPONENT S/N DATA
SPECIFIC ELASTIC COMPONENT S/N DATA

RETURN

Figure 4-14 Flowchart for Subprogram DECOMP, Strain Formulation (Cont'd)

4 - 48
CALCULATED PLASTIC COMPONENTS

SW2SU2
REGRESS In $S_p$ ON In $N$
REGRESS In $N$ ON In $S_p$
(See Section 4.1.3.4)

MUSIG
PERFORM BAYESIAN ANALYSIS
TO OBTAIN $m_{sp}$ & $\sigma_{sp}^2$ FOR
PLASTIC COMPONENTS
(See Section 4.1.3.13)

NORRNG
COMPUTE POSTERIOR CREDIBILITY RANGE
(See Section 4.1.3.14)

CALCULATED ELASTIC COMPONENTS

SW2SU2
REGRESS In $S_E$ ON In $N$
REGRESS In $N$ ON In $S_E$
(See Section 4.1.3.4)

MUSIG
PERFORM BAYESIAN ANALYSIS
TO OBTAIN $m_{se}$ & $\sigma_{se}^2$ FOR
ELASTIC COMPONENTS
(See Section 4.1.3.13)

NORRNG
COMPUTE POSTERIOR CREDIBILITY RANGE
(See Section 4.1.3.14)

WRITE TO DUMP
PLASTIC: $\hat{m}_p$, $\pi(m_p)$
ELASTIC: $\hat{m}_e$, $\pi(m_e)$

Figure 4-14 Flowchart for Subprogram DECOMP, Strain Formulation (Cont'd)
required by those routines shared with the stress formulation calculations. Linear regressions are performed by routine SW2SU2 on the combined specific and related plastic strain component data. Routine INTRVL then calculates the median value for the shape parameter \( m_p \). EXPCTD finds the median location parameter \( K_p \) for the plastic components. Then SW2SU2, INTRVL, and EXPCTD are called using the elastic strain components to find the median \( m_E \) and \( K_E \). Routines PREP, SW2SU2, INTRVL, and EXPCTD are described in Sections 4.1.4.3, 4.1.3.4, 4.1.3.6, and 4.1.3.12, respectively.

The actual strain decomposition is performed by routine PECOMP using the median \( m_p, K_p, m_E, \) and \( K_E \) found above. Routine PREP is used again to store the plastic and elastic strain component data into the required arrays for the information aggregation calculations. PECOMP and PREP are described in Sections 4.1.4.4 and 4.1.4.3. The remaining routine calls depend upon the choice of distribution for the shape parameters \( m_p \) and \( m_E \).

The information aggregation for the Uniform distribution case begins with linear regression calculations performed by routine SW2SU2 on the specific and related plastic strain components. The confidence interval calculations for the plastic strain components are performed by INTRVL. The prior credibility range is defined to be the confidence interval. The credibility range for \( m_p \) and the user-provided range information are combined by routine FNRNG to obtain the posterior credibility range on the shape parameter \( \pi(m_p) \). The results of these calculations are written to file DUMR. The median S/N curve is then calculated by routine EXPCTD and written to file DUMP. The calls to SW2SU2, INTRVL, FNRNG, and EXPCTD are repeated for the elastic strain components. \( \beta_0 \), defined as the average of the \( \beta_0 \)'s resulting from the two calls to EXPCTD, is calculated. Routines SW2SU2, INTRVL, FNRNG, and EXPCTD are described in Sections 4.1.3.4, 4.1.3.6, 4.1.3.8, and 4.1.3.12, respectively.

The truncated Normal distribution case begins with linear regression calculations performed by routine SW2SU2 on the combined specific and related plastic strain components. A Bayesian analysis is performed by MUSIG to find the Normal distribution parameters for \( m_p \). The user-provided range information is translated by routine NFRNG into a posterior credibility range on the shape parameter \( m_p \). The results of these calculations are written to file DUMR. The calls to SW2SU2, MUSIG, and NFRNG are repeated for the elastic strain components. Routines SW2SU2, MUSIG, and NFRNG are described in Sections 4.1.3.4, 4.1.3.13, and 4.1.3.14, respectively.

---

23 Combining information to obtain the posterior credibility ranges on \( m \) is discussed on Page 2-13.
For both Uniform and truncated Normal distribution cases, if materials process variation is requested, GTPVAR calculates $\sigma^2$, the extent of departures from the multiple heat median S/N curve warranted by the available information, by using Equation 2-49. Routine GTPVAR is described in Section 4.1.3.7.

### 4.1.4.1 Routine INITD

The routine initializes the arrays used in the strain formulation information aggregation routine, DECOMP, to zero.

### 4.1.4.2 Routine RDECHO

The flowchart for the RDECHO routine is given in Figure 4-15. The routine controls the input/output of the specific and related materials data, and exogenous information. RDECHO begins by reading the data from file SPECFD which contains the specific S/N data, and exogenous information, and echoes the information to file SPECFO. First, the general information pertaining to the specific material data set is read, including the material description, the number of S/N data points with plastic and elastic decomposition information, the total number of S/N data points, and the number of tensile points.

First the S/N data with decomposition information is read and echoed. The S/N data is in the form of $(S, N, S_p, S_E)$ quadruplets, where $S$ is the total strain, $N$ is the cyclic fatigue life, $S_p$ is the plastic strain component, and $S_E$ is the elastic strain component. Then the remaining S/N data in the form of $(S, N)$ pairs is read and echoed. Next, the tensile data is read and echoed. Inclusion of tensile data is discussed in Section 2.1.2.2.

The last information in file SPECFD used by all strain formulation options is the explicit constraints on the shape parameters $m_p$ and $m_E$. The explicit constraint consists of a point value or range of values for each strain component curve of the specific material data set.\(^\text{24}\)

When the truncated Normal variation of the shape parameters is specified, RDECHO reads and echoes the Bayesian prior information for each strain component curve.\(^\text{25}\) If materials process variation is specified, the process variation information is read and echoed. Process variation in materials is discussed in Section 2.1.2.3.

---

\(^\text{24}\) The explicit constraint on the materials shape parameter provided by prior information on the materials shape parameter is discussed on Page 2-12.

\(^\text{25}\) Specifications of the Bayesian prior distribution for the truncated Normal case is discussed on Page 2-14.
READ AND ECHO SPECIFIC MATERIAL S/N DATA SET INFORMATION

READ AND ECHO S, N, S_p, AND S_E FOR GIVEN DECOMPOSITION DATA

READ AND ECHO S, N FOR REMAINING DATA

READ AND ECHO TENSILE POINTS

READ AND ECHO EXPPLICIT CONSTRAINTS ON THE SHAPE PARAMETERS

TYPE OF VARIATION?

UNIFORM

TRUNCATED NORMAL

READ AND ECHO BAYESIAN PRIOR INFORMATION

PROCESS VARIATION?

NO

YES

1

A

Figure 4-15 Flowchart for Subprogram RDECHO, Strain Formulation
READ AND ECHO
PROCESS VARIATION INFORMATION

READ AND ECHO
NUMBER OF RELATED S/N DATA SETS

DO J → 1
TO NSETS BY 1

READ AND ECHO
RELATED MATERIAL
S/N DATA SET INFORMATION

READ AND ECHO
S, N, SP, AND SE FOR
GIVEN DECOMPOSITION DATA

READ AND ECHO
S, N FOR REMAINING DATA

READ AND ECHO
TENSILE POINTS

RETURN

Figure 4-15 Flowchart for Subprogram RDECHO, Strain Formulation (Cont'd)
Next, RDECHO reads the data from file RELATD which contains the related S/N data and echoes the information to file RELATO. First, the number of related data sets is read, stored in variable NSETS, and echoed. The data set DO loop is performed for each related data set. The general information pertaining to the related material data set is read, including the material description, the number of S/N data points with plastic and elastic decomposition information, the total number of S/N data points, and the number of tensile points. The S/N data with decomposition information is read and echoed. The S/N data is in the form of \((S, N, S_p, S_E)\) quadruplets, where \(S\) is the total strain, \(N\) is the cyclic fatigue life, \(S_p\) is the plastic strain component, and \(S_E\) is the elastic strain component. Then, the remaining S/N data in the form of \((S, N)\) pairs is read and echoed. Finally, the tensile data is read and echoed. Inclusion of tensile data is discussed in Section 2.1.2.2.

**4.1.4.3 Routine PREP**

The routine stores the plastic and elastic strain component data in arrays with the data structure required by routines SW2SU2 and EXPCTD. Routines SW2SU2 and EXPCTD are described in Sections 4.1.3.4 and 4.1.3.12.

**4.1.4.4 Routine PECOMP**

The flowchart for the PECOMP routine is given in Figure 4-16. The routine performs the calculations to decompose the total strain data into plastic and elastic strain components. The decomposition is based upon \(\hat{R}_p\), \(\hat{m}_p\), \(\hat{R}_E\), and \(\hat{m}_E\), estimates of the location and shape parameters, for the given plastic and elastic strain data. PECOMP starts by initializing the arrays for the storage of the calculated plastic and elastic strain components and the given plastic and elastic strain data.

The plastic and elastic strain components are calculated from the total strain and fatigue life using Equations 2-46 and 2-47, and then stored in the appropriate arrays. The elastic strain and total strain are calculated for the tensile points, assuming that the tensile point is the plastic strain at one cycle given by Equation 2-45. Finally, the results of the decomposition calculations are written to file DUMP.

**4.1.5 PAREST Routine**

The flowchart for the PAREST routine is given in Figure 4-17. The routine controls the calls to the parameter estimation calculations. The parameter estimation begins by selecting the \(m\)'s for each region. The \(m\) selection is performed by FINDM for the Uniform distribution case and FINDMN for the truncated Normal distribution case. Routines FINDM and FINDMN are described in Sections 4.1.5.1 and 4.1.5.2.

---

26 Related S/N data is discussed on Page 2-7.
INITIALIZE STRAIN COMPONENT ARRAYS FOR DECOMPOSITION CALCULATIONS

STORE GIVEN DECOMPOSITION DATA IN STRAIN COMPONENT ARRAYS

CALCULATE AND STORE STRAIN COMPONENTS FOR TOTAL STRAIN / LIFE DATA
(Eqs 2-46 & 2-47)

\[ \alpha_i = \frac{\hat{K}_P}{\hat{K}_E} N_i \left( \frac{1}{n_p} - \frac{1}{n_E} \right) \]

\[ \lambda_i = \frac{\alpha_i}{1 + \alpha_i} \]

\[ S_{P_i} = \lambda_i S_i \]

\[ S_{E_i} = S_i - S_{P_i} \]

CALCULATE AND STORE \( S_E \) AND \( S \) FOR TENSILE DATA

NOTE: \( N = 1 \) CYCLE

\[ \alpha_i = \frac{\hat{K}_P}{\hat{K}_E} \]

\[ S_{P_i} = \text{TENSILE POINT} \]

\[ S_{E_i} = S_{P_i} / \alpha_i \]

\[ S_i = S_{P_i} + S_{E_i} \]

Figure 4-16 Flowchart for Subprogram PECOMP, Strain Formulation

4 - 55
Figure 4-16 Flowchart for Subprogram PECOMP, Strain Formulation (Cont'd)
Figure 4-17 Flowchart for Subprogram PAREST
FINDK

COMPUTE \( \{K_i\} \)
(See Section 4.1.5.6)

FINDSB

CALCULATE \( S_{ij+1}^* \) FOR USE IN LIFE CALCULATION
(See Section 4.1.5.7)

RETURN

\[ \beta_{o}, \{K_i, m_i\}, S_{ij+1}^* \]

Figure 4-17 Flowchart for Subprogram PAREST (Cont'd)
The remaining calculations find the \( K_i \) and \( \beta_0 \) parameters consistent with the randomly selected \( \{m_i\} \) and the specific material data set. The calculations begin by routine TRNSFM transforming the specific material S/N data. The transformation produces the \( \{Z_i\} \) as a function of the S/N data, the \( \{m_i\} \), and the life region boundaries. Then, the sample mean and variance of \( Z \) are calculated by routine SMNVAR. KBETA computes the estimates of \( k \) and \( \beta_0 \). Then, the \( \{K_i\} \) are calculated by routine FINDK using Equations 2-37 through 2-41. Finally, the stress values corresponding to the life region boundaries are obtained from FINDSB. Routines TRNSFM, SMNVAR, KBETA, FINDK, and FINDSB are described in Sections 4.1.5.3 through 4.1.5.7.

4.1.5.1 Routine FINDM

The flowchart for the FINDM routine is given in Figure 4-18. The routine performs the random selection of the \( \{m_i\} \) off the \( \pi(m_i) \) for the Uniform distribution case. The subprogram begins by initializing the array that is to contain the \( \{m_i\} \). The remaining calculations are performed for each life region.

There are three possible cases that must be considered. If the range for \( \pi(m) \) has a point value, then the \( m \) in that life region will have that point value. If the DO loop counter is on region 1, then \( m_1 \) will be randomly selected off of \( U(L_1, U_1) \) where \( L_1 \) is the lower bound of \( \pi(m_1) \) and \( U_1 \) is the upper bound of \( \pi(m_1) \). Otherwise, \( m_i \) is randomly selected off of \( U(\max \{m_{i-1}, L_i\}, U_i) \), where \( m_{i-1} \) is the randomly selected \( m \) in region \( i-1 \), \( L_i \) is the lower bound of \( \pi(m_i) \), and \( U_i \) is the upper bound of \( \pi(m_i) \).

4.1.5.2 Routine FINDMNN

The flowchart for the FINDMNN routine is given in Figure 4-19. The routine performs the random selection of the \( \{m_i\} \) off the \( \pi(m_i) \) for the truncated Normal distribution case. The subprogram begins by initializing the array that is to contain the \( \{m_i\} \). The remaining calculations are performed for each life region.

There are three possible cases that must be considered. If the range for \( \pi(m) \) has a point value, then the \( m \) in that life region will have that point value. If the DO loop counter is on region 1, \( m_1 \) will be randomly selected off of \( N(m_1, \sigma_{11}^2) \), then FINDMNN checks to see if the selected \( m \) is within the range of \( \pi(m_1) \) given by \( [L_1, U_1] \), where \( L_1 \) is the lower bound of \( \pi(m_1) \) and \( U_1 \) is the upper bound of \( \pi(m_1) \). If the randomly selected \( m \) is not in the range, values are selected until a value is found within the range. If \( \pi(m) \) is not a point and \( i \) is not 1 then, \( m_i \) is randomly selected off of \( N(m_i, \sigma_{ii}^2) \), then FINDMNN checks to see if the selected \( m \) is within the interval \( [\max(m_{i-1}, L_i), U_i] \), where \( m_{i-1} \) is the randomly selected \( m \) in region \( i-1 \), \( L_i \) is the

---

27 The S/N data transformation is discussed on Page 2-16.
Figure 4-18 Flowchart for Subprogram FINDM, Uniform Distribution
Figure 4-19 Flowchart for Subprogram FINDMN, Truncated Normal Distribution
Figure 4-19 Flowchart for Subprogram FINDMN, Truncated Normal Distribution (Cont'd)
lower bound of \( \pi(m_i) \), and \( U_i \) is the upper bound of \( \pi(m_i) \). If the randomly selected \( m \) is not in the range, values are selected until a value is found within the range.

4.1.5.3 Routine TRNSFM

The flowchart for the TRNSFM routine is given in Figure 4-20. The routine performs the transformation, Equations 2-39 and 2-40, which produces the \( \{Z_k\} \) as a function of the S/N data, the \( \{m_i\} \), and the life region boundaries \( \{N_{i-1,j}\} \). The subprogram begins by initializing the array that is to contain the \( \{Z_k\} \). The remaining calculations are performed as follows. First, calculate \( Z_k \) for each data point in region \( I \), \( i = 1, ..., R \)

\[ Z_k = \ln \left( S_k \frac{1}{N_k} \right) \]

Then for each life region to the left \( II, III, ... \)

\[ Z_k = Z_k \ln \left( S_k \frac{N_{i-1,j}}{N_{i-1,j}} \right) \]

4.1.5.4 Routine SMNVAR

The flowchart for the SMNVAR routine is given in Figure 4-21. The routine performs the calculations to obtain the sample mean and variance of the \( \{Z_k\} \) given by the following equations:

for the mean \( \bar{Z} = \frac{1}{N_0} \sum_{i=1}^{N_0} Z_i \)

for the variance \( S_Z^2 = \frac{1}{N_0 - 1} \sum_{i=1}^{N_0} (Z_i - \bar{Z})^2 \)

4.1.5.5 Routine KBETA

KBETA calculates \( \hat{k} \) and \( \beta_o \) using Equation 2-42 and the sample mean and variance obtained in routine SMNVAR where

\[ \hat{k} = \bar{Z} \quad \text{and} \quad \beta_o = \frac{\pi}{S_Z \sqrt{6}} \]

4.1.5.6 Routine FINDK

The flowchart for the FINDK routine is given in Figure 4-22. The routine performs the calculations of Equations 2-41 and 2-37 to obtain the \( \{K_i\} \) as a function of \( \hat{k}, \beta_o \), the \( \{m_i\} \), and the life region boundaries \( \{N_{i-1,j}\} \). The subprogram begins by initializing

4 - 63
INITIALIZE ARRAYS

DO L ← 1
TO R BY 1

DO K ← 1
TO N_I BY 1

CALCULATE Z_k IN REGION L
Z_k = \ln \left( \frac{1}{m_i} \right)

DO LL ← 2
TO L BY 1

CALCULATE Z_k FOR EACH REGION LL
Z_k = Z_k \ln \left( \frac{1}{m_{i-1}} \cdot \frac{1}{m_i} \right)

RETURN

Figure 4-20 Flowchart for Subprogram TRNSFM
Figure 4-21 Flowchart for Subprogram SMNVAR

\[
(N - 1) S_z^2 = \sum_{i=1}^{N} (Z_i - \bar{Z})^2
\]
INITIALIZE ARRAYS

CALCULATE $K_1$

$$K_1 = (\ln 2)^{P_0} \exp \left( k + \frac{\gamma}{P_0} \right)$$

DO $L \rightarrow 2$

TO $R$ BY 1

CALCULATE $K_L$ FOR EACH REGION $L$

$$K_L = K_{L-1} \cdot N_{L-1,L}$$

RETURN

Figure 4-22 Flowchart for Subprogram FINDK
the array that is to contain the \( \{K_i\} \). The remaining calculations are performed as follows. First, calculate \( K_1 \) given by Equation 2-41

\[
K_1 = (\ln 2)^{\gamma_0} \exp \left( k + \frac{\gamma}{\beta_0} \right)
\]

where \( \gamma \) is Euler's Constant. Then, using Equations 2-37 for each life region \( l, l = 2, ..., R \)

\[
K_l = K_{l-1} \left( \frac{1}{m_l} - \frac{1}{m_{l-1}} \right)
\]

4.1.5.7 Routine FINDSB

Subprogram FINDSB calculates the life region "tie-points", or stress values \( S^* \), which correspond to the "life boundaries" conditional on the randomly selected \( \{m_l\} \), the \( \{K_l\}, \beta_0 \) and \( k \) using Equation 2-11, with \( l = 1, ..., R \)

\[
S^*_l = K_l N^*_l \left( \frac{1}{m_l} \right).
\]

Note: If \( N^*_R = \infty \) indicated by \( 10^{36} \), then \( S^*_R = 0 \).

4.1.6 Routine KOMO

The KOMO routine calculates \( K_o \) and \( m_o \) for the zero region, the no-data region to the left of the first data region, and extends the S/N curve consistent with the tensile point at \( S_o \) for the stress formulation of the materials model.\(^{28}\) The subprogram begins by setting \( K_o \) equal to the value of \( S_o \). Then, the S/N curve parameters are checked and adjusted to maintain consistency with \( S_o \). Finally, \( m_o \) is calculated according to the following relation

\[
m_o = m_1 \frac{\ln K_1 - \ln S^*_o + \ln (\phi \lambda^*_K Z)}{\ln S_o - \ln S^*_o}.
\]

4.1.7 Routine ADJSTM

Routine ADJSTM adjusts the posterior credibility range for the elastic shape parameter \( m_E \) to be consistent with the concavity constraints of the strain formulation of the S/N model. ADJSTM set the lower bound of the \( m_E \) range to be the maximum of the lower bound of \( \pi(m_E) \) and \( m_p \).

\(^{28}\) Extension of the S/N curve to the left is discussed on Page 2-17.
4.1.8 Routine GTLIFE

Routine GTLIFE calculates the fatigue life (cycles) given by Equation 2-48 at a user-provided stress level for the stress formulation of the materials characterization model. The subprogram begins by checking to see if the tensile point $S_0$ is being used. If $S_0$ is being used, the subprogram checks to see if the stress $S$ is greater than or equal to $S_0$, then the life $N$ will be set to one cycle. Otherwise the life is calculated as

$$N = K^m S^{-m} \varphi^m \left[ \lambda_K^* Z \right]^m.$$

When process variation is not in use the parameters $\lambda_K^*$ and $Z$ are defined to be one. Routine GTLIFE has another implementation for use with the PFM's. This implementation differs in that the $K$ and $\varphi$ parameters are raised to the $m$ power by the PFM before GTLIFE is called.

4.1.9 Routine GTLIF2

Routine GTLIF2 provides the fatigue life (cycles) at a user-provided strain level $S$ for the strain formulation of the materials characterization model. The fatigue life is obtained by solving Equation 2-50 for $N$ using Newton's method. The initial value provided to the Newton's method routine NEWTON is given by the elastic strain component

$$N = \left[ K_E \varphi \lambda_K^* Z / S \right]^{m_E}.$$

When process variation is not in use, the parameters $\lambda_K^*$ and $Z$ are defined to be one. Subprogram NEWTON is described in Section 4.1.9.1.

4.1.9.1 Routine NEWTON

Routine NEWTON is a modified version of subroutine RTNI taken from IBM Application Program, System/360 Scientific Subroutine Package, Version III, Programmer's Manual, Program Number 360-CM-03X, Page 220. The estimates of the life $N$ for each iteration are obtained by a call to routine FCT discussed in Section 4.1.9.2.

4.1.9.2 Routine FCT

Routine FCT is used by subprogram NEWTON to calculate the value of the function and its derivative at the value $N$, in order to find the solution of the strain formulation S/N curve. The function is Equation 2-50, rewritten so as to find the zero,

$$F = \left[ K_F N^{-1/m_p} + K_E N^{-1/m_E} \right] \varphi \left[ \lambda_K^* Z \right] - S.$$
and the derivative is given by

\[
\frac{dF}{dN} = - \left[ \frac{K_P}{m_P} \mathcal{N}(-1 - 1/m_p) + \frac{K_E}{m_E} \mathcal{N}(-1 - 1/m_e) \right] \varphi \left( \hat{\lambda}_K Z \right).
\]

Routine NEWTON is discussed in Section 4.1.9.1.

4.1.10 Routine SORTM

The flowchart for the SORTM routine is given in Figure 4-23. The routine sorts the \( m \) values in increasing order for each life region or strain component for the truncated Normal distribution case.\(^{29}\)

4.1.11 Routine TRMNAT

Subprogram TRMNAT performs the premature termination of the program when the program has detected a fatal error during execution.

\(^{29}\) The need for saving \( m \)'s is discussed on Page 2-15.
Figure 4-23 Flowchart for Subprogram SORTM

START

DO L ← 1 TO R BY 1

J = N

J > 1

J = J / 2
INORDER = TRUE

DO 1 ← 1 TO N - J BY 1

X(I, L) > X(I + J, L)

TRUE

FALSE

A B C 1 D E F

4 - 70

C = 2
EXCHANGE VALUES
\[
Y = X(I, L) \\
X(I, L) = X(I+J, L) \\
X(I+J, L) = Y
\]
INORDER = FALSE

Figure 4-23 Flowchart for Subprogram SORTM (Cont'd)
Section 4.2
Prior Distribution Parameter Estimation Software

4.2.1 Introduction

This section presents a description of the computer programs which implement the prior failure distribution parameter estimation and assurance calculation discussed in Section 2.1.1. The programs are described in detail using flowcharts. The user's guide for running these programs is given in Section 6.4, and the source listings, including a definition of key variables, are given in Section 7.4. A glossary of standard flowchart symbols is given for the reader's benefit in Appendix 5A.

4.2.2 BFIT Program

The prior failure distribution parameter \( \beta \) estimation procedure of Section 2.1.1 is implemented as the FORTRAN program BFIT. This program can be used to estimate the prior failure distribution parameter \( \beta \), based on failure lives generated by the appropriate probabilistic failure modeling. The flowchart for the BFIT program is given in Figure 4-24. The program starts by opening the input and output files. They are:

<table>
<thead>
<tr>
<th>NAME</th>
<th>TYPE</th>
<th>CONTENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>BFITD</td>
<td>Input</td>
<td>Analysis indices</td>
</tr>
<tr>
<td>LOWLIF</td>
<td>Input</td>
<td>Sorted fatigue lives</td>
</tr>
<tr>
<td>BFITO</td>
<td>Output</td>
<td>Results</td>
</tr>
<tr>
<td>IOUTPR</td>
<td>Output</td>
<td>User-requested information</td>
</tr>
</tbody>
</table>

The indices which define the data base used to estimate \( \beta \) are read from file BFITD. Then the failure times are read from file LOWLIF, and the values of

\[
Y_i = \ln \left( - \ln \left[ 1 - F(N_i) \right] \right)
\]

are calculated for each failure time.

The estimation of \( \beta \) by \( b \) is performed by subprogram LLS described in Section 4.2.2.1. LLS utilizes a linear least squares algorithm to perform the parameter estimation using \( N \) simulated failure lives. The results are then written to the output file BFITO.

4.2.2.1 LLS Routine

The flowchart for the LLS routine is given in Figure 4-25. The routine uses linear least squares regression of \( \ln \left( - \ln \left[ 1 - F(N_i) \right] \right) \) on \( \ln(N) \) to estimate \( \beta \) by \( b \) where

\[
X_i = \ln N_i
\]

\[
Y_i = \ln \left( - \ln \left[ 1 - F(N_i) \right] \right).
\]
START

OPEN DATA FILES

READ INPUT DATA

CALCULATE

\[ Y_i = \ln \left( - \ln \left( 1 - F(N_i) \right) \right) \]

LLS

PERFORM LINEAR LEAST SQUARES FROM START TO END

\[ Y = \ln(\alpha/\beta) + \beta \ln(N) \]

(Equation 2.9)

WRITE \( b \) to BFITO

STOP

Figure 4-24 Flowchart for the Prior Failure Distribution Parameter \( \beta \) Estimation Program BFIT
START

INITIALIZE ARRAYS

CALCULATE $\bar{x}$ AND $\bar{y}$

DO 1 -- START

TO END BY 1

SUM OVER ALL DATA POINTS

$$N S_x^2 = \sum_{i=\text{START}} \left( x_i - \bar{x} \right)^2$$

$$N S_{xy} = \sum_{i=\text{START}} \left( x_i - \bar{x} \right) (y_i - \bar{y})$$

$N = \text{END} - \text{START}$

CALCULATE SAMPLE VARIANCES $S_x^2$ AND $S_{xy}$

CALCULATE $b$ AND $\ln c$

$b = S_{xy} / S_x^2$

$\ln c = \bar{y} - b \bar{x}$

RETURN

Figure 4-25 Flowchart for Subprogram LLS
LLS starts by initializing the arrays required for the calculations. Then the sample means $X$ and $Y$ are calculated. The sample variances are calculated as follows:

$$NS_x^2 = \sum_{i = \text{START}}^{\text{END}} (x_i - \bar{x})^2$$

$$NS_{xy} = \sum_{i = \text{START}}^{\text{END}} (x_i - \bar{x})(y_i - \bar{y})$$

where $N = \text{END} - \text{START}$, and $S_x^2$ and $S_{xy}$ are the sample variance of $X$, and sample covariance of $X$ and $Y$, respectively. The sample means and variances are used to calculate the regression parameters $b$ and $\ln c$ of Equations 2-9,

$$b = S_{xy}/S_x^2 \quad \text{and} \quad \ln c = \bar{y} - b\bar{x}$$

$\beta$ is estimated by $b$ and $\ln c$ is computed for the user's information only.

4.2.3 ABTFIT Program

The prior failure distribution parameters $\alpha$ and $\theta$ estimation procedure of Section 2.1.1 is implemented as the FORTRAN program ABTFIT. This program is used to estimate $\alpha$ and $\theta$, given $\beta = b$, based on the failure lives produced by the probabilistic failure modeling. The flowchart for the ABTFIT program is given in Figure 4-26. The program starts by opening the input file PARAMS, reading the least squares parameters, and then closing PARAMS. If IOUT is equal to 10 or 20, then file IOUTPR must be opened. The input file LOWLIF is opened, the failure times are read, the value of

$$Y_i = -\ln [1 - F(N_i)]$$

is calculated for each failure time and LOWLIF is closed.

The estimate of $\beta$ is provided exogenously or by the program BFit described in Section 4.2.2. The estimates of the parameters $\alpha$ and $\theta$ using the $N$ simulated failure lives are performed by the nonlinear least squares IMSL subprogram DUNLSJ. Subprogram DUNLSJ is described in "User's Manual," IMSL Math/Library FORTRAN Subroutines for Mathematical Applications MALB-USM-UNBND-EN8901-1.1, Version 1.1, Volume 3, IMSL Inc., January 1989, pp. 841-846. The results are then written to the output files ABTOUT and BAYESD.
Figure 4-26 Flowchart for the Prior Failure Distribution Parameter Estimation Program ABTFIT

\[ Y_i = - \ln \left( 1 - F(N_i) \right) \]
PERFORM NONLINEAR LEAST SQUARES TO FIND $\alpha$ AND $\theta$ GIVEN $\beta = b$

**ABT**

FUNCTION EVALUATION

$f = Y - \alpha \ln [1 + N^b / \theta]\n
(Equation 2-10)

**JABT**

JACOBIAN EVALUATION

\[
\frac{\partial f}{\partial \theta} = \frac{\alpha N^b}{\theta^2 [1 + N^b / \theta]}
\]

\[
\frac{\partial f}{\partial \alpha} = -\ln [1 + N^b / \theta]
\]

(Equation 2-10)

OPEN ABTOUT

---

Figure 4-26 Flowchart for the Prior Failure Distribution Parameter Estimation Program ABTFIT (Cont’d)
WRITE ESTIMATES OF $\alpha, \beta, \theta$ AND NUMBER OF ITERATIONS TO ABTOUT

CLOSE ABTOUT

OPEN BAYESD

WRITE ESTIMATES OF $\beta, \theta, \alpha$ TO BAYESD

CLOSE BAYESD

STOP

Figure 4-26 Flowchart for the Prior Failure Distribution Parameter Estimation Program ABTFIT (Cont'd)
4.2.3.1 ABT Routine

Routine ABT performs the function evaluation for each failure time required by DUNLSJ. The function to be evaluated is given by Equation 2-10

\[ f = Y - \alpha \ln \left( 1 + \frac{N^b}{\theta} \right) \]

4.2.3.2 JABT Routine

Routine JABT performs the Jacobian evaluation for each failure time required by DUNLSJ. The Jacobian to be evaluated is given by the partial derivatives with respect to \( \theta \) and \( \alpha \) of the function in Equation 2-10

\[ \frac{\partial f}{\partial \theta} = \frac{\alpha N^b}{\theta^2 \left( 1 + \frac{N^b}{\theta} \right)} \]

\[ \frac{\partial f}{\partial \alpha} = - \ln \left( 1 + \frac{N^b}{\theta} \right) \]

4.2.4 LZERO Program

The assurance calculation of Section 2.1.1 is implemented as the FORTRAN program LZERO. This program is used to calculate \( \lambda_o \) in Equation 2-5 for a specified assurance level \( A \). The flowchart for the LZERO program is given in Figure 4-27. The program starts by opening the input and output files. They are:

<table>
<thead>
<tr>
<th>NAME</th>
<th>TYPE</th>
<th>CONTENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAYESD</td>
<td>Input</td>
<td>Failure distribution parameters</td>
</tr>
<tr>
<td>LDAT</td>
<td>Input</td>
<td>Assurance level and ( \lambda ) bounds</td>
</tr>
<tr>
<td>LOUT</td>
<td>Output</td>
<td>Results</td>
</tr>
<tr>
<td>IOUTPR</td>
<td>Output</td>
<td>User-requested information</td>
</tr>
</tbody>
</table>

LZERO reads from file BAYESD the parameters \( \alpha \) and \( \theta \) derived for the failure life distribution using the program ABTFIT. Then IOUT, the desired assurance level \( A \), and the bounds, \( \lambda_{lb} \) and \( \lambda_{ub} \), on \( \lambda_o \) are read from file LDAT. If IOUT is equal to 10, then file IOUTPR is opened and the intermediate calculations are written in the file.

\( F(\lambda_{ib}) \) and \( F(\lambda_{ub}) \) are evaluated in routine GAMMA and written to file LOUT. If the desired assurance is not bounded by these two values the routine TRMNAT is called to terminate the program run. Subprograms GAMMA and TRMNAT are described in Sections 4.2.4.1 and 4.2.4.5. If the desired assurance is bounded by \( F(\lambda_{ib}) \) and \( F(\lambda_{ub}) \) then the assurance is obtained by using Mueller’s iteration method performed by routine MUELLR. MUELLR is described in Section 4.2.4.3. The results are then written to the output file LOUT.
Figure 4-27 Flowchart for the Assurance Calculation Program

1

START

OPEN INPUT DATA FILES

READ INPUT DATA

CLOSE INPUT DATA FILES

IOUT = 10

TRUE

OPEN IOUTPR

GAMMA

EVALUATE CDF AT $\lambda_{lb}$

GAMMA

EVALUATE CDF AT $\lambda_{ub}$

WRITE FL AND FU TO LOUT

FALSE
USE MUELLER'S ITERATION METHOD TO FIND $\lambda_o$ FOR A DESIRED ASSURANCE $A$

FCT
FUNCTION EVALUATION
$f = F(x) - A$

OPEN LOUT

WRITE ESTIMATES OF ASSURANCE TO LOUT

STOP

Figure 4-27 Flowchart for the Assurance Calculation Program LZERO (Cont'd)
4.2.4.1 Routine GAMMA

The cumulative distribution function $F(x)$ for a Gamma variate is calculated in this routine. This is done by integrating the Gamma density function, Equation 2-1, by using a series representation given as follows:

$$F(x) = (\theta x)^\alpha \exp(-\theta x) \sum_{i=0}^{\infty} \frac{(\theta x)^i}{i!(\alpha + 1 + i)}$$

(4-1)

and for ease of calculation, $F(x)$ may be approximated as a finite sum in the form

$$F(x) = \sum_{i=0}^{NS} \exp \left( - \ln \left[ \Gamma(\alpha + 1 + i) \right] + (i + \alpha) \ln \theta x - \theta x \right)$$

(4-2)

The flowchart for the GAMMA routine is given in Figure 4-28. The routine DLGAM calculates the logarithm of the gamma function.

4.2.4.2 Routine DLGAM

This routine calculates the double precision value of the gamma function (i.e., $\ln \Gamma(x)$). It is a modified version of subroutine DLGAM taken from IBM Application Program, System/360 Scientific Subroutine Package, Version III, Programmer's Manual, Program Number 360-CM-03X, Page 362.

4.2.4.3 Routine MUELLR

Routine MUELLR is a modified version of subroutine DRTMI taken from IBM Application Program, System/360 Scientific Subroutine Package, Version III, Programmer's Manual, Program Number 360-CM-03X, Page 219. The estimates of the assurance for each iteration are obtained by a call to routine FCT discussed in Section 4.2.4.4.

4.2.4.4 Routine FCT

Routine FCT is used by subprogram MUELLR to calculate the value of the function at the value $x$, in order to find the desired assurance level. The function is written so as to find the zero

$$f = F(x) - A$$

where $F(x)$ is the cumulative distribution function for a Gamma variate and $A$ is the desired assurance level. Routine MUELLR is discussed in Section 4.2.4.3.

4.2.4.5 Routine TRMNAT

Subprogram TRMNAT performs the premature termination of the program when the program has detected a fatal error during execution.
START

INITIALIZE VARIABLES
I = -1, F = 0.0

DO I = 1
TO NUMBER OF TERMS NS

FB = \exp(- \ln \left(I(1 + \alpha + l)\ldots\right))
(Equation 4-2)

\left|\frac{FB}{F}\right| \leq \text{PSI} \\
TRUE \quad \text{RETURN}

FALSE

F = F + FB

RETURN

Figure 4-28 Flowchart for Subprogram GAMMA
Section 4.3
Bayesian Statistical Procedure Software

4.3.1 Introduction

This section presents a description of the computer program that implements the Bayesian procedure described in Section 2.1.1. The program is described below in detail using a flowchart. The user's guide for running this program is given in Section 6.5, and the complete source listing, including a definition of key variables, is given in Section 7.5. A glossary of standard flowchart symbols is given for the reader's benefit in Appendix 5.A.

4.3.2 BAYES Program

The Bayesian statistical procedure of Section 2.1.1 is implemented as the FORTRAN program BAYES. This program is used to combine operating experience with the prior failure distribution obtained from probabilistic failure modeling. The flowchart for the BAYES program is given in Figure 4-29. The program starts by opening the following input and output files:

<table>
<thead>
<tr>
<th>NAME</th>
<th>TYPE</th>
<th>CONTENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAYESD</td>
<td>Input</td>
<td>Prior failure distribution parameters and operating experience</td>
</tr>
<tr>
<td>BAYESO</td>
<td>Output</td>
<td>Echo of input data and results of analysis</td>
</tr>
<tr>
<td>UBAYES</td>
<td>Output</td>
<td>Posterior failure distribution parameters</td>
</tr>
</tbody>
</table>

The array for storing the operating experience is initialized and the input data is read from the BAYESD file. The parameters of the posterior failure distribution \( \alpha' \) and \( \theta' \) are calculated by means of Equation 2-2, using the parameters of the prior failure distribution and the operating experience. Then B-lives\(^{30} \) for both the prior and the posterior failure distributions are calculated using Equation 2-6. The parameters of the posterior failure distribution \( \beta, \theta', \) and \( \alpha' \) are written on file UBAYES. Finally, an echo of the input information, the posterior distribution, and the calculated B-lives are written to file BAYESO.

---

\(^{30}\) A B-life is the value of the failure parameter (e.g., time) at a failure probability specified as a percent: e.g., B.1 is the failure time at a probability of 0.001 or 0.1%.
Figure 4-29 Flowchart for the Bayesian Statistical Procedure
Program BAYES

START

OPEN BAYESD, BAYESO, AND UBAYES

INITIALIZE ARRAY

READ INPUT DATA

CALCULATE $\alpha'$ AND $\theta'$

$\alpha' = \alpha + s$

$\theta' = \theta + \sum_{i=1}^{n} t_i \beta$

(Equation 2-2)

CALCULATE BLIVES

WRITE POSTERIOR DISTRIBUTION PARAMETERS $\beta$, $\theta'$, $\alpha'$
TO FILE UBAYES

WRITE RESULTS AND ECHO INPUT TO FILE BAYESO

STOP
Section 4.4
Random Number Generation Software

4.4.1 Introduction
This section presents a description of the random number generation routines mentioned throughout Sections 4, 5, and 7. The complete source listings, including the definitions of key variables, are given in Section 7.6.

4.4.2 RANDOM Routine
The Uniform(0,1) random number generation is implemented as the FORTRAN routine RANDOM. The random variates are generated using the Linear Congruential Algorithm described in [1].

4.4.3 NORMGN Routine
The Normal(μ, σ²) random number generation is implemented as the FORTRAN routine NORMGN. The random variates are generated using the “Direct Method,” Abramowitz and Stegun [2], pg. 953.

4.4.4 GAM Routine
The Gamma(α) random number generation is implemented as the FORTRAN routine GAM. The random variates are generated using an “Acceptance/Rejection Method,” Fishman [3].

4.4.5 BETAGN Routine
The Beta(x; a, b, ρ, θ) random number generation is implemented as the FORTRAN routine BETAGN. A standard Beta random variate is defined by

\[ y = \frac{X_1}{X_1 + X_2} \]

where \( X_1 \sim \text{Gamma}(\alpha) \) and \( X_2 \sim \text{Gamma}(\beta) \) are independently distributed, Johnson and Kotz [4], pp.181-182.

\[ g(y) = y^{\alpha - 1} (1 - y)^{\beta - 1} \frac{\Gamma(\alpha + \beta)}{\Gamma(\alpha) \Gamma(\beta)} \quad 0 \leq y \leq 1 \]

That standard Beta distribution can be related to the Beta distribution we use, Equation 2-54.
\[ f(x) = \frac{(x - a)^\rho (b - x)^\theta (1 - \rho)^\theta}{(b - a)^\theta + 1} \frac{\Gamma(\theta + 2)}{(\rho \theta + 1) \Gamma((1 - \rho) \theta + 1)} \]

\[ a \leq x \leq b \quad 0 \leq \rho \leq 1 \quad \theta \geq 0 \]

by the transformations
\[ X = a + (b - a) Y \]
\[ \alpha = \rho \theta + 1 \]
\[ \beta = (1 - \rho) \theta + 1 \]

### 4.4.6 WEIBGN Routine

The Weibull(\(\beta, \eta\)) random number generation is implemented as the FORTRAN routine WEIBGN. This Weibull distribution is implemented with the median constrained to be 1, which implies dependence between \(\eta\) and \(\beta\) given by

\[ 1 = \eta (\ln 2)^{1/\beta} \]

A Weibull random variate is obtained with the "Inverse Transformation Method" by solving the Weibull cumulative distribution function for \(N\), where \(F(N)\) is treated as a Uniform(0,1) variate

\[ F(N) = 1 - \exp \left[ - \left( \frac{N}{\eta} \right)^\beta \right]. \]
Section 4.5
Reference Time History Generation Software

4.5.1 Introduction

This section presents a description of the computer program that was used to generate the reference time histories which are required as inputs to the HCF computer codes described in Section 5.1 in order to construct the stress-time histories used in the HCF analyses. Since each stress-time history component (random or sinusoidal) is a scalar multiple of a corresponding reference time history component, we have used a computer code that has the capability to compute stress-time history components with all scale factors set to one in order to generate reference time history components. The pertinent methodology is given in Section 2.1.4. The program is described in detail using a flowchart. The random variate generators are described in Section 4.4. The user's guide for running this program is given in Section 6.6, and a list of subprograms, a definition of key variables, and the complete source listing are given in Section 7.7. A glossary of standard flowchart symbols is given for the reader's benefit in Appendix 5.A.

4.5.2 NBSIN Program

The reference time history generation is implemented using the stress-time history generation FORTRAN program NBSIN. The flowchart for the NBSIN program is given in Figure 4-30. The program uses the following input and output files:

<table>
<thead>
<tr>
<th>NAME</th>
<th>TYPE</th>
<th>CONTENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>NBSIN</td>
<td>Input</td>
<td>Generation parameters</td>
</tr>
<tr>
<td>IOUTPR</td>
<td>Output</td>
<td>Intermediate calculations</td>
</tr>
<tr>
<td>User-Specified</td>
<td>Output</td>
<td>Narrow-band and sinusoidal time histories</td>
</tr>
</tbody>
</table>

The input data is read from the NBSIN file; the angular frequencies and phase angles are calculated for the sinusoidal reference time histories, then file NBSIN is closed. The time increment and the parameters for each of the narrow-band reference time histories to be generated are subsequently calculated.

Generation of the narrow-band reference time histories begins by initializing the AR(1) process.\(^{31}\) Two independent draws from the N(0, 1) distribution are obtained by calling subroutine NORMGN for each set of loads in a given direction. Since NBSIN has the ability to compute stress-time history components, the Normal variates can be transformed to N(0, \(\sigma_{Nk}^2\)) variates; however, for reference time histories the

\(^{31}\) The AR(1) process is described in Section 2.1.4.
START

OPEN NBSIN AND IOUTPR

READ INPUT DATA

CALCULATE ANGULAR FREQUENCIES $\omega_c_j$ AND PHASE ANGLES $\varphi_j$ FOR SINUSOIDS

CLOSE NBSIN

CALCULATE TIME INCREMENT $\Delta t$

$$\Delta t = \frac{1}{N_f} \quad (Eq. 2-60)$$

CALCULATE NARROW-BAND PARAMETERS

$$\rho_k = \exp \left[ -\frac{2\pi \xi f_{ok}}{N_f} \right]$$

$$\sigma_{ck} = \sigma_{sk} = \sigma_N (1 - \rho_k^2)^{1/2} \quad (Eq. 2-60)$$

$$\omega_{ok} = 2\pi f_{ok} \quad k = 1, \ldots, R$$

NORMGN

INITIALIZE NARROW-BAND PROCESSES

$$Z_{11}, Z_{12}, Z_{21}, Z_{22}, Z_{31}, Z_{32}, Z_{41}, Z_{42} \sim N(0,1)$$

Figure 4-30 Flowchart for the Time History Generation Program

NBSIN

4 - 90
TRANSFORM VARIATES

\[ k = 1, ..., k_1 \]
\[ N_c(t_{-1}) = s_{nk} Z_{11}, N_s(t_{-1}) = s_{nk} Z_{12} \]
\[ k = (k_1 + 1), ..., (k_1 + k_2) \]
\[ N_c(t_{-1}) = s_{nk} Z_{21}, N_s(t_{-1}) = s_{nk} Z_{22} \]
\[ k = (k_1 + k_2 + 1), ..., (k_1 + k_2 + k_3) \]
\[ N_c(t_{-1}) = s_{nk} Z_{31}, N_s(t_{-1}) = s_{nk} Z_{32} \]
\[ k = (k_1 + k_2 + k_3 + 1), ..., (k_1 + k_2 + k_3 + k_4) = R \]
\[ N_c(t_{-1}) = s_{nk} Z_{41}, N_s(t_{-1}) = s_{nk} Z_{42} \]

OPEN FILES FOR NARROW-BAND HISTORY STORAGE

INCREMENT TIME STEP

\[ t_i = t_{i-1} + \Delta t \]

NORMGN

OBTAIN

\[ Z_{11}, Z_{12}, Z_{21}, Z_{22}, Z_{31}, Z_{32}, Z_{41}, Z_{42} \sim N(0,1) \]

TRANSFORM VARIATES

\[ k = 1, ..., k_1 \]
\[ U_{ck}(t_i) = s_{ck} Z_{11}, U_{sk}(t_i) = s_{sk} Z_{12} \]
\[ k = (k_1 + 1), ..., (k_1 + k_2) \]
\[ U_{ck}(t_i) = s_{ck} Z_{21}, U_{sk}(t_i) = s_{sk} Z_{22} \]
\[ k = (k_1 + k_2 + 1), ..., (k_1 + k_2 + k_3) \]
\[ U_{ck}(t_i) = s_{ck} Z_{31}, U_{sk}(t_i) = s_{sk} Z_{32} \]
\[ k = (k_1 + k_2 + k_3 + 1), ..., (k_1 + k_2 + k_3 + k_4) = R \]
\[ U_{ck}(t_i) = s_{ck} Z_{41}, U_{sk}(t_i) = s_{sk} Z_{42} \]

Figure 4-30 Flowchart for the Time History Generation Program

NBSIN (Cont'd)
CALCULATE COSINE AND SINE COMPONENTS OF NARROW-BAND PROCESSES

\[ N_{ck}(t_i) = \rho_k N_{ck}(t_{i-1}) + u_{ck}(t_i) \quad \text{(Eq. 2-60)} \]

\[ N_{sk}(t_i) = \rho_k N_{sk}(t_{i-1}) + u_{sk}(t_i) \quad k = 1, \ldots, R \]

CALCULATE NARROW-BAND PROCESSES

\[ N_k(t_i) = N_{ck}(t_i) \cos \omega_{ok} t_i + N_{sk}(t_i) \sin \omega_{ok} t_i \quad \text{(Eq. 2-57)} \]

CLIP PEAKS AT USER-SPECIFIED LEVELS

WRITE \( N_k(t_i) \) TO HISTORY STORAGE FILES

TRUE

\[ t_i < T \]

CLOSE NARROW-BAND HISTORY STORAGE FILES

FALSE

Figure 4-30 Flowchart for the Time History Generation Program
NBSIN (Cont'd)
OPEN FILES FOR SINUSOIDAL HISTORY STORAGE

CALCULATE SINUSOIDAL PROCESSES

\[ S_j(t_i) = A_j \cos(\omega_j t_i + \varphi_j + \psi) \]

WRITE \( S_j(t_i) \) TO HISTORY STORAGE FILES

TRUE

\( t_i < T \)

FALSE

STOP

Figure 4-30 Flowchart for the Time History Generation Program
NBSIN (Cont'd)
transformation is an identity transformation, so $\sigma_{NK}^2 = 1$ is required. After initialization of the AR(1) process, the files for the narrow-band reference time history storage are opened.

The narrow-band reference time history is generated by obtaining two independent $N(0, 1)$ random variates from NORMGN for each set of loads in a given direction, transforming them to pairs of $N(0, \sigma_{ck}^2)$ random variates, and then calculating the cosine and sine components $N_{ck}(t_i)$ and $N_{sk}(t_i)$, respectively. The narrow-band reference time histories $N_k(t_i)$ are then obtained using Equation 2-57. NBSIN provides the option to clip peaks at a user-specified level in order to limit them to finite bounds. Finally, the values of $N_k(t_i)$ are written to their corresponding storage files. When all the narrow-band reference time histories have been generated and written to their files, the files are closed.

The sinusoidal reference time histories are generated next. The reference time history storage files are opened, then the sinusoids $S_k(t_i)$ are calculated at the same times as the narrow-band processes and written to their corresponding storage files.
References


5.0 Fatigue Analysis Software
Section 5.1
High Cycle Fatigue Analysis Software

5.1.1 Introduction

The codes for analyzing the HPOTP main discharge duct, the LPFTP turbine drive duct, and the HPOTP HEX coil small tube outlet are described here. The pertinent HCF methodology is given in Section 2.2.1. A list of subroutines and the key variables along with the complete source listing are given in Section 7.1. The relevant user’s guides for running these codes are given in Section 6.1.

Figure 2-18 shows a general schematic for the HCF analysis. Two stand-alone programs, namely the DCTHCF and HEXHCF, were developed for the HCF analyses. The DCTHCF has the capability for analyzing elbow ducts with welds and was used for the study of the main discharge duct and the turbine drive duct. HEXHCF can analyze straight ducts with welds having large temperature differences across the duct wall. The HEXHCF program was used for analyzing the HEX coil. From the description given below, it will become clear to the reader that both of these programs share many subroutines, including the S/N materials characterization modules. The reason for developing them as separate programs is to demonstrate the probabilistic fatigue analysis methodology using efficient software for specific case studies.

The two programs are described here by the use of algorithmic flowcharts. A glossary of standard flowchart symbols is given for the reader’s benefit in Appendix 5.A. The overall layout of the programs is described using the main flowcharts. Reference is made in the main flowcharts to other secondary flowcharts which describe subprograms. Flowcharts for the input, output, and driver transformation subprograms are given here. However, the subprograms related to materials characterization and general purpose probability distribution routines are described in Section 4.1 and Section 4.4, respectively.

When describing FORTRAN statements that relate to the equations given in the methodology section, a one-to-one correspondence is established in most cases. Equation numbers are given in parentheses where applicable. A single equation may result in several FORTRAN statements. Sometimes this is done for reasons of efficiency. Also, the codes have been written to exploit vector processing.
5.1.2 DCTHCF Program

The HCF analyses of the HPOTP main discharge duct and the LPFTP turbine drive duct are implemented as the FORTRAN program DCTHCF. Figure 5-1 shows the structure of the Probabilistic Failure Model (PFM) for the ducts. This section provides the description and flowcharts for program DCTHCF.

5.1.2.1 Main Routine

The main flowchart for the DCTHCF program is given in Figure 5-2. The program starts by opening the input and output files. They are:

<table>
<thead>
<tr>
<th>NAME</th>
<th>TYPE</th>
<th>CONTENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>DCTHCD</td>
<td>Input</td>
<td>Analysis data</td>
</tr>
<tr>
<td>DCTHCO</td>
<td>Output</td>
<td>Input data echo, results</td>
</tr>
<tr>
<td>RELATD</td>
<td>Input</td>
<td>Related material data input</td>
</tr>
<tr>
<td>RELATO</td>
<td>Output</td>
<td>Echo of information in RELATD</td>
</tr>
<tr>
<td>DUMP</td>
<td>Output</td>
<td>Results of materials characterization calculations</td>
</tr>
<tr>
<td>IOUTPR</td>
<td>Output</td>
<td>Run information and user-requested information</td>
</tr>
<tr>
<td>LOWUF</td>
<td>Output</td>
<td>First one percent of sorted fatigue lives</td>
</tr>
<tr>
<td>User-Specified</td>
<td>Input</td>
<td>Random and sinusoidal reference time histories</td>
</tr>
</tbody>
</table>

The arrays and variables are then set to their default or initial values. The input data is read from the DCTHCD file. An echo of the input data is written onto DCTHCO. The related materials data is read from the file RELATD and processed in the INFAGG routine. INFAGG controls the materials information aggregation and is described in Section 4.1.3.

The selection of hyperparameters\(^2\) is performed in the outer DO loop of the simulation. This includes calling the RANDOM and PRYRV subroutines to set up the \(p\) and \(\theta\) parameters for drivers with Beta distributions. The PAREST routine controls the calculations for estimating the parameters for the S/N model. Routine PAREST is described in Section 4.1.5. Materials process variation may be included in the S/N model on request.

The inner DO loop for the simulation performs the driver draws. Drivers are selected by calling BETAGN, NORMGN and PRYRV, which draw from Beta, Normal, and Uniform distributions, respectively. The region-dependent S/N curve is calculated by scaling the median S/N curve with a random draw from a Weibull distribution by using WEIBGN. The general purpose probability distribution subroutines RANDOM, BETAGN, NORMGN, WEIBGN, and PRYRV are described in Sections 4.4 and 7.6.

---

1 Files RELATD and RELATO are opened in INFAGG.
2 Hyperparameters are discussed in Section 2.1.1.
Figure 5-1 Structure of the Probabilistic Failure Model for the Elbow Ducts with Welds
START
OPEN INPUT AND OUTPUT FILES
INITIALIZE ARRAYS AND SET DEFAULTS
READ AND ECHO INPUT DATA
INFAGG
PERFORM MATERIALS INFORMATION AGGREGATION
(See Section 4.1.3)
DO J ← 1
TO NYPHER BY 1 OUTER LOOP
RANDOM, PRYRV
OBTAIN ($\rho$, $\theta$) AND ($\mu$, $\sigma$) PAIRS FOR DISTRIBUTION
SELECTION OF INNER LOOP CALCULATIONS
(See Sections 4.4.2 and 7.6.6)
PAREST
PERFORM MATERIALS PARAMETER ESTIMATION
(See Section 4.1.5)
OPTIONAL
SELECT MATERIALS PROCESS VARIATION

Figure 5-2 Main Flowchart for the Duct Analysis Program
DCTHCF
Figure 5-2 Main Flowchart for the Duct Analysis Program
DCTHCF (Cont'd)
The routine ELWELD performs the driver transformation and calculates the fatigue life. The flowchart for ELWELD is given in Figure 5-3 and the routine is described below.

Once a fatigue life is calculated in ELWELD, it is sorted and saved in a list containing the lowest fifty percent of the lives. The INSORT routine performs an insertion sort with the new fatigue life. When the two simulation DO loops are completed, a list of lives representing the left-hand tail of the failure distribution is written to the file LOWLIF.

Finally, if truncated Normal variation was used for the materials shape parameter \( m \), an empirical median S/N curve may be calculated on request. The routine SORTM is called to sort the \( m \) values and routine EXPCTD calculates the median S/N curve. Section 4.1.10 and 4.1.3.12 describe the routines SORTM and EXPCTD, respectively.

### 5.1.2.2 ELWELD Routine

The flowchart for the ELWELD routine is given in Figure 5-3. The routine essentially controls the calls to the stress and fatigue life calculation routines based on the critical location. The routine NARBN1 calculates the fatigue life and is described below. The stress magnitudes are calculated for the different locations by calling the following routines.

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>POSITION</th>
<th>ROUTINE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Exterior Surface</td>
<td>M2L1</td>
</tr>
<tr>
<td>2</td>
<td>Interior Surface</td>
<td>M2L2</td>
</tr>
</tbody>
</table>

Both stress routines are called when fatigue life is calculated for both locations and a critical location is identified as the one having the lowest life.

### 5.1.2.3 M2L1 Routine

The stress influence coefficients for the critical location on the exterior surface and the outer bend of the elbow are calculated within M2L1. The coefficients vary for the different locations but the layout for routine M2L2 is similar to M2L1. Hence, only M2L1 is described.

The flowchart for the M2L1 routine is given in Figure 5-4. First, the stress concentration factor \( K_{off} \) due to weld offset is calculated by using Equation 2-73. The equation numbers referenced here are contained in the HCF methodology Section 2.2.1.3. The elbow effects are given by Equations 2-74 through 2-80. The stress increase due to the torus effect \( \beta \) is calculated by using Equation 2-79. Equation 2-80 gives the decay rate \( Q_T \) for the torus effect. Then the ovality stress effect coefficients \( \gamma_{iy}, \gamma_{cz}, \gamma_{ly}, \) and \( \gamma_{oy} \) of Equations 2-74 through 2-77 and the associated decay rate \( Q_o \) of Equation 2-78 are calculated. Finally, routine CALCS is called to obtain the stress magnitudes.
STRESS TERM CALCULATIONS FOR LOCATION 1
(See Figure 5-4)

CALCULATE COMPOSITE STRESS TIME HISTORY AND FATIGUE LIFE
(See Figure 5-6)

STRESS TERM CALCULATIONS FOR LOCATION 2
(Similar to M2L1)

CALCULATE COMPOSITE STRESS TIME HISTORY AND FATIGUE LIFE
(See Figure 5-6)

Figure 5-3 Flowchart for the Subprogram ELWELD
START

CALCULATE STRESS CONCENTRATION FACTOR DUE TO ECCENTRICITY OF THE WELD

\[ K_{off} = \lambda_{off} (1 + 3F_k W_{off}) \]  (Eq. 2-73)

CALCULATE THE STRESS INCREASE DUE TO TORUS EFFECT

\[ \beta = 1 + Q_T [\beta' - 1] \]  (Eq. 2-79)
\[ \beta' = \frac{2 R_B + R_m \sin \phi}{2 (R_B + R_m \sin \phi)} \]
\[ Q_T = 1 - \frac{W_D}{R_m} \]  (Eq. 2-80)

CALCULATE THE STRESS INCREASE DUE TO OVALITY EFFECT

\[ \gamma_{iz} = \lambda_{oval} [\sin \phi + Q_o (C_{iz} \gamma_{iz}' - \sin \phi)] \]  (Eq. 2-74)
\[ \gamma_{cz} = \lambda_{oval} Q_o C_{cz} \gamma_{cz}' \]  (Eq. 2-75)
\[ \gamma_{iy} = \lambda_{oval} [\cos \phi + Q_o (C_{iy} \gamma_{iy}' - \cos \phi)] \]  (Eq. 2-76)
\[ \gamma_{cy} = \lambda_{oval} Q_o C_{cy} \gamma_{cy}' \]  (Eq. 2-77)
\[ Q_o = 1 - \frac{W_D}{4R_m} \]  (Eq. 2-78)

CALCS

CALCULATE THE STRESSES
(See Figure 5-5)

RETURN

Figure 5-4  Flowchart for the Subprogram M2L1
5.1.2.4 CALCS Routine

Figure 5-5 gives the flowchart for the CALCS routine. Equations 2-68, 2-69, 2-71 and 2-72 are used to derive the four stress components. The input to this routine includes the coefficients $\gamma_{lz}$, $\gamma_{cz}$, $\gamma_{ly}$, $\gamma_{cy}$, and the angular position $\phi$. Also, radius $R$ in the stress equations is equal to $R_i$ for the interior surface and $R_o$ for the exterior surface. First, the static stress components are calculated. The ducts had no external pressure or thermal gradient. Thus, both $p_o$ and $\sigma_{TH}$ are zero in Equations 2-68, 2-69, 2-70, and 2-71. Next, the non-time-varying stress magnitudes are calculated for each dynamic load component. The dynamic stresses are not affected by static internal pressure, external pressure, and temperature difference across the wall.

5.1.2.5 NARBN1 Routine

The flowchart for the NARBN1 routine is given in Figure 5-6. The composite stress history, which is a summation of the static, random and sinusoidal loads, is derived in this routine. First, the static stresses are assigned to the four stress component histories. Then, the reference time histories for each load component are scaled by the non-time-varying dynamic stress magnitudes and added to the stress time history components, as given by Equation 2-82. Next, the four stress components are collapsed to a single equivalent von Mises stress by using Equation 2-84. The resulting equivalent stress history is assigned the algebraic sign of the maximum principal stress (in this case the axial stress). Finally, the RAINF1 routine is called. This routine performs a rainflow cycle count and derives the fatigue life.

5.1.2.6 RAINF1 Routine

The flowchart for RAINF1 is given in Figure 5-7. First, the equivalent stress history is scanned to identify the largest stress and its location. The history is resequenced such that the largest stress is placed at the beginning and end of the stress array. Then, the intermediate points in the history are filtered leaving only the peaks and troughs. This is done by testing for a sign change in the gradients of adjacent segments. Next, the counting of the cycles begins. Consecutive peaks and troughs are added to a holding array, each time checking whether the new peak-trough segment is greater than the previous one; if so, then a cycle has been closed. Then, the peak and trough corresponding to the closed cycle are removed from the holding array. The cycle is saved if it is large enough, i.e., larger than a user-specified threshold. The procedure is repeated by adding new peaks and troughs to the holding array until another cycle is identified.

Once all the cycles have been identified, the alternating and mean values of each stress cycle are calculated. An equivalent mean stress is calculated for the entire history based on the mean of the biggest cycle. The routine PGETSM, described below, is called to estimate the mean stress. The alternating stresses for each cycle are adjusted to equivalent zero-mean stresses using the Goodman relation given by
CALCULATE STATIC STRESSES

\[ \sigma_{ST1} = K_{T1} K_{OFF} \left( \frac{P_{ST} A}{A} + \gamma_{H} \frac{M_{STR}}{l} \right) \quad \text{(Eq. 2-68)} \]

\[ \sigma_{ST2} = K_{T2} \left( \beta \left( \frac{R_i^2 (R_o^2 + R_i^2)}{R^2 (R_o^2 - R_i^2)} \right) \right) \quad \text{(Eq. 2-69)} \]

\[ \sigma_{ST3} = - \rho_i \quad \text{(Eq. 2-71)} \]

\[ \sigma_{ST4} = \frac{M_{STR}}{2 l} \quad \text{(Eq. 2-72)} \]

DO I = 1 TO NUMBER OF LOAD COMPONENTS NLOAD

CALCULATE NON-TIME-VARYING DYNAMIC STRESSES

\[ \sigma_{D1i} = K_{T1} K_{OFF} \left( \frac{P_{i} A}{A} + \gamma_{H} \left( \frac{M_{i} R}{l} \right) \right) \quad \text{(Eq. 2-68)} \]

\[ \sigma_{D2i} = K_{T2} \left( \gamma_{CY} \left( \frac{M_{i} R}{l} \right) \right) \quad \text{(Eq. 2-69)} \]

\[ \sigma_{D3i} = 0.0 \quad \text{(Eq. 2-71)} \]

\[ \sigma_{D4i} = \frac{M_{i} R}{2 l} \quad \text{(Eq. 2-72)} \]

RETURN

Figure 5-5 Flowchart for the Subprogram CALCS
START

DO J = 1 TO NUMBER OF REFERENCE TIME HISTORY POINTS M

ASSIGN THE STATIC STRESSES
\[ \sigma_{jk} = \sigma_{STk} \quad (k = 1,2,3,4) \]

DO I = 1 TO NUMBER OF LOAD COMPONENTS NLOAD

DO J = 1 TO NUMBER OF REFERENCE TIME HISTORY POINT M

SCALE THE REFERENCE HISTORIES
\[ \sigma_{jk} = \sigma_{jk} + \sigma_{Dki} \cdot \sigma_{ij} \quad (Eq. 2-82) \]
\[ (k = 1,2,3,4) \]

A

Figure 5-6 Flowchart for the Subprogram NARBN1

5 - 13
Figure 5-6  Flowchart for the Subprogram NARB1 (Cont'd)
Figure 5-7  Flowchart for Subprogram RAINF1

START

DO I = 1 TO NUMBER OF STRESS HISTORY POINTS M BY 1

\( \sigma_{\text{effmax}} \leq \sigma_{\text{effi}} \)

TRUE

RECORD THE LARGEST \( \sigma_{\text{eff}} \) AND ITS LOCATION

\( \sigma_{\text{effmax}} = \sigma_{\text{effi}} \)

JMAX = 1

DO I = 1 TO (M - JMAX + 1) BY 1

J = JMAX - 1 + 1

\( \sigma_{P_i} = \sigma_{\text{effi}} \)

DO I = (M - JMAX + 2) TO M BY 1

STOP
Figure 5-7 Flowchart for Subprogram RAINF1 (Cont'd)
TOTAL NUMBER OF POINTS IN ARRAY

NEWTOT = K + 1
INDEX_NEWTOT = M + 1

DO I ← 1
TO NEWTOT BY 1

SET UP THE PEAK- TROUGH ARRAY
K = INDEX
σ_i = σ_{F_k}

INITIALIZE COUNTERS
I = 0, J = 0, K = 0

INCREMENT COUNTERS
J = J + 1
K = K + 1

J > NEWTOT
TRUE
FALSE

Figure 5-7 Flowchart for Subprogram RAINF1 (Cont'd)
COPY STRESS POINTS TO A HOLDING ARRAY

\[ E_k = \sigma_j \]

\[ K < 3 \]

\[ |E_k - E_{k-1}| < |E_{k-1} - E_{k-2}| \]

\[ |E_{k-1} - E_{k-2}| > \text{TRUNC} \]

SINCE CYCLE IS LARGE ENOUGH TO SAVE

\[ I = I + 1 \]

\[ \sigma_{\text{eff 1}} = \max [E_{k-1}, E_{k-2}] \]

\[ \sigma_{\text{eff 2}} = \min [E_{k-1}, E_{k-2}] \]

DISCARD POINTS K-1 AND K-2 AND DECREMENT THE COUNTER

\[ E_{k-2} = E_k \]

\[ K = K - 2 \]

*Figure 5-7 Flowchart for Subprogram RAINF1 (Cont'd)*
RECORD THE FINAL NUMBER OF CYCLES FOUND

\[ N = I \]

DO I = 1

to number of cycles N by 1

\[ \sigma_{ALT_i} = \frac{(\sigma_{eff_1} - \sigma_{eff_2})}{2.0} \]  
(Eq. 2-85)

\[ \sigma_{MEAN_i} = \frac{(\sigma_{eff_1} - \sigma_{eff_2})}{2.0} \]  
(Eq. 2-86)

SM = PGETSM

CALCULATE EQUIVALENT MEAN STRESS  
(See Figure 5-8)

DO I = 1

to number of cycles N by 1

CALCULATE THE EQUIVALENT STRESS USING GOODMAN RELATION

\[ \sigma_i = \frac{\sigma_{ALT_i}}{\left(1 - \frac{SM}{\sigma_{ULT}}\right)} \]  
(Eq. 2-90)

DO I = 1

to number of cycles N by 1

Figure 5-7 Flowchart for Subprogram RAINF1 (Cont'd)
LIFE\(_i\) = GTLIFE

CALCULATE THE FATIGUE LIFE FROM THE S/N CURVE (See Section 4.1.8)

\[ \text{INVU} F_i = \frac{1}{\text{UFE}} \]

DO I \(\rightarrow\) 1

TO NUMBER OF CYCLES N BY 1

INVERT THE LIFE

DO I \(\rightarrow\) 1

TO NUMBER OF CYCLES N BY 1

SUM THE DAMAGE FRACTIONS

SUMDAM = SUMDAM + INVLI\(_F_i\)

RAINF1 = PERIOD/SUMDAM

RETURN

Figure 5-7 Flowchart for Subprogram RAINF1 (Cont'd)
Equation 2-90. The life corresponding to each stress cycle is obtained from the S/N curve by calling the GTLIFE routine. The GTLIFE routine is described under materials characterization in Section 4.1.8. Miner's rule is used to accumulate the damage due to each cycle. There are four separate DO loops over the number of cycles in the last four steps starting with the Goodman transformation. This was done to enable vectorization of the DO loops. For running on a scalar machine, these four steps may be embedded within a single DO loop.

5.1.2.7 PGETSM Routine

The flowchart for PGETSM is given in Figure 5-8. An elastic-perfectly-plastic stress vs. strain behavior is assumed here for the material. First, the total stress is calculated by summing the alternating and mean stress of the largest cycle. This stress is checked against the yield stress. Three different cases occur, as given by Equation 2-87. If the total stress is below yield, then the mean stress is unchanged. If it is above the yield stress, then the adjusted mean stress is the yield stress minus the alternating stress. If the alternating stress alone is larger than the yield stress, then the mean stress is set to zero.

5.1.3 HEXHCPC Program

The HCF analysis of the HPOTP heat exchanger (HEX) coil small tube outlet is implemented as the FORTRAN program HEXHCPC. Figure 5-9 shows the structure of the Probabilistic Failure Model (PFM) for the coil. This section provides the description and flowcharts for program HEXHCPC:

5.1.3.1 Main Routine

The main flowchart for the HEXHCPC program is given in Figure 5-10. The program starts by opening the input and output files. They are:

<table>
<thead>
<tr>
<th>NAME</th>
<th>TYPE</th>
<th>CONTENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>HEXHCD</td>
<td>Input</td>
<td>Analysis data</td>
</tr>
<tr>
<td>HEXHCO</td>
<td>Output</td>
<td>Input data echo, results</td>
</tr>
<tr>
<td>RELATD</td>
<td>Input</td>
<td>Related material data input</td>
</tr>
<tr>
<td>RELATO</td>
<td>Output</td>
<td>Echo of information in RELATD</td>
</tr>
<tr>
<td>DUMP</td>
<td>Output</td>
<td>Results of materials characterization calculations</td>
</tr>
<tr>
<td>IOUTPR</td>
<td>Output</td>
<td>Run information and user-requested information</td>
</tr>
<tr>
<td>LOWLF</td>
<td>Output</td>
<td>First one percent of sorted fatigue lives</td>
</tr>
<tr>
<td>User-Specified</td>
<td>Input</td>
<td>Random and sinusoidal reference time histories</td>
</tr>
</tbody>
</table>

The arrays and variables are then set to their default or initial values. The input data is read from the HEXHCD file. An echo of the input data is written onto HEXHCO. The related materials data is read from the file RELATD and processed in the INFAGG.

---

3 Files RELATD and RELATO are opened in INFAGG.
CALCULATE THE TOTAL STRESS

\[ \sigma_T = K_T (\sigma_{ALT} + \sigma_{MEAN}) \]

\[ \sigma_T > \sigma_y \]

ELASTIC CASE
\[ PGETSM = \sigma_{MEAN} \]

FALSE

PLASTIC CASE
\[ \sigma_x = K_T \cdot \sigma_{ALT} \]

\[ \sigma_x > \sigma_y \]

FALSE
\[ PGETSM = \sigma_y - \sigma_x \]

TRUE
\[ PGETSM = 0 \]

RETURN

Figure 5-8 Flowchart for Subprogram PGETSM
Figure 5-9  Structure of the Probabilistic Failure Model for Straight Ducts with Welds and Temperature Differences Across the Wall
I OPEN INPUT AND OUTPUT RLES
I INITIAU ARRAYS AND SET DEFAULTS
READ AND ECHO INPUT DATA

INFAGG
PERFORM MATERIALS INFORMATION AGGREGATION
(See Section 4.1.3)

DO J ← 1 TO NYPHER BY 1 OUTER LOOP

RANDOM, PRYRV
OBTAIN (ρ, θ) AND (μ, σ) PAIRS FOR DISTRIBUTION
SELECTION OF INNER LOOP CALCULATIONS
(See Sections 4.4.2 and 7.6.6)

PAREST
PERFORM MATERIALS PARAMETER ESTIMATION
(See Section 4.1.5)

OPTIONAL
SELECT MATERIALS PROCESS VARIATION

Figure 5-10 Main Flowchart for the HEX Coil Analysis Program
HEXHC1F
Figure 5-10 Main Flowchart for the HEX Coil Analysis Program
HEXHCF (Cont'd)
routine. INFAGG controls the materials information aggregation and is described in Section 4.1.3.

The selection of hyperparameters\(^4\) is performed in the outer DO loop for the simulation. This includes calling the RANDOM and PRYRV subroutines to set up the \(\rho\) and \(\theta\) parameters for drivers with Beta distributions. The PAREST routine controls the calculations for estimating the parameters for the S/N model. Routine PAREST is described in Section 4.1.5. Materials process variation may be included in the S/N model on request.

The inner DO loop for the simulation performs the driver draws. Drivers are selected by calling BETAGN, NORMGN and PRYRV, which draw from Beta, Normal, and Uniform distributions, respectively. The region-dependent S/N curve is calculated by scaling the median S/N curve with a random draw from a Weibull distribution by using WEIBGN. The general purpose probability distribution subroutines RANDOM, BETAGN, NORMGN, WEIBGN, and PRYRV are described in Sections 4.4 and 7.6.

The routine THWELD performs the driver transformation and calculates the fatigue life. The flowchart for THWELD is given in Figure 5-11 and the routine is described below.

Once a fatigue life is calculated in THWELD, it is sorted and saved in a list containing the lowest fifty percent of the lives. The INSORT routine performs an insertion sort with the new fatigue life. When the two simulation DO loops are completed, a list of lives representing the left-hand tail of the failure distribution is written to the file LOWLIF.

Finally, if truncated Normal variation was used for the materials shape parameter \(m\), an empirical median S/N curve may be calculated on request. The routine SORTM is called to sort the \(m\) values and the routine EXPCTD calculates the median S/N curve. Sections 4.1.10 and 4.1.3.12 describe the routines SORTM and EXPCTD, respectively.

5.1.3.2 THWELD Routine

The flowchart for the THWELD routine is given in Figure 5-11. The routine essentially controls the calls to the stress and fatigue life calculation routines, based on the critical location. The routine NARBN2 calculates the fatigue life and is described below. The stress magnitudes are calculated for the different locations by calling the following routines.

\(^4\) Hyperparameters are discussed in Section 2.1.1.
START

LOCATION IS EXTERIOR SURFACE

TRUE

M4L1
STRESS TERM CALCULATIONS FOR LOCATION 1
(See Figure 5-12)

NARBN2
CALCULATE COMPOSITE STRESS TIME HISTORY AND FATIGUE LIFE
(See Figure 5-13)

FALSE

LOCATION IS INTERIOR SURFACE

TRUE

M4L2
STRESS TERM CALCULATIONS FOR LOCATION 2
(Similar to M4L1)

NARBN2
CALCULATE COMPOSITE STRESS TIME HISTORY AND FATIGUE LIFE
(See Figure 5-13)

FALSE

RETURN

Figure 5-11 Flowchart for Subprogram THWELD
M4L1 and M4L2 routines are called when fatigue life is calculated for both locations and a critical location is identified as the one associated with the lowest life.

5.1.3.3 M4L1 Routine
The flowchart for the M4L1 routine is given in *Figure 5-12*. This contains stress component calculations for the exterior surface. The routine M4L2 is similar to M4L1, and it calculates the stresses for the internal surface. First, the stress concentration factor $K_{off}$ due to weld offset is calculated by using *Equation 2-73*. Then, *Equations 2-68* through *2-72* are used to calculate the four stress components. These stress equations are for a general elbow case. The HEX was treated as a straight cylinder and the coefficients $\gamma_x = \sin \phi$, $\gamma_y = \cos \phi$, $\gamma_c = \gamma_y = 0$, and $\beta = 1$ and the equations reduce to the standard pressure vessel case. For the exterior surface, the radius $R$ is set to $R_o$.

First, the static stress components are calculated. Then, the non-time-varying stress magnitudes are calculated for each dynamic load component. The dynamic stresses are not affected by static internal pressure $p_i$, external pressure $p_o$, and temperature difference $\Delta T$.

5.1.3.4 NARBN2 Routine
The flowchart for the NARBN2 routine is given in *Figure 5-13*. The composite stress history, which is a summation of the static, random, sinusoidal and aerodynamic loads, is derived in this routine. First, the static stresses are assigned to the four stress component histories. Then, the reference time histories for each load component are scaled by the non-time-varying dynamic stress magnitudes and added to the stress time history components as given by *Equation 2-82*. Next, the four stress components are collapsed to a single equivalent von Mises stress by using *Equation 2-84*. The resulting equivalent stress history is assigned the algebraic sign of the maximum principal stress (in this case, the axial stress). Finally, the RAINF2 routine is called. This routine performs a rainflow cycle count and derives the fatigue life.

The NARBN2 routine performs the same calculations as the NARBN1 routine employed in DCTHCF. The only difference between the two is that RAINF1 is called by NARBN1 for the rainflow counting and fatigue life derivation.

5.1.3.5 RAINF2 Routine
The flowchart for RAINF2 is given in *Figure 5-14*. First, the equivalent stress history is scanned to identify the largest stress and its location. The history is resequenced such that the largest stress is placed at the beginning and end of the stress array.
CALCULATE STRESS CONCENTRATION FACTOR DUE TO ECCENTRICITY OF THE WELD

\[ K_{off} = \lambda_{off} (1 + 3F_k W_{off}) \]  
(Eq. 2-73)

CALCULATE STATIC STRESSES

\[ \sigma_{ST1} = K_{T1} K_{off} \left[ \frac{P_{ST}}{A} + \frac{M_{ST} R_0}{l} \sin \theta \right] \]  
(Eq. 2-68)

\[ \sigma_{ST2} = K_{T2} \left[ \frac{2 P_I R_1^2}{R_0^2 - R_1^2} - P_o \left( \frac{R_0^2 + R_1^2}{(R_0^2 - R_1^2)} \right) \right] \]  
(Eq. 2-69)

\[ \sigma_{ST3} = P_o \]  
(Eq. 2-71)

\[ \sigma_{ST4} = \frac{M_{ST} R_0}{2 l} \]  
(Eq. 2-72)

DO I ← 1

TO NUMBER OF LOAD COMPONENTS NLOAD

CALCULATE NON-TIME-VARYING DYNAMIC STRESSES

\[ \overline{\sigma_{D1i}} = K_{T1} K_{off} \left[ \frac{P_i}{A} + \frac{M_i R_0}{l} \sin \theta \right] \]  
(Eq. 2-68)

\[ \overline{\sigma_{D2i}} = 0.0 \]  
(Eq. 2-69)

\[ \overline{\sigma_{D3i}} = 0.0 \]  
(Eq. 2-71)

\[ \overline{\sigma_{D4i}} = \frac{M_i R_0}{2 l} \]  
(Eq. 2-72)

RETURN

Figure 5-12 Flowchart for Subprogram M4L1
Figure 5-13 Flowchart for the Subprogram NARBN2
DO J ← 1
TO NUMBER OF REFERENCE
TIME HISTORY POINTS M

CALCULATE VON MISES EFFECTIVE
STRESS AND ASSIGN IT THE ALGEBRAIC
SIGN OF THE MAXIMUM PRINCIPAL STRESS

\[ \sigma_j = \frac{\sigma_{11}}{|\sigma_{11}|} \sqrt{(\sigma_{11} - \sigma_{12})^2 + \ldots} \]  
(Eq. 2-84)

FATLIFE = RAINF2

PERFORM RAINFLOW COUNTING AND
CALCULATE FATIGUE LIFE
(See Figure 5-14)

RETURN

Figure 5-13 Flowchart for Subprogram NARBN2 (Cont'd)
To number of stress history points $M$ by 1

$\sigma_{\text{eff,max}} < \sigma_{\text{eff,i}}$

True

Record the largest $\sigma_{\text{eff}}$ and its location

$\sigma_{\text{eff,max}} = \sigma_{\text{eff,i}}$

$J_{\text{MAX}} = 1$

Do $I = 1$

To $(M - J_{\text{MAX}} + 1)$ by 1

$J = J_{\text{MAX}} - 1 + 1$

$\sigma_{P,I} = \sigma_{\text{eff,i}}$

Do $I = (M - J_{\text{MAX}} + 2)$

To $M$ by 1

Figure 5-14 Flowchart for Subprogram RAINF2
Figure 5-14 Flowchart for Subprogram RAINF2 (Cont'd)
TOTAL NUMBER OF POINTS IN ARRAY

\[ \text{NEWTOT} = K + 1 \]
\[ \text{INDEX}_{\text{NEWTOT}} = M + 1 \]

DO \( I \leftarrow 1 \) TO NEWTOT BY 1

SET UP THE PEAK-TRough ARRAY

\[ K = \text{INDEX}_I \]
\[ \sigma_i = \sigma_p \]

INITIALIZE COUNTERS

\( I = 0, J = 0, K = 0 \)

INCREMENT COUNTERS

\( J = J + 1 \)
\( K = K + 1 \)

\( J > \text{NEWTOT} \)

TRUE

FALSE

Figure 5-14 Flowchart for Subprogram RAINF2 (Cont'd)

5 - 34
COPY STRESS POINTS TO A HOLDING ARRAY

\[ E_k = \sigma_j \]

\( K < 3 \)

\( |E_k - E_{k-1}| < |E_{k-1} - E_{k-2}| \)

\( |E_{k-1} - E_{k-2}| > \text{TRUNC} \)

SINCE CYCLE IS LARGE ENOUGH TO SAVE

\[ I = I + 1 \]

\[ \sigma_{\text{eff } 1_i} = \max \{E_{k-1}, E_{k-2}\} \]

\[ \sigma_{\text{eff } 2_i} = \min \{E_{k-1}, E_{k-2}\} \]

DISCARD POINTS K-1 AND K-2 AND DECREMENT THE COUNTER

\[ E_{k-2} = E_k \]

\[ K = K - 2 \]

Figure 5-14 Flowchart for Subprogram RAINF2 (Cont'd)
RECORD THE FINAL NUMBER OF CYCLES FOUND

\[ N = 1 \]

**DO** \( i = 1 \) TO NUMBER OF CYCLES \( N \) BY 1

\[
\sigma_{\text{ALT}_i} = \frac{\sigma_{\text{eff}_1} - \sigma_{\text{eff}_2}}{2.0} \quad \text{(Eq. 2-85)}
\]

\[
\sigma_{\text{MEAN}_i} = \frac{\sigma_{\text{eff}_1} + \sigma_{\text{eff}_2}}{2.0} \quad \text{(Eq. 2-86)}
\]

SM = NEUBER

CALCULATE EQUIVALENT MEAN STRESS

(See Figure 5-15)

**DO** \( i = 1 \) TO NUMBER OF CYCLES \( N \) BY 1

CALCULATE THE EQUIVALENT STRESS USING GOODMAN RELATION

\[
\sigma_i = \frac{\frac{\sigma_{\text{ALT}_i}}{\sigma_{\text{MEAN}_i}}}{1 - \frac{\sigma_{\text{MEAN}_i}}{\sigma_{\text{ULT}}}} \quad \text{(Eq. 2-90)}
\]

**DO** \( i = 1 \) TO NUMBER OF CYCLES \( N \) BY 1

Figure 5-14 Flowchart for Subprogram RAINF2 (Cont’d)
CALCULATE THE FATIGUE LIFE FROM THE S/N CURVE (See Section 4.1.8)

DO I = 1
TO NUMBER OF CYCLES N BY 1

INVERT THE LIFE

\[ \text{INVLIF}_i = \frac{1}{\text{LIFE}_i} \]

DO I = 1
TO NUMBER OF CYCLES N BY 1

SUM THE DAMAGE FRACTIONS

\[ \text{SUMDAM} = \text{SUMDAM} + \text{INVLIF}_i \]

RAINF2 = PERIOD/SUMDAM

RETURN

Figure 5-14 Flowchart for Subprogram RAINF2 (Cont'd)
Then, the intermediate points in the history are filtered leaving only the peaks and troughs. This is done by testing for a sign change in the gradients of adjacent segments. Next, the counting of the cycles begins. Consecutive peaks and troughs are added to a holding array, each time checking whether the new peak-trough segment is greater than the previous one; if so, then a cycle has been closed. Then, the peak and trough corresponding to the closed cycle are removed from the holding array. The cycle is saved if it is large enough, i.e., larger than a user-specified threshold. The procedure is repeated by adding new peaks and troughs to the holding array until another cycle is identified.

Once all the cycles have been identified, the alternating and mean values of each stress cycle are calculated. An equivalent mean stress is calculated for the entire history based on the mean of the biggest cycle. The routine NEUBER, described below, is called to estimate the equivalent mean stress. The alternating stresses for each cycle are adjusted to equivalent zero-mean stresses by using the Goodman relation given by Equation 2-90. The life corresponding to each stress cycle is obtained from the S/N curve by calling the GTLIFE routine. The GTLIFE routine is described under materials characterization in Section 4.1.8. Miner's rule is used to accumulate the damage due to each cycle. There are four separate DO loops over the number of cycles in the last four steps, starting with the Goodman transformation. This was done to enable vectorization of the DO loops. For running on a scalar machine, these four steps may be embedded within a single DO loop.

The RAINF2 performs the same calculations as RAINF1, which is used in DCTHCF. The only difference is that RAINF1 calls PGETSM and RAINF2 calls NEUBER for the equivalent mean stress calculation.

5.1.3.6 NEUBER Routine

The flowchart for NEUBER is given in Figure 5-15. The total stress is calculated by summing the mean stress and the alternating stress with the algebraic sign of the mean applied to the latter. The stress-strain product is calculated next. The goal is to find the intersection of the stress vs. strain curve to the hyperbola, given by Equation 2-88, which represents the constant stress-strain product. First, the product is checked as to whether it is in the elastic region; if so, then the stress is unchanged. Otherwise, the intersection of the stress vs. strain curve with the hyperbola is determined by checking through the segments of the curve. The intersection defines the desired Neuber stress value. The new mean stress is the Neuber stress minus the alternating stress, as given by Equation 2-89.
ASSIGN THE ALGEBRAIC SIGN OF THE STRESS TO THE MEAN

\[ \text{NEUBER} = \frac{\text{TEMP}}{\sigma} \cdot \sigma_{\text{ALT}} \]

Figure 5-15 Flowchart for Subprogram NEUBER
Section 5.2
Low Cycle Fatigue Analysis Software

5.2.1 Introduction

This section presents a description of the computer program which implements the LCF analysis discussed in Section 2.2.2.2. The code for analyzing the ATD-HPFTP second stage turbine disk is described here. The overall layout of the program is described by using a main flowchart that refers to other flowcharts, which describe subprograms and key portions of the main program in greater detail. The materials characterization subprograms and those subprograms that are of a generic nature, such as the random variate generators, are described in Section 4.1 and Section 4.4, respectively. The relevant user's guide for running this code is given in Section 6.2, and a list of subprograms, a definition of key variables, and the complete source code listing are given in Section 7.2. A glossary of standard flowchart symbols is given for the reader's benefit in Appendix 5.A.

5.2.2 TRBPWA Program

The LCF analysis of the ATD-HPFTP second stage turbine disk is implemented as the FORTRAN program TRBPWA. Figure 5-16 shows the structure of the Probabilistic Failure Model (PFM) for the disk. This section provides the description and flowcharts for program TRBPWA.

5.2.2.1 Main Routine

The main flowchart for the TRBPWA program is given in Figure 5-17. The program starts by opening the following input and output files:

<table>
<thead>
<tr>
<th>NAME</th>
<th>TYPE</th>
<th>CONTENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRBPWD</td>
<td>Input</td>
<td>Analysis data</td>
</tr>
<tr>
<td>TRBPWO</td>
<td>Output</td>
<td>Input data echo, results</td>
</tr>
<tr>
<td>RELATD</td>
<td>Input</td>
<td>Related material data input</td>
</tr>
<tr>
<td>RELATO</td>
<td>Output</td>
<td>Echo of information in RELATD</td>
</tr>
<tr>
<td>DUMP</td>
<td>Output</td>
<td>Results of materials characterization calculations</td>
</tr>
<tr>
<td>IOUTPR</td>
<td>Output</td>
<td>Run information and user-requested information</td>
</tr>
<tr>
<td>LOWLIF</td>
<td>Output</td>
<td>First one percent of sorted fatigue lives</td>
</tr>
</tbody>
</table>

The arrays and variables are then set to their default or initial values. The input data is read from the TRBPWD file. An echo of the input data is written onto TRBPWO. The related material S/N information is read from the file RELATD and processed in

---

5 Files RELATD and RELATO are opened in INFAGG.
Figure 5-16 Structure of the Probabilistic Failure Model for the ATD-HPFTP Second Stage Turbine Disk
START

READ AND ECHO INPUT DATA

INFAGG
PERFORM MATERIALS INFORMATION AGGREGATION
(See Section 4.1.3)

INITIALIZE ARRAYS AND SET DEFAULTS

DO J ← 1
TO NHYPER BY 1 OUTER LOOP

RANDOM, PRYRV
CHOOSE ΔT, REGIME AND DISTRIBUTION
(See Sections 4.4.2 & 7.6.6)

PAREST
PERFORM MATERIALS PARAMETER ESTIMATION
(See Section 4.1.5)

OPTIONAL
IF MATERIALS PROCESS VARIATION WAS USED
SELECT MATERIALS HEAT
(See Section 4.1.5)

DO I ← 1
TO NLIFE BY 1 INNER LOOP

NORMGN, BETAGN, PRYRV
DRIVER SELECTION FOR
ω, ΔT, λK, λK
(See Sections 4.4.3, 4.4.5 & 7.6.6)

Figure 5-17 Main Flowchart for the ATD Disk LCF Analysis Program TRBPWA
Figure 5-17 Main Flowchart for the ATD Disk LCF Analysis Program TRBPWA (Cont'd)
the INFAGG routine. INFAGG controls the materials information aggregation and is described in Section 4.1.3.

The selection of hyperparameters\(^6\) is performed in the outer DO loop of the simulation by calling the RANDOM and PRYRV routines to obtain the Beta distribution parameters \(\rho\) and \(\theta\) for \(\Delta T\); it is the only driver whose probability distribution is described by Beta distributions. The PAREST routine controls the calculations for estimating the parameters for the S/N model. Routine PAREST is described in Section 4.1.5. If materials process variation is included, the materials parameter \(Z\) in Equation 2-48 is selected by calling the NORMGN routine and then transforming the resulting Normal variate to a Lognormal variate.

The inner DO loop for the simulation performs the driver selection. The drivers \(\omega\), \(\Delta T\), \(K\), and \(\lambda\) are selected by calling NORMGN, BETAGN, and PRYRV, which draw from Normal, Beta, and Uniform distributions, respectively. The random variate routines RANDOM, BETAGN, NORMGN, and PRYRV are described in Sections 4.4 and 7.6.

In the symmetry DO loop, the materials model parameter \(\phi\) is found from the minimum of 50 draws of a Weibull distribution. Calls to WEIBGN provide the 50 values of \(\phi\). Subroutine WEIBGN is described in Sections 4.4.6.

When all the S/N model parameters have been selected for the region with S/N data, the S/N curve is tied to the tensile point \(S_o\) by routine KOMO. The driver transformation, discussed in Section 5.2.2.2, is then performed. The result of the driver transformation is the reference stress \(S_R\) used by subprogram GTLIFE to calculate a fatigue life by using the randomly selected S/N curve. Subprograms KOMO and GTLIFE are described in Sections 4.1.6 and 4.1.8, respectively.

The fatigue lives are arranged in ascending order in a list containing the lowest fifty percent of the lives. The INSORT routine performs an insertion sort with each new fatigue life. When the outer DO loop is completed, the list of lives representing the left-hand tail of the failure distribution is written to file LOWLIFE. Subprogram INSORT is described in Appendix 5.B.

If a truncated Normal distribution was used for the materials shape parameter \(m\), the empirical median S/N curve will be calculated upon user request. The routine SORTM is called to sort the values of \(m\) and the routine EXPCTD calculates the median

---

\(^6\) Hyperparameters are discussed in Section 2.1.1.
S/N curve. Sections 4.1.10 and 4.1.3.12 describe the routines SORTM and EXPCTD, respectively.

5.2.2.2 Driver Transformation

The flowchart for the driver transformation discussed in Section 2.2.2.2 is given in Figure 5-18. The driver transformation is performed in several steps. The first step is to calculate $C_s, \lambda_m$ and $\lambda_G$ by using the parametric relationships of Equations 2.94 through 2.98 and the values of $\omega$ and $\Delta T_f$. Then $C_s, \lambda_m, \lambda_G$; the nominal stresses $S_{Mo}, S_m, S_G$; and the model accuracy factors $\lambda_K$ and $\lambda_{K'}$ are combined by using Equation 2-103. The result is the reference stress $S_R$ for the single-cycle stress history, which is then used in the low cycle fatigue life calculation.
CALCULATE THE SPEED VARIABILITY CORRECTION FACTOR
\[ C_s = \left(\frac{\omega}{\omega_0}\right)^2 \]  
(Eq. 2-94)

CALCULATE THE DEVIATION FROM NOMINAL METAL TEMPERATURE
\[ \Delta T_m = C_{mf} \Delta T_f \]  
(Eq. 2-95)

CALCULATE THE SENSITIVITY OF STRESS TO METAL TEMPERATURE VARIATION
\[ \lambda_m = 1 + C_m \frac{\Delta T_m}{S_m} \]  
(Eq. 2-97)

CALCULATE THE DEVIATION FROM NOMINAL THERMAL GRADIENT
\[ \Delta T_f < 0 \]

\[ \Delta G_T = C_{G1} \Delta T_f \]  
(Eq. 2-96)

\[ \Delta G_T = C_{G2} \Delta T_f \]  
(Eq. 2-96)

CALCULATE THE SENSITIVITY OF STRESS TO THERMAL GRADIENT VARIATION
\[ \lambda_G = 1 + C_G \frac{\Delta G_T}{S_{G_0}} \]  
(Eq. 2-98)

CALCULATE THE REFERENCE STRESS
\[ S_R = \lambda_{K_d} \lambda_{K} \left[ C_S S_{M_0} + \lambda_m S_{M_0} + \lambda_G S_{G_0} \right] K_d / K_t \]  
(Eq. 2-103)

Figure 5-18 Flowchart of Driver Transformation
Appendix 5.A
Program Flowchart Symbols

The symbols employed in the flowcharts are given in Figure 5-19.

**Figure 5-19 Program Flowchart Symbols**
Appendix 5.B
INSORT Routine

The flowchart for the FORTRAN routine INSORT is given in Figure 5-20. The routine performs an insertion sort on the failure times provided by the Probabilistic Failure Models (PFMs). Only the lowest fifty percent of the failure times are saved.

![Flowchart for Subprogram INSORT](image)

**Figure 5-20 Flowchart for Subprogram INSORT**
Figure 5-20 Flowchart for Subprogram INSORT (Cont'd)
6.0 Software User’s Documentation
Section 6.1
High Cycle Fatigue Analysis User’s Guides

The user’s guides for running the two high cycle fatigue (HCF) analysis codes DCTHCF and HEXHCF are given here. The HCF methodology is discussed in Section 2.2.1, the program descriptions and flowcharts are presented in Section 5.1, and the code structures and listings are provided in Section 7.1.

6.1.1 DCTHCF Program

The DCTHCF program was used to analyze high cycle fatigue failure of the HPOTP main discharge duct and the LPFTP turbine drive duct. The dynamic load input for the program consists of narrow-band and sinusoidal reference time histories. These reference time histories are generated using the program NBSIN. The output of DCTHCF includes the simulated B-lives and a list of the lowest one percent of lives. The list of lives may be used as input to the regression programs of Section 4.2 to compute the parameters of the Bayesian prior failure distribution. This prior distribution and success/failure data are used as input to the Bayesian updating program BAYES to obtain a posterior failure distribution.

6.1.2 How To Use Program DCTHCF

The program DCTHCF is intended to be run in batch (i.e., background) mode. DCTHCF requires two input data files: DCTHCD and RELATD. The materials characterization model portion of the program requires both files for all runs, even when no related S/N data is used. DCTHCF also uses a set of load data files containing the reference time histories. The names of the load data files must be defined by the user. The file DCTHCD contains the analysis control parameters, driver distributions, engineering analysis parameters, and specific and exogenous materials information. The file RELATD contains the related materials information. A complete description of the input data for the DCTHCD and RELATD data files is given in Section 6.1.3.

The results from the DCTHCF program are written to five output files: DCTHCO, RELATO, DUMP, IOUTPR, and LOWLIF. DCTHCO contains the echo of the information in DCTHCD, the results of any stress ratio transformations performed on specific materials data, and the results of the simulation. RELATO contains the echo of the information in RELATD and the results of any stress ratio transformations performed on related materials data. The results of the materials characterization calculations are primarily given in DUMP. These calculations include point and interval estimates for S/N curve parameters m and C, posterior credibility ranges for m, and an estimate of the median S/N curve. File IOUTPR contains an echo of the analysis parameters and, if requested, a dump of intermediate calculations. If the program terminates
prematurely, an error message will be printed in the IOUTPR file. A list of error messages and possible remedies for the problems is given in Section 6.1.6. LOWLIF contains the first one percent of the lives of the simulated failure distribution.

6.1.3 Description of Input Data Files

Annotated examples of the complete data file format structure for DCTHCD and RELATD are presented in Figures 6-1 and 6-2, respectively. The data lines of the input files are given in boxes, with a description of each data line located adjacent to each box. The specific input parameters of Figures 6-1 and 6-2 are individually defined in Sections 6.1.3.1 and 6.1.3.2. Input parameter values given in Figures 6-1 and 6-2 are not necessarily those used in the application case studies of Section 3.1.

The input data is read by free format statements from files DCTHCD and RELATD. Thus, the numbers may be provided sequentially on a line up to 80 characters in length, with each number separated by a blank character or comma. Each number may also be on a separate line in the file. However, it is recommended that the input format suggested in Figures 6-1 and 6-2 be followed whenever possible.

6.1.3.1 Input File DCTHCD

The required data for the DCTHCD file is divided into the four blocks shown in Figure 6-3: analysis parameters, driver information, load and geometry, and materials information. The analysis parameters block contains the analysis parameters and the keys to select the program options. The driver information block contains the parameters that define the driver distributions. The number of dynamic loads, the magnitudes of the dynamic loads, the load file names, the static loads, and duct geometry are given in the load and geometry block. The materials information block contains the specific material S/N data, including the yield and ultimate strengths, stress ratio, the S/N data points, life region boundaries, and materials characterization model parameter constraints.

The input parameters are described below by using the following convention: the input variable names are indicated by BOLD UPPERCASE letters; the variable types are specified as character [CHR], integer [INT], real [RE], and double precision real [DRE]; the function of the variable is underlined and followed by a description and a list of options, when appropriate; the program and file names are indicated by UPPERCASE letters. A consistent set of units is given in parentheses for specifying dimension, load, and stress input parameters. All character strings must be enclosed by 'single quotes'. The user is reminded about the difference between the number "0" and the letter "O" when preparing the input files.
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<td>Outer loop size</td>
<td>2</td>
<td>Type of S/N variation</td>
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</table>

Decimal equivalent of percentages for B-lives

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Weld offset two Beta distribution information

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Outer diameter weld axial stress concentration factor Beta distribution information

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Inner diameter weld axial stress concentration factor Beta distribution information

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Outer diameter geometric axial stress concentration factor Beta distribution information

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<td>10.</td>
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<td>In-plane circumferential stress carryover factor</td>
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<td></td>
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<td></td>
<td>Number of dynamic loads</td>
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Figure 6-1 Format for File DCTHCD
Static loads: \( P, M_x, M_y, M_z, V_x, V_z \)

<table>
<thead>
<tr>
<th>Value</th>
<th>Value</th>
<th>Value</th>
<th>Value</th>
<th>Value</th>
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Dynamic loads: file name, load type, \( P, M_x, M_y, M_z, V_x, V_z \)

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<th>Load Type</th>
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<th>( M_x )</th>
<th>( M_y )</th>
<th>( M_z )</th>
<th>( V_x )</th>
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<td>1.88731</td>
<td>3.002265</td>
<td>8.618995</td>
<td>13.910155</td>
<td>0.829459</td>
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<tr>
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<td>12.6415</td>
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<td>4.07806</td>
</tr>
</tbody>
</table>

1. Inner wall limit pressure, \( P_i \)
2. Elbow bend radius, \( R_B \)
3. Weld distance from the elbow tangency line, \( W_D \)
4. Inside diameter, \( D_i \)
5. Minimum wall thickness, outer diameter, \( t_w_1 \)
6. Wall thickness at bend, inner diameter, \( t_w_2 \)
7. Young's modulus of elasticity, \( E \)
8. Critical duct location
9. Angular position about the duct circumference, \( \phi \)
10. Reference time history period, \( T \)
11. Noise filter
12. Number of points in reference time history

**Figure 6-1** Format for File DCTHCD (Cont'd)
<table>
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<tr>
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<tr>
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<td>12.50</td>
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<tr>
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<tr>
<td>0.993</td>
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<tr>
<td>1.029</td>
<td>24.00</td>
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<tr>
<td>1.053</td>
<td>30.00</td>
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<tr>
<td>1.053</td>
<td>200.00</td>
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</tbody>
</table>

The ten points of the piecewise linear $F_k$ vs. $R/t$ curve

Description of specific material S/N data set

'320 HOURGLASS + STRAIGHT'

Specific materials information: yield and ultimate strengths, number of data divisions, and total number of points in data set

```
178600. 220400. 1 20
```

Specific materials information for each data division: number of points in data division, stress ratio, and life region

```
20 0.05 1
```
<table>
<thead>
<tr>
<th>Life Boundary Constraint</th>
<th>Stress Tensile Point</th>
<th>Number of life regions with and without data</th>
<th>C constraint</th>
<th>Prior Information on m</th>
</tr>
</thead>
<tbody>
<tr>
<td>150000. 65000.</td>
<td>$S_1, N_1$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>140000. 261000.</td>
<td>$S_2, N_2$</td>
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<td></td>
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</tr>
<tr>
<td>120000. 265000.</td>
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<tr>
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<tr>
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<tr>
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<tr>
<td>105000. 5053000.</td>
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<tr>
<td>92000. 9210000.</td>
<td>$S_9, N_9$</td>
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<td></td>
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</tr>
<tr>
<td>95000. 9667000.</td>
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<tr>
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</tr>
<tr>
<td>0.00</td>
<td>2 3.596 5.874</td>
<td>Stress tensile point</td>
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Bayesian prior distribution information

Materials process variation information

Figure 6-1 Format for File DCTHCD (Cont'd)
Number of related data sets

“TITANIUM, -423F, 0.14 Fe” Description of related material S/N data set

Related materials information: yield and ultimate strengths, number of data divisions, and total number of points in data set

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>201700.</td>
<td>215300.</td>
<td>2 10</td>
</tr>
</tbody>
</table>

Related materials information for data division 1: number of points in data division, stress ratio, and life region

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
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<p>| | | |</p>
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</thead>
<tbody>
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<td>38000.</td>
<td>S1, N1</td>
</tr>
<tr>
<td>130000.</td>
<td>30000.</td>
<td>S2, N2</td>
</tr>
<tr>
<td>130000.</td>
<td>713000.</td>
<td>S3, N3</td>
</tr>
<tr>
<td>130000.</td>
<td>310000.</td>
<td>S4, N4</td>
</tr>
</tbody>
</table>

Number of points in division 2, stress ratio, region

<p>| | | |</p>
<table>
<thead>
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</tr>
</thead>
<tbody>
<tr>
<td>6</td>
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<p>| | | |</p>
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</thead>
<tbody>
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<td>3224000.</td>
<td>S6, N6</td>
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<tr>
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<td>910000.</td>
<td>S7, N7</td>
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<td>S8, N8</td>
</tr>
<tr>
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<td>665000.</td>
<td>S9, N9</td>
</tr>
<tr>
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<td>56000.</td>
<td>S10, N10</td>
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</tbody>
</table>

**Figure 6-2** Format for File RELATD

**Figure 6-3** Data Blocks for Input File
Analysis Parameters Block

RAND
[DRE]

Random number seed
Needed by DCTHCF's built-in random number generator.

IOUT
[INT]

Output dump controller
DCTHCF has the ability to write intermediate calculations to file IOUTPR. The following integer values control the "dump" of DCTHCF's calculations.

- IOUT = 0  no intermediate calculation output
- IOUT = 10 materials characterization model calculations
- IOUT = 15 driver sampling
- IOUT = 20 cycle counting and damage accumulation calculations
- IOUT = 25 stress analysis calculations

NLIFE
[INT]

Inner loop number
Size of the inner loop of the Monte Carlo (MC) simulation. A positive value is required.

NHYPHER
[INT]

Outer loop number
Size of the outer loop of the MC simulation. The program requires a positive value.

VARY
[INT]

Type of S/N variation
Controls the type of stochastic variation to be included in the materials characterization model S/N curve.

1 A discussion of the possible stochastic specifications of the materials model shape parameter $m$ is given in Pages 2-13 through 2-14.
VARY = 0  no variation will be included
VARY = 1  allows only intrinsic materials variation
VARY = 2  allows Uniform variation of the materials model shape parameter $m$
          and intrinsic materials variation
VARY = 3  allows truncated Normal variation of the materials model shape
          parameter $m$ and intrinsic materials variation

NMED  [INT]

Request for truncated Normal median S/N curve\(^2\)
If $\text{VARY} = 3$, then $\text{NMED}$ controls the calculation of the empirical median S/N curve.

- $\text{NMED} = 0$  no median curve calculation is required
- $\text{NMED} = 1$  median curve calculation is required

MPROC  [INT]

Controls materials process variation
Controls the inclusion of materials process variation (heat-to-heat variation). Process
variation in materials is discussed in Section 2.1.2.3.

- $\text{MPROC} = 0$  no variation to be included
- $\text{MPROC} = 1$  variation is to be included

NBLIFE  [INT]

Number of B-lives
The number of B-lives to be provided from the simulated distribution of life. A B-life
is the value of accumulated operating time to failure at a failure probability specified
as a percentage; e.g., B.1 is the failure time at a probability of 0.001 or 0.1%. $\text{NBLIFE}$
must be non-negative and cannot exceed 10.

\(^2\) The median S/N curve for the truncated Normal distribution is discussed on Page 2-15.
B-life percentages
The decimal equivalent of the percentages at which the B-lives are required; e.g., if the B.1 life is desired, then BLFPER = 0.001. A total of NBLIFE percentages must be provided. The percentage cannot exceed 50% (BLFPER ≤ 0.50).

Driver Information Block

<table>
<thead>
<tr>
<th>WEOFA</th>
<th>WEOFB</th>
<th>WEOFR1</th>
<th>WEOFR2</th>
<th>WEOFT1</th>
<th>WEOFT2</th>
</tr>
</thead>
<tbody>
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<td>[RE]</td>
<td>[RE]</td>
<td>[RE]</td>
<td>[RE]</td>
<td>[RE]</td>
</tr>
<tr>
<td>WEOFC</td>
<td>WEOFD</td>
<td>WEOFR3</td>
<td>WEOFR4</td>
<td>WEOFT3</td>
<td>WEOFT4</td>
</tr>
<tr>
<td>[RE]</td>
<td>[RE]</td>
<td>[RE]</td>
<td>[RE]</td>
<td>[RE]</td>
<td>[RE]</td>
</tr>
<tr>
<td>WEOFE</td>
<td>[RE]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Weld offset Beta distribution information
$W_{OFF}$ in Equation 2.73 is the weld offset and may be characterized by two Beta distributions. The first two lines are the two Beta distributions, one per line. See Section 2.1.3.1 and Equation 2.54 for defining parameters for setting up a Beta driver distribution. The first two parameters are the lower and upper bounds, respectively, for $W_{OFF}$. The next two parameters are the lower and upper bounds for the Uniform distribution on $\rho$. Similarly, the last two parameters describe the Uniform distribution on $\theta$. The third line is the decimal equivalent percentage weight for the first Beta distribution and must be between 0.00 and 1.00.

| WEOFA | $W_{OFF}$ lower bound of Beta distribution 1
| WEOFB | $W_{OFF}$ upper bound of Beta distribution 1
| WEOF1 | $\rho$ Uniform distribution lower bound of Beta distribution 1 of $W_{OFF}$
| WEOF2 | $\rho$ Uniform distribution upper bound of Beta distribution 1 of $W_{OFF}$
| WEOFT1 | $\theta$ Uniform distribution lower bound of Beta distribution 1 of $W_{OFF}$
| WEOFT2 | $\theta$ Uniform distribution upper bound of Beta distribution 1 of $W_{OFF}$
| WEOFC | $W_{OFF}$ lower bound of Beta distribution 2
| WEOF3 | $W_{OFF}$ upper bound of Beta distribution 2
| WEOF4 | $\rho$ Uniform distribution lower bound of Beta distribution 2 of $W_{OFF}$
| WEOF5 | $\rho$ Uniform distribution upper bound of Beta distribution 2 of $W_{OFF}$

6 - 12
The outer diameter weld axial stress concentration factor is characterized by a Beta distribution. See Section 2.1.3.1 and Equation 2-54 for defining parameters for setting up a Beta driver distribution. The first two parameters are the lower and upper bounds, respectively, for the outer diameter weld axial stress concentration factor. The next two parameters are the lower and upper bounds for the Uniform distribution on $\rho$. Similarly, the last two parameters describe the Uniform distribution on $\theta$. The outer diameter weld axial stress concentration factor is used to calculate $K_{T1}$ in Equation 2-68.

- Outer diameter weld axial stress concentration factor lower bound of Beta distribution
- Outer diameter weld axial stress concentration factor upper bound of Beta distribution
- Outer diameter weld axial stress concentration factor lower bound of outer diameter weld axial stress concentration factor
- Outer diameter weld axial stress concentration factor upper bound of outer diameter weld axial stress concentration factor
- Outer diameter weld axial stress concentration factor lower bound of outer diameter weld axial stress concentration factor
- Outer diameter weld axial stress concentration factor upper bound of outer diameter weld axial stress concentration factor

The inner diameter weld axial stress concentration factor is characterized by a Beta distribution. See Section 2.1.3.1 and Equation 2-54 for defining parameters for setting up a Beta driver distribution. The first two parameters are the lower and upper bounds, respectively, for the inner diameter weld axial stress concentration factor.
The next two parameters are the lower and upper bounds for the Uniform distribution on $\theta$. Similarly, the last two parameters describe the Uniform distribution on $\theta$. The inner diameter weld axial stress concentration factor is used to calculate $K_{T1}$ in Equation 2-68.

- **KWIDA** inner diameter weld axial stress concentration factor lower bound of Beta distribution
- **KWIDB** inner diameter weld axial stress concentration factor upper bound of Beta distribution
- **KWIDR1** $\rho$ Uniform distribution lower bound of Beta distribution of inner diameter weld axial stress concentration factor
- **KWIDR2** $\rho$ Uniform distribution upper bound of Beta distribution of inner diameter weld axial stress concentration factor
- **KWIDT1** $\theta$ Uniform distribution lower bound of Beta distribution of inner diameter weld axial stress concentration factor
- **KWIDT2** $\theta$ Uniform distribution upper bound of Beta distribution of inner diameter weld axial stress concentration factor

**Outer diameter geometric axial stress concentration factor Beta distribution information**

The outer diameter geometric axial stress concentration factor is characterized by a Beta distribution. See Section 2.1.3.1 and Equation 2-54 for defining parameters for setting up a Beta driver distribution. The first two parameters are the lower and upper bounds, respectively, for the outer diameter geometric axial stress concentration factor. The next two parameters are the lower and upper bounds for the Uniform distribution on $\rho$. Similarly, the last two parameters describe the Uniform distribution on $\theta$. The outer diameter geometric axial stress concentration factor is used to calculate $K_{T1}$ in Equation 2-68.

- **KGODA** outer diameter geometric axial stress concentration factor lower bound of Beta distribution
- **KGODB** outer diameter geometric axial stress concentration factor upper bound of Beta distribution
- **KGODR1** $\rho$ Uniform distribution lower bound of Beta distribution of outer diameter geometric axial stress concentration factor
- **KGODR2** $\rho$ Uniform distribution upper bound of Beta distribution of outer diameter geometric axial stress concentration factor
- **KGODT1** $\theta$ Uniform distribution lower bound of Beta distribution of outer diameter geometric axial stress concentration factor
- **KGODT2** $\theta$ Uniform distribution upper bound of Beta distribution of outer diameter geometric axial stress concentration factor

6 - 14
Uniform distribution upper bound of Beta distribution of outer diameter geometric axial stress concentration factor

Narrow-band random load scale factor distribution information
This line contains the parameters to define the narrow-band random load scale factor $\lambda_{D_{\text{random}}}$ in Equation 2-81. See Section 2.1.3.2 on load scale factors for a detailed description of the parameters $k$, coefficient of variation $C$, and strain gage factor $d$.

- **LAMNA**: lower bound of Uniform distribution of $k$ for the narrow-band random load scale factor
- **LAMNB**: upper bound of Uniform distribution of $k$ for the narrow-band random load scale factor
- **LAMNC**: coefficient of variation $C$ for the narrow-band random load scale factor
- **LAMND**: strain gage factor $d$ for the narrow-band random load scale factor

Sinusoidal load scale factor distribution information
This line contains the parameters to define the sinusoidal load scale factor $\lambda_{D_{\text{sinusoidal}}}$ in Equation 2-81. See Section 2.1.3.2 on load scale factors for a detailed description of the parameters $k$, coefficient of variation $C$, and strain gage factor $d$.

- **LAMSA**: lower bound of Uniform distribution of $k$ for the sinusoidal load scale factor
- **LAMSB**: upper bound of Uniform distribution of $k$ for the sinusoidal load scale factor
- **LAMSC**: coefficient of variation $C$ for the sinusoidal load scale factor
- **LAMSD**: strain gage factor $d$ for the sinusoidal load scale factor

Static load scale factor distribution information
This is the static load scale factor and it is characterized by a Uniform distribution.
Dynamic stress analysis accuracy factor Uniform distribution information $\lambda_{\text{DYN}_{str}}$ in Equation 2-81. This is the dynamic stress analysis accuracy factor and it is characterized by a Uniform distribution.

- **DSTRA**: Dynamic stress analysis accuracy factor Uniform distribution lower bound
- **DSTRB**: Dynamic stress analysis accuracy factor Uniform distribution upper bound

Static stress analysis accuracy factor Uniform distribution information $\lambda_{\text{ST}_{str}}$ in Equation 2-81. This is the static stress analysis accuracy factor and it is characterized by a Uniform distribution.

- **SSTRA**: Static stress analysis accuracy factor Uniform distribution lower bound
- **SSTRB**: Static stress analysis accuracy factor Uniform distribution upper bound

Stress carryover factors

The stress carryover factors $C_{lz}$, $C_{ly}$, $C_{cz}$, and $C_{cy}$ in Equations 2-74 through 2-77. They are characterized by Uniform distributions. The stress carryover factors are required to evaluate the stresses at the elbow-straight pipe junction, given the stresses on the elbow away from end-effects.

- **CLZA**: In-plane axial stress carryover factor $C_{lz}$ Uniform distribution lower bound
- **CLZB**: In-plane axial stress carryover factor $C_{lz}$ Uniform distribution upper bound
- **CLYA**: In-plane axial stress carryover factor $C_{lz}$ Uniform distribution lower bound
- **CLYB**: In-plane axial stress carryover factor $C_{lz}$ Uniform distribution upper bound
- **CCZA**: In-plane circumferential stress carryover factor $C_{cz}$ Uniform distribution lower bound
- **CCZB**: In-plane circumferential stress carryover factor $C_{cz}$ Uniform distribution upper bound
- **CCYA**: In-plane circumferential stress carryover factor $C_{cz}$ Uniform distribution lower bound
- **CCYB**: In-plane circumferential stress carryover factor $C_{cz}$ Uniform distribution upper bound
CLZB in-plane axial stress carryover factor \( C_{lx} \) Uniform distribution upper bound

CLYA out-of-plane axial stress carryover factor \( C_{ly} \) Uniform distribution lower bound

CLYB out-of-plane axial stress carryover factor \( C_{ly} \) Uniform distribution upper bound

CCZA in-plane circumferential stress carryover factor \( C_{cz} \) Uniform distribution lower bound

CCZB in-plane circumferential stress carryover factor \( C_{cz} \) Uniform distribution upper bound

CCYA out-of-plane circumferential stress carryover factor \( C_{cy} \) Uniform distribution lower bound

CCYB out-of-plane circumferential stress carryover factor \( C_{cy} \) Uniform distribution upper bound

**OVALA** OVALB
[RE] [RE]

Ovality effect analysis accuracy factor Uniform distribution information
\( \lambda_{oval} \) in Equations 2-74 through 2-77. This is the ovality effect analysis accuracy factor and it is characterized by a Uniform distribution.

OVALA \( \lambda_{oval} \) Uniform distribution lower bound

OVALB \( \lambda_{oval} \) Uniform distribution upper bound

**LAMWA** LAMWB
[RE] [RE]

Weld offset accuracy factor Uniform distribution information
\( \lambda_{off} \) in Equation 2-73. This is the weld offset eccentricity stress concentration accuracy factor and it is characterized by a Uniform distribution.

LAMWA \( \lambda_{off} \) Uniform distribution lower bound

LAMWB \( \lambda_{off} \) Uniform distribution upper bound

**GAMA** GAMB
[RE] [RE]
Damage accumulation model accuracy factor distribution information

This line contains the Uniform distribution bounds in loge space for the damage accumulation model accuracy factor \( \lambda_{dem} \) in Equation 2-91. See Section 2.2.1.4 for a discussion of the damage accumulation calculations.

- **GAMA**: lower bound of damage accumulation accuracy factor
- **GAMB**: upper bound of damage accumulation accuracy factor

Load and Geometry block

**NLOAD**

[Int]

Number of dynamic loads

Total number of dynamic or time-varying loads. **NLOAD** cannot exceed 16.

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<th>TSTAT</th>
<th>MSTAT(1)</th>
<th>MSTAT(2)</th>
<th>VSTAT(1)</th>
<th>VSTAT(2)</th>
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<td>[RE]</td>
<td>[RE]</td>
<td>[RE]</td>
<td>[RE]</td>
<td>[RE]</td>
</tr>
</tbody>
</table>

Static loads

This line contains the six beam-end force components due to static loads.

- **PSTAT**: \( P \) (lbs) in Equation 2-68, the static axial load component
- **TSTAT**: \( M_x \) (in.-lbs) in Equation 2-72, the static torsional load component
- **MSTAT(1)**: \( M_y \) (in.-lbs) in Equation 2-68, the static moment load component about the y axis
- **MSTAT(2)**: \( M_z \) (in.-lbs) in Equation 2-68, the static moment load component about the z axis
- **VSTAT(1)**: \( V_y \) (lbs) in Equation 2-72, the static shear load component along the y axis
- **VSTAT(2)**: \( V_z \) (lbs) in Equation 2-72, the static shear load component along the z axis

<table>
<thead>
<tr>
<th>LDNAME(I)</th>
<th>TYPE(I)</th>
<th>P(I)</th>
<th>T(I)</th>
<th>M(1,I)</th>
<th>M(2,I)</th>
<th>V(1,I)</th>
<th>V(2,I)</th>
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<td>[RE]</td>
<td>[RE]</td>
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<td>[RE]</td>
<td>[RE]</td>
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</tbody>
</table>

Dynamic loads

This line contains the dynamic load file names, load types, and the six components of the beam-end force magnitudes. A total of **NLOAD** lines must be specified (i.e., the value of I goes from 1 to **NLOAD**).
File names containing the reference time history for load I. The file name cannot be more than six characters long and must be enclosed by single quotes.

Load-type of load I, used to assign the appropriate load scale factor

\[ \text{TYPE}(I) = 1 \quad \text{Narrow-band random load} \]
\[ \text{TYPE}(I) = 2 \quad \text{Sinusoidal load} \]

\[ P(I) \quad \text{in Equation 2-68, the dynamic axial load magnitude for load I} \]

\[ T(I) \quad M_x \quad \text{(in.-lb) in Equation 2-72, the dynamic torsional load magnitude for load I} \]

\[ M(1,I) \quad M_y \quad \text{(in.-lb) in Equation 2-68, the dynamic moment load magnitude about the y axis for load I} \]

\[ M(2,I) \quad M_z \quad \text{(in.-lb) in Equation 2-68, the dynamic moment load magnitude about the z axis for load I} \]

\[ V(1,I) \quad V_y \quad \text{(lb) in Equation 2-72, the dynamic shear load magnitude along the y axis for load I} \]

\[ V(2,I) \quad V_z \quad \text{(lb) in Equation 2-72, the dynamic shear load magnitude along the z axis for load I} \]

Fatigue stress concentration factors

Inner diameter geometric axial and hoop fatigue stress concentration factors. The geometric axial stress concentration factors are used to calculate the total axial stress concentration factor, \( K_{T1} \) in Equation 2-68, by the multiplication of the geometric factors \( K_{GOD} \) and \( K_{GID} \), and the weld factors \( K_{WOD} \) and \( K_{WID} \), specified above.

\[ K_{GID} \quad \text{inner diameter axial geometric stress concentration factor} \]
\[ K_{T(2,1)} \quad \text{outer diameter hoop stress concentration factor} \]
\[ K_{T(2,2)} \quad \text{inner diameter hoop stress concentration factor} \]

Limit pressure

\[ p_i \quad \text{(psi) in Equation 2-68, the inner wall limit pressure} \]

BNRD

[RE]
Bend radius
\( R_B \) (in.) in Equation 2-74, the elbow bend radius.

**WEDS**
[RE]

Weld distance
\( W_D \) (in.) in Equation 2-78. This is the weld distance from the elbow tangency line.

**IDWE**
[RE]

Inside diameter
\( D_i \) (in.) the duct inside wall diameter is used to calculate \( R_i \) in Equation 2-68.

**MNWT**
[RE]

Minimum wall thickness
\( t_{w_1} \) (in.) the duct minimum wall thickness assumed to occur at the bend outer diameter is used to calculate \( t_m \) and other geometric quantities in Equations 2-68 through 2-80.

**WTID**
[RE]

Wall thickness at bend
\( t_{w_2} \) (in.) the duct wall thickness at the bend inner diameter is used to calculate \( t_m \) and other geometric quantities in Equations 2-68 through 2-80.

**EMOD**
[RE]

Elastic modulus
\( E \) (psi) in Equation 2-70. This is Young's modulus of elasticity for the component material.

**LOCAT**
[INT]

Critical location
Critical location of interest on the duct.

\[
\begin{align*}
\text{LOCAT} &= 1 \quad \text{outer wall} \\
\text{LOCAT} &= 2 \quad \text{inner wall}
\end{align*}
\]
ANGLE

Critical angle $\phi$ (degrees) in Equation 2-68. This is the angle measured counterclockwise from the Z-direction to the critical circumferential location of the duct.

PERIOD

Period $T$ (sec) in Equation 2-91. This is the period of the reference time histories, and it is required so that life may be provided in seconds.

TRUNC

Noise filter Value (psi) used to filter out the insignificant cycles in the composite stress-time history during rainflow cycle counting.

NRAN

Number of history points Number of points in the reference time history files for the dynamic loads. NRAN cannot exceed 24,000.

$F_k$ versus $R/t$ curve

$F_k$ versus $R/t$ points for each segment of the curve are used by Equation 2-73 in the weld offset eccentricity stress concentration calculations. A block of 10 segments must be provided (i.e., the value of $I$ goes from 1 to 10). Both $F_k$ and $R/T$ must be positive and increase with increasing $I$ (i.e., $I = 1$ is the lower bound of the first segment and $I = 10$ is the upper bound of the last segment).

$F_k(I)$ $F_k(R/t)$ value

$R/T(I)$ $R/t$ value
Materials Information Block

DESCRP(0)  
[CHR]

Description of specific material S/N data set  
Name and test environment for the specific material S/N data. This is a character string no more than 40 characters long, enclosed by single quotes.

FTY  FTU  NDIV  NPTS(0)  
[RE]  [RE]  [INT]  [INT]

Specific materials information  
Yield strength, ultimate strength, number of divisions of data, number of points in S/N data set. The data may be divided when they are assigned to a different life region or have different stress ratios. NPTS(0) cannot exceed fifty. The next two data sets have to be provided for each data division.

FTY  yield strength corresponding to the specific material data set (psi)  
FTU  ultimate strength corresponding to the specific material data set (psi)  
NDIV  number of data divisions for the specific material data set  
NPTS(0)  total number of points in the specific material S/N data set

NUM  RATIO  REG  
[INT]  [RE]  [INT]

Materials information for each data division of the specific S/N data set  
Number of points, stress ratio, and the life region of interest for each data division. This line must be provided for each data division.

NUM  number of S/N data points in the data division  
RATIO  stress ratio for the data in the data division  
REG  life region number to be assigned to the data in the data division

RAWSTR(1,0)  RAWNF(1,0)  
[RE]  [RE]
Specific material S/N data points
Stress versus fatigue life data points for each data division. A block of NUM lines must be specified (i.e., the value of I goes from 1 to NUM). This block must be provided for each data division.

RAWSTR(I,0) stress value (psi)
RAWNF(I,0)  fatigue life value (cycles)

SZERO
[RE]

Tensile point
Stress tensile point S₀ (psi). Must be non-negative. A value of zero indicates no tensile point. For HCF applications, this aspect of the materials model has been disabled, however, a value of SZERO must be provided.

NUMREG  NNODAT
[INT]   [INT]

Data regions
Number of life regions that are data-determined and not data-determined. NUMREG + NNODAT cannot exceed three. NUMREG must be 1, 2, or 3, and NNODAT must be non-negative, and should be 0 or 1.

NUMREG  number of life regions determined by data
NNODAT  number of life regions (to the right) not determined by data

NBND(L)
[RE]

Life Boundaries
The upper boundaries of the life regions are specified (cycles). The value of L goes from ZROREG to the total number of regions (equal to NUMREG + NNODAT). If a non-zero tensile point is specified, then ZROREG = 0 else ZROREG = 1. The program expects the upper bound of the last life region to be 10^36, a proxy for ∞.

---

3 Extension of the S/N curve to the left is discussed on Page 2-17.
4 Extension of the S/N curve to the right is discussed on Page 2-17.
5 Life region boundaries are discussed on Page 2-15.
CZERO

[RE]

Prior information on coefficient of variation of fatigue strength

Information in the form of a constraint on the coefficient of variation of fatigue strength $C$ for the specific material S/N data set. Value must be non-negative and a value of zero indicates that CZERO is not in use.

<table>
<thead>
<tr>
<th>MPNT(L)</th>
<th>MZERO(1,L)</th>
<th>MZERO(2,L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[INT]</td>
<td>[RE]</td>
<td>[RE]</td>
</tr>
</tbody>
</table>

Prior information on the materials shape parameter $m$

The number of MZERO values in each life region, and the lower and upper bound for the range of $m$. The value of $L$ goes from 1 to (NUMREG + NNODAT). If VARY = 3 is specified (truncated Normal distribution on $m$), then a prior range of $m$ must be specified for each region.

- **MPNT(L)**: The number of points, 0, 1, or 2 (no prior on $m$, a point prior on $m$, or a prior over a range of $m$, respectively), in MZERO() for each region.
- **MZERO(1,L)**: The lower bound on the range of $m$ or the value of the point prior for $m$.
- **MZERO(2,L)**: The upper bound on the range of $m$. Program requires that the value be zero if a point prior for $m$ is specified.

<table>
<thead>
<tr>
<th>DELTA(L)</th>
<th>MO(L)</th>
<th>SIGMA2(L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[RE]</td>
<td>[RE]</td>
<td>[RE]</td>
</tr>
</tbody>
</table>

Information on the Bayesian prior distribution for the truncated Normal distribution

If VARY = 3, then the materials model uses the truncated Normal distribution. The truncated Normal distribution requires some prior information on the Normal distribution parameters because a Bayesian analysis is performed. The information is required for each life region. The value of $L$ goes from 1 to (NUMREG + NNODAT).

- **DELTA(L)**: The shape parameter $\delta$ of the Bayesian prior distribution is used to compute the Bayesian posterior distribution parameters. Value must be non-negative, a value of zero indicates a diffuse prior distribution.

---

6 The implicit constraint on the materials shape parameter provided by prior information on the coefficient of variation of fatigue strength is discussed on Pages 2-12 through 2-13.

7 The explicit constraint on the materials shape parameter provided by prior information on the materials shape parameter is discussed on Page 2-12.

8 Specification of the Bayesian prior distribution for the truncated Normal case is discussed on Page 2-14.
MO(L)  Location parameter \( m_0 \) of the Bayesian prior distribution of the shape parameter \( m \). Must be positive. Required when DELTA(L) is non-zero.

SIGMA2(L)  \( \sigma^2 \), the known variance of \( \ln(fatigue\ life) \), \( V(\ln N | \ln S) \). Must be non-negative.

**KRATIO**  **LAMN**

Materials process variation information
If MPROC = 1, then specification of KRATIO and LAMN is required. KRATIO is \( Z_K \), the ratio \( \text{MED } K^* / \text{MED } K \) where \( \text{MED } K^* \) is the median value over all heats for the stress (psi) at a life of one cycle, and \( \text{MED } K \) is the median value for the specific S/N data for the stress (psi) at a life of one cycle. LAMN is the ratio of the variance of \( \ln(life) \) conditional on stress over all heats to the intrinsic materials variation for the given S/N data conditional on stress. Process variation in materials is discussed in Section 2.1.2.3.

### 6.1.3.2 Input File RELATD

The input data for file RELATD, which contains the related materials information, is given below. The data format is similar to that used to specify the S/N data in the specific materials information block in the DCTHCF file.

**NSETS**

[Int]

Number of related data sets
Number of related material S/N data sets. The following data groups have to be repeated as a block for each data set. The value of J varies from 1 to NSETS. If there is no related data, then file RELATD will only contain the number "0". NSETS cannot exceed five.

**DESCRP(J)**

[CHR]

Description of related material S/N data set
Name and test environment for related material S/N data set J. This is a character string no more than 40 characters long, enclosed by single quotes.

---

9  Related S/N data is discussed on Page 2-7.
### Table 1: Related Materials Information

<table>
<thead>
<tr>
<th>FTY</th>
<th>FTU</th>
<th>NDIV</th>
<th>NPTS(J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[RE]</td>
<td>[RE]</td>
<td>[INT]</td>
<td>[INT]</td>
</tr>
</tbody>
</table>

#### Related Materials Information

Yield strength, ultimate strength, number of divisions of data, number of points in S/N data set. The data may be divided when they are assigned to a different life region or have different stress ratios. If all the data has a stress ratio of -1.0, then the yield and ultimate strengths are not required, but zero values must be specified as placeholders. **NPTS(J)** cannot exceed fifty. The next two data sets have to be provided for each data division.

- **FTY**: yield strength corresponding to related material data set J (psi)
- **FTU**: ultimate strength corresponding to related material data set J (psi)
- **NDIV**: number of data divisions for related material data set J
- **NPTS(J)**: total number of points in related material S/N data set J

### Table 2: Materials Information

<table>
<thead>
<tr>
<th>NUM</th>
<th>RATIO</th>
<th>REG</th>
</tr>
</thead>
<tbody>
<tr>
<td>[INT]</td>
<td>[RE]</td>
<td>[INT]</td>
</tr>
</tbody>
</table>

#### Materials Information for Each Data Division of the Related S/N Data Set

Number of points, stress ratio, and the life region of interest for each data division. This line must be provided for each data division.

- **NUM**: number of S/N data points in the data division
- **RATIO**: stress ratio for the data in the data division
- **REG**: life region number to be assigned to the data in the data division

### Table 3: Related Material S/N Data Points

<table>
<thead>
<tr>
<th>RAWSTR(I,J)</th>
<th>RAWNF(I,J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[RE]</td>
<td>[RE]</td>
</tr>
</tbody>
</table>

#### Related Material S/N Data Points

Stress versus fatigue life data points for each data division. A block of **NUM** lines must be specified (i.e., the value of I goes from 1 to **NUM**). This block must be provided for each data division.

- **RAWSTR(I,J)**: stress value (psi)
- **RAWNF(I,J)**: fatigue life value (cycles)
6.1.3.3 Reference Time History Files

The data format for the reference time history files is given below. There must be NLOAD files with the same names, as specified by LDNAME(i) in file DCTHCD. Reference time histories are typically generated by program NBSIN described in Sections 4.5, 6.6, and 7.7.

STRHIS(i,j)
[RE]

The points of the i-th reference time history.
The points of the time history specified by LDNAME(i). The data is entered one point per line for j = 1, ..., NRAN.

6.1.4 Options and Capabilities

DCTHCF is a Monte Carlo simulation program which generates a sequence of component lives for a particular failure mode, where life is defined as the accumulated operating time at failure. The simulation has a double-loop structure with NHYPER outer loops and NLIFE inner loops. The simulation size is dependent on the failure probability at which a life estimate is desired and the precision desired. For the HPOP main discharge duct and LPFTP turbine drive duct applications, single-loop runs with NHYPER = 20,000 and NLIFE = 1 were used to characterize component reliability, and single-loop runs with NHYPER = 1000 and NLIFE = 1 were used for the marginal analysis to assess the importance of drivers.

During a run, it may be desirable to "hold" a driver at a fixed value. This may be the nominal or median value of the driver. This is done for drivers with a Beta or a Uniform distribution by merely specifying both the upper and lower bounds to be the desired value. For drivers with a Normal distribution, the standard deviation \( \sigma \), or coefficient of variation \( C \), is set at zero and the mean \( \mu \) is set at the desired value.

The procedure of holding certain drivers at fixed values while letting the other drivers vary according to their probability distributions may be used for driver variation sensitivity studies. That is, the effect on life of driver variation may be evaluated by letting it vary while holding other drivers at fixed values. Each driver variation sensitivity was determined in the case studies of this report with the intrinsic variation of the fatigue life of the material included (VARY = 1).

A printout of intermediate calculations in various parts of the program may be obtained via the IOUP option. This output will be printed in the IOUPPR file. It is recommended that such output not be requested when the simulation size is large since the information will be dumped during every simulation loop. The NMED option provides for calculation of an empirical median S/N curve if the truncated Normal
distribution is employed.\textsuperscript{10} In this case, the median S/N curve is based on the empirical median \( m \) from all the shape parameters used in the simulation. The \texttt{MPROC} option activates the computations for the process variation feature of the materials characterization model, as discussed in Section 2.1.2.3.

### 6.1.5 Code Execution Example

The following example run of the HCF analysis code DCTHCF was carried out with random variation of all drivers for the HPOTP main discharge duct. In this example run, 1000 lives were simulated (\texttt{NLIFE = 1 times NHYPER = 1000}) by using Uniform shape parameter variation \texttt{VARY = 2} and \texttt{NMED = 0}; and no materials process variation, \texttt{MPROC = 0}. The B-lives\textsuperscript{11} to be provided are B.1, B.2, B.3, B.4, B.5, B.6, B.7, B.8, B.9, and B1 (\texttt{NBLIFE = 10}, \texttt{BLFPER(1) = 0.001, BLFPER(2) = 0.002, BLFPER(3) = 0.003, BLFPER(4) = 0.004, BLFPER(5) = 0.005, BLFPER(6) = 0.006, BLFPER(7) = 0.007, BLFPER(8) = 0.008, BLFPER(9) = 0.009, BLFPER(10) = 0.01}). The user may refer to Section 2.2.1.5 for additional information on the engineering analysis and to Section 3.1 for the results of the case study for this component.

Figure 6-4 shows the component in detail and the location of the critical weld, designated as \( \text{A} \). The bend radius for the elbow \texttt{BNRD} is 6.0 inches, and the weld distance from the elbow tangency line \texttt{WEDS} is 0.112 inches. The minimum wall

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure64.png}
\caption{Detail of the HPOTP Main Discharge Duct, Near Weld 6}
\end{figure}

\textsuperscript{10} The truncated Normal distribution for the materials model shape parameter \( m \) is discussed on Page 2-14.

\textsuperscript{11} A B-life is the value of accumulated operating time to failure at a failure probability specified as a percent; e.g., B.1 is the failure time at a probability of 0.001 or 0.1%.
thickness **MNWT** is 0.1115 inches, and the wall thickness at the bend inner diameter is 0.1378 inches. The duct inside wall diameter **IDWE** is 4.00 inches.

The drivers for the HCF failure of a welded duct are as follows:

<table>
<thead>
<tr>
<th>DRIVER</th>
<th>DISTRIBUTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Weld Offset</td>
<td>Beta</td>
</tr>
<tr>
<td>2. $K_T$ Weld and Geometry Factors</td>
<td>Beta</td>
</tr>
<tr>
<td>3. Dynamic Load Scale Factors</td>
<td>Normal</td>
</tr>
<tr>
<td>4. Static Load Scale Factor</td>
<td>Uniform</td>
</tr>
<tr>
<td>5. Dynamic Stress Analysis Accuracy</td>
<td>Uniform</td>
</tr>
<tr>
<td>6. Static Stress Analysis Accuracy</td>
<td>Uniform</td>
</tr>
<tr>
<td>7. Axial Stress Carryover Factors</td>
<td>Uniform</td>
</tr>
<tr>
<td>8. Circumferential Stress Carryover Factors</td>
<td>Uniform</td>
</tr>
<tr>
<td>9. Ovality Effect Analysis Accuracy</td>
<td>Uniform</td>
</tr>
<tr>
<td>10. $K_T$ Weld Offset Eccentricity Accuracy</td>
<td>Uniform</td>
</tr>
<tr>
<td>11. Damage Accumulation Model Accuracy</td>
<td>Uniform</td>
</tr>
</tbody>
</table>

The rationale for the specification of the driver distributions is given in Section 3.1.3. The weld offset was held at 13% by fixing the upper and lower bounds of the distribution at **WEOWA** = **WEOFB** = 0.13.

In addition to the static loads, there were two narrow-band random loads and one sinusoidal load. The three dynamic loads (**NLOAD** = 3) used here are a subset of the significant loads for this component. The procedure for identifying the significant loads is described in Sections 2.2.1.5 and 2.3.7. The three reference time histories are in the files named NBP, NBM3, and SIN10, and the contents of these input files are given below. The reference time histories have five points (**NRAN** = 5) and represent 0.00025 seconds (**PERIOD** = 0.00025) of the loading. The reference time histories used for the case studies of the discharge duct given in Section 3.1 consisted of 20,000 points. Shorter histories are used here to permit their inclusion in this example. The critical location is the outer-wall at an angle of 20° counterclockwise from the crown (**LOCAT** = 1, **ANGLE** = 20) at weld 6.

Twenty S/N data points, **NUM** = 20 with a stress ratio of 0.05 (**RATIO** = 0.05) are provided. The number of regions with data, **NUMREG**, is 1, and there are no regions to the right without data, **NNODAT** = 0. The data is in one division, **NDIV** = 1, and the total number of points is twenty, **NPTS(0)** = 20. No related data is provided. Thus, the RELATD file is empty, except for a single entry to indicate **NSETS** = 0. If further explanation of file DCTHCD is required, refer to Section 6.1.3.1 and Figure 6-1.
The echo of the input data is in the output file DCTHCO. The simulated B-lives are also given for the component. For instance, the B.1 life is $1.8 \times 10^6$ seconds. This value is different from the B.1 life obtained during the case study of this component as given in Section 3.1.5 because the number and size of the reference time histories and the number of simulation trials have been reduced to facilitate the example run. There are only three time histories with just five points each used here, and therefore they do not properly represent the loads. Also, the $F_k$ versus $R/t$ curve is only an example curve.

The IOUTPR file gives an echo of the analysis parameters. The dump parameter IOUT is zero; therefore, no other output is in this file. The LOWLIF file contains the lowest one percent of the 1000 simulation lives. Finally, the DUMP file contains the results of the materials characterization model information aggregation calculations.\textsuperscript{12}

\textbf{Input File - DCTHCD}

```
675
0
1
1000
2
0
10
0.001
0.002
0.003
0.004
0.005
0.006
0.007
0.008
0.009
0.010
0.13 0.13 0.00 0.00 0.0 0.0
0.00 0.00 0.00 0.00 0.0 0.0
1.00
1.20 3.50 0.08696 0.3478 10. 10.
1.04 1.43 0.30 0.70 0.5 10.
1.20 1.34 0.30 0.70 0.5 10.
2.00 2.00 0.15 0.866667
2.00 2.00 0.20 0.933333
0.90 1.10
0.80 1.20
0.90 1.10
```

\textsuperscript{12} The information aggregation calculations are discussed on Pages 2-6 through 2-14.
<p>| | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.40</td>
<td>0.60</td>
<td>0.40</td>
<td>0.60</td>
<td>0.40</td>
<td>0.60</td>
<td>0.40</td>
</tr>
<tr>
<td>0.85</td>
<td>1.15</td>
<td>0.80</td>
<td>1.20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-1.38629</td>
<td>0.95166</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

```
8130.00  20900.00  42010.00  42010.00  3805.00  3805.00

'NBP' 1  237.675  0.00  0.00  0.00  0.00  0.00

'NBM3' 1  0.00  0.00  0.00  626.175  0.00  0.00

'SIN10' 2  79.7046 7.056975 2.48936 35.04565 36.66045 4.07806
```

1.
1.
1.
4675.
6.0
.112
4.
0.1115
0.1378
3.071E+07
1
20.
0.00025
0.00
5
0.615  2.00
0.693  4.80
0.753  7.20
0.813  9.60
0.873 12.50
0.933 15.80
0.993 20.00
1.029 24.00
1.053 30.00
1.053 200.00

'320 HOURGLASS + STRAIGHT'

```
178600.  220400.  1  20
20  0.05  1
150000.  65000.
140000.  261000.
120000.  265000.
160000.  377000.
130000.  694000.
110000.  2175000.
100000.  4198000.
105000.  5053000.
92000.  9210000.
95000.  9667000.
```

6 - 31
150000. 418000.
140000. 732000.
130000. 740000.
120000. 859000.
110000. 1181000.
100000. 4020000.
92000. 5917000.
94000. 6522000.
90000. 6891000.
86000. 4460000.

0.00
1 0
1.0E+36
0.00
0 0.00 0.00

Input File - RELATD

0

Input File - NBP

0.629458884176211
0.59673661621406
-0.119721868089590
-0.820795694851671
-1.16311124100903

Input File - NBM3

-0.645335663562470
-0.592612186107565
-0.570937436536749
-0.532482208042243
-0.797739965345054

Input File - SIN10

0.973888469945478
0.921335424736327
0.516863543379789
-0.850326546259054D-001
-0.654449266970346
INPUT DATA

<table>
<thead>
<tr>
<th>DRIVERS</th>
<th>PARAMETER DISTRIBUTIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>WELD OFFSET (%)</td>
<td>RHO</td>
</tr>
<tr>
<td>Be(0.13, 0.13)</td>
<td>U(0.00000, 0.00000)</td>
</tr>
<tr>
<td>Be(0.00, 0.00)</td>
<td>U(0.00000, 0.00000)</td>
</tr>
<tr>
<td>TEST = 1.00</td>
<td></td>
</tr>
<tr>
<td>K WELD (OD)</td>
<td>Be(1.20, 3.50)</td>
</tr>
<tr>
<td>K WELD (ID)</td>
<td>Be(1.04, 1.43)</td>
</tr>
<tr>
<td>K GEOM (OD)</td>
<td>Be(1.20, 1.34)</td>
</tr>
<tr>
<td>LAMBDA RANDOM</td>
<td>k: U(2.00000, 2.00000)</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>LAMBDA SINE</td>
<td>k: U(2.00000, 2.00000)</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>LAMBDA STATIC</td>
<td>U(0.90000, 1.10000)</td>
</tr>
<tr>
<td>DYNAMIC STRESS ANALYSIS</td>
<td>U(0.80000, 1.20000)</td>
</tr>
<tr>
<td>STATIC STRESS ANALYSIS</td>
<td>U(0.90000, 1.10000)</td>
</tr>
<tr>
<td>STRESS CARRYOVER FACTORS IN-PLANE AXIAL</td>
<td>U(0.40000, 0.60000)</td>
</tr>
<tr>
<td>OUT-OF-PLANE AXIAL</td>
<td>U(0.40000, 0.60000)</td>
</tr>
<tr>
<td>IN-PLANE CIRCUMFERENTIAL</td>
<td>U(0.40000, 0.60000)</td>
</tr>
<tr>
<td>OUT-OF-PLANE CIRCUMFERENTIAL</td>
<td>U(0.40000, 0.60000)</td>
</tr>
<tr>
<td>OVALITY ANALYSIS FACTOR</td>
<td>U(0.85000, 1.15000)</td>
</tr>
<tr>
<td>LAMBDA KOFF</td>
<td>U(0.80000, 1.20000)</td>
</tr>
</tbody>
</table>
LOADS INPUT

<table>
<thead>
<tr>
<th>LOADS</th>
<th>P LOADS (LBS)</th>
<th>T LOADS (IN.-LBS)</th>
<th>M2 LOADS (IN.-LBS)</th>
<th>M3 LOADS (IN.-LBS)</th>
<th>V2 LOADS (LBS)</th>
<th>V3 LOADS (LBS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>STATIC</td>
<td>8130.0000</td>
<td>20900.0000</td>
<td>42010.0000</td>
<td>42010.0000</td>
<td>3805.0000</td>
<td>3805.0000</td>
</tr>
<tr>
<td>NBP</td>
<td>237.6750</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>NBM3</td>
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<td>0.0000</td>
<td>0.0000</td>
<td>626.1750</td>
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</tr>
<tr>
<td>SIN10</td>
<td>79.7046</td>
<td>7.0570</td>
<td>2.4894</td>
<td>35.0457</td>
<td>36.6604</td>
<td>4.0781</td>
</tr>
</tbody>
</table>

GEOMETRIC AND OTHER INPUT

<table>
<thead>
<tr>
<th>GEOMETRIC AND OTHER INPUT</th>
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</tr>
</thead>
<tbody>
<tr>
<td>K GEOM (ID)</td>
<td>1.00</td>
</tr>
<tr>
<td>K HOOP (OD)</td>
<td>1.00</td>
</tr>
<tr>
<td>K HOOP (ID)</td>
<td>1.00</td>
</tr>
<tr>
<td>LIMIT PRESSURE, PSI</td>
<td>4675.</td>
</tr>
<tr>
<td>BEND RADIUS, IN.</td>
<td>6.00</td>
</tr>
<tr>
<td>WELD DISTANCE FROM ELBOW TANGENCY LINE, IN.</td>
<td>0.112</td>
</tr>
<tr>
<td>DUCT INSIDE DIAMETER, IN.</td>
<td>4.00</td>
</tr>
<tr>
<td>MINIMUM WALL THICKNESS, IN.</td>
<td>0.1115</td>
</tr>
<tr>
<td>WALL THICKNESS AT BEND (ID), IN.</td>
<td>0.1378</td>
</tr>
<tr>
<td>ELASTIC MODULUS, PSI</td>
<td>0.301E+08</td>
</tr>
<tr>
<td>ANALYSIS LOCATION</td>
<td>1</td>
</tr>
<tr>
<td>ANGLE PHI (DEG)</td>
<td>20.0</td>
</tr>
</tbody>
</table>
STRESS-TIME HISTORY PERIOD, SEC 0.00
STRESS-TIME HISTORY NOISE FILTER, PSI 0.0
NUMBER OF TIME-VARYING LOADS 3
NUMBER OF POINTS IN HISTORIES 5

MATERIAL INPUT

DESCRIPTION: -320 HOURGLASS + STRAIGHT

YIELD STRENGTH 0.17860E+06
ULTIMATE STRENGTH 0.22040E+06
NUMBER OF POINTS 20

<table>
<thead>
<tr>
<th>ORIGINAL S/N</th>
<th>STRESS</th>
<th>LIFE</th>
<th>STRESS RATIO</th>
<th>REGION</th>
<th>TRANSFORMED S/N STRESS</th>
<th>LIFE</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>0.15000E+06</td>
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<tr>
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<td>0.14000E+06</td>
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<td>0.05</td>
<td>1</td>
<td>0.99773E+05</td>
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<tr>
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<td>0.12000E+06</td>
<td>265000.</td>
<td>0.05</td>
<td>1</td>
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<td>1</td>
<td>0.55964E+05</td>
<td>9210000.</td>
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</tr>
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<tr>
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<td>4460000.</td>
<td>0.05</td>
<td>1</td>
<td>0.51374E+05</td>
<td>4460000.</td>
</tr>
</tbody>
</table>

THERE IS 1 REGION(S) WITH DATA
AND 0 REGION(S) TO THE RIGHT WITHOUT DATA
THE UPPER BOUND(S) OF THE REGION(S) ARE (CYCLES):

0.100E+37

EXOGENOUS INFORMATION

CONSTRAINT ON COEFFICIENT OF VARIATION, C: 0.0000

EXPLICIT CONSTRAINT ON m FOR EACH REGION:

<table>
<thead>
<tr>
<th>REGION</th>
<th># OF POINTS</th>
<th>LOWER BOUND</th>
<th>UPPER BOUND</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

B LIVES: EMPIRICAL

0.00100 0.178612E+07
0.00200 0.454616E+07
0.00300 0.490656E+07
0.00400 0.495901E+07
0.00500 0.508289E+07
0.00600 0.583508E+07
0.00700 0.645511E+07
0.00800 0.701038E+07
0.00900 0.716342E+07
0.01000 0.757381E+07
0.50000 0.315738E+10

Output File - RELATO

NUMBER OF DATA SETS: 0

NOTE: ALL Kt ASSUMED TO BE 1.0

TRANSFORMED DATA

Output File - DUMP

Copyright (C) 1990, California Institute of Technology. U.S. Government Sponsorship under NASA Contract NAS7-918 is acknowledged.
RESULTS OF INFORMATION AGGREGATION CALCULATIONS

95% CONFIDENCE INTERVALS ON C AND \( m \) FOR EACH REGION

REGION: 1  
\( I_o = (0.092758540, 0.181539600) \)  
\( J_o = (3.596348000, 5.874000000) \)

POINT ESTIMATES OF C AND \( m \) FOR EACH REGION

<table>
<thead>
<tr>
<th>REGION</th>
<th>( E(C) )</th>
<th>( E(m) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.122759400</td>
<td>4.735174</td>
</tr>
</tbody>
</table>

POSTERIOR CREDIBILITY RANGE ON \( m \) FOR EACH REGION

<table>
<thead>
<tr>
<th>REGION</th>
<th>LOWER BOUND</th>
<th>UPPER BOUND</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.5963</td>
<td>5.8740</td>
</tr>
</tbody>
</table>

PARAMETER VALUES FOR MEDIAN S/N CURVE

NUMBER OF REGIONS: 1  
\( E(\beta_o) = 9.6555 \)  
\( E(k) = 14.2292 \)

<table>
<thead>
<tr>
<th>REGION</th>
<th>( m )</th>
<th>( K )</th>
<th>LIFE BOUND</th>
<th>STRESS BOUND</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.73517</td>
<td>0.15458E+07</td>
<td>0.100E+37</td>
<td>0.00000E+00</td>
</tr>
</tbody>
</table>

Output File - IOUTPR

RANDOM NUMBER SEED = 675.00000000000000
IOUT (MATCHR = 10, DCTHCF = 15, ELWELD = 25) = 0
INNER LOOP SIZE = 1
OUTER LOOP SIZE = 1000
TYPE OF S/N VARIATION DESIRED = 2
NORMAL MEDIAN CURVE (0 - NO, 1 - YES) = 0
MATERIALS PROCESS VARIATION DESIRED (0 - NO, 1 - YES) = 0

Output File - LOWLIF

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.100000E-02</td>
<td>0.178612E+07</td>
</tr>
<tr>
<td>2</td>
<td>0.200000E-02</td>
<td>0.454616E+07</td>
</tr>
<tr>
<td>3</td>
<td>0.300000E-02</td>
<td>0.490656E+07</td>
</tr>
<tr>
<td>4</td>
<td>0.400000E-02</td>
<td>0.495901E+07</td>
</tr>
<tr>
<td>5</td>
<td>0.500000E-02</td>
<td>0.508289E+07</td>
</tr>
<tr>
<td>6</td>
<td>0.600000E-02</td>
<td>0.583508E+07</td>
</tr>
<tr>
<td>7</td>
<td>0.700000E-02</td>
<td>0.645511E+07</td>
</tr>
<tr>
<td>8</td>
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<td>0.701038E+07</td>
</tr>
<tr>
<td>9</td>
<td>0.900000E-02</td>
<td>0.716342E+07</td>
</tr>
<tr>
<td>10</td>
<td>0.100000E-01</td>
<td>0.757381E+07</td>
</tr>
</tbody>
</table>

6.1.6 Error Messages and Possible Remedies

The following messages, when applicable, will appear in file IOUTPR. These messages are primarily generated by the materials characterization model (MATCHR) portion of DCTHCF. An error message stating that a limit has been exceeded will require that the user increase those limits, as directed, and reviewing or consulting Section 7.3.1.3 is desirable. The messages are listed in alphabetical order for the convenience of the user.

ERROR: BAD VALUE FOR DELTA OR VALUE OF MO INCONSISTENT WITH DELTA IN REGION 'L'

*Fatal* This error can occur during the use of the truncated Normal variation option of the materials characterization model for two reasons. First, the value of $\delta$ may be negative. Second, a value of $\delta$ was specified, but the value for $m_o$ is not positive. Check file DCTHCD.

ERROR: CANNOT FIND CULPRIT LOCATION

*Fatal* Program error in identification of culprit failure location for LOCAT = 0. Please take note of all input parameters for this run and contact the analyst.

ERROR: CANNOT OPEN FILE, 'filename' DOES NOT EXIST

*Fatal* DCTHCF attempted to open the indicated file, however the file did not exist. Check the directory for existence of the file and also check file DCTHCD for correct spelling of the filename.
ERROR: Co TOO LOW
    Fatal   The constraint, C_o, imposed on the coefficient of variation of fatigue strength is inconsistent with the observed S/N data.

ERROR: EXCEEDED LIMIT ON DEGREES OF FREEDOM IN CHI-SQUARE TABLE, IN REGION 'L'
    Fatal   As implemented, the credibility interval calculations can handle no more than 150 degrees of freedom, and the amount of data in the region indicated requires more. The $\chi^2$ tables of routine INTRVL must be increased. See Sections 4.1.3.6 and 7.3.1.3 for more information.

ERROR: EXCEEDED LIMIT ON NUMBER OF REGIONS
    Fatal   The materials characterization model can handle no more than 3 life regions. Check file DCTHCD because the sum of the number of regions with data and the number of regions without data is greater than 3.

ERROR: INVALID RESPONSE TO NORMAL MEDIAN CURVE QUESTION
    Fatal   NMED can only have the integer value 0 or 1. Check file IOUTPR for the value used.

ERROR: INVALID TYPE OF MATERIALS PROCESS VARIATION DESIRED
    Fatal   MPROC can only have the integer value 0 or 1. Check file IOUTPR for the value used.

ERROR: INVALID TYPE OF S/N VARIATION DESIRED
    Fatal   VARY can only have the integer value 0, 1, 2, or 3. Check file IOUTPR for the value used.

ERROR: INVALID VALUE FOR RATIO: 'RATIO'
    Fatal   An invalid value for the stress ratio has been declared for the specific material data set. Only values between -1.0 and +1.0 inclusive, are possible. Check file DCTHCD.

ERROR: INVALID VALUE OF RATIO: 'RATIO'
    Fatal   An invalid value for the stress ratio has been declared for a related material data set. Only values between -1.0 and +1.0 inclusive, are possible. Check file RELATD.

ERROR: LOAD INCORRECTLY TYPED
    Fatal   TYPE(I) can only have the integer value 1 or 2. Check file DCTHCD for the value used.
ERROR: LOCATION INCORRECTLY SPECIFIED

Fatal LOCAT can only have the integer value 0, 1, or 2. Check file DCTHCD for the value used.

ERROR: NO INTERSECTION BETWEEN Jo AND Mc
ERROR: NO INTERSECTION BETWEEN Jo AND Mo
ERROR: NO INTERSECTION BETWEEN Jo, Mo, AND Mc

Fatal These errors indicate that the specified C constraint and/or prior credibility range on m do not agree with each other and/or the observed S/N data.

ERROR: NORMAL VARIATION REQUIRES A PRIOR RANGE ON M

Fatal The truncated Normal variation option of the materials characterization model requires a prior range on m. The number of points for the prior range on m has been incorrectly specified. Check file DCTHCD to verify that the number of points indicated for each range has an integer value of 1 or 2.

ERROR: NUMBER OF POINTS PER DIVISION INCORRECTLY SPECIFIED IN SET 'J'

Fatal The materials characterization model has been given conflicting information about the number of points in one of the related S/N data sets. Check file RELATD to compare for each related data set the total number of points declared with the sum of the numbers of points in each data division.

ERROR: NUMBER OF POINTS PER DIVISION INCORRECTLY SPECIFIED IN SPECIFIC DATA SET

Fatal The materials characterization model has been given conflicting information about the number of points in the specific S/N data set. Check file DCTHCD, since the total number of points in the specific data set declared and the sum of the numbers of points in each data division do not agree.

ERROR: OVERALL PRIOR RANGE INCORRECTLY SPECIFIED IN REGION WITHOUT DATA

Fatal The prior credibility range on m in one of the regions without data has been incorrectly specified. Check file DCTHCD to verify that either more regions without data have been indicated than intended or that the number of points in the prior on m in a region without data has been incorrectly specified. Only the integer value 0, 1, or 2 is acceptable.

ERROR: OVER LIMIT ON NUMBER OF POINTS IN SET 'J'

Fatal The materials characterization model cannot accept more than 50 S/N points in any related material data set. Check file RELATD for the total num-
ber of points in each related data set declared, or there may be more than
50 S/N points with an incorrect total declaration. It is suggested that the
number of S/N data points in each related set be recounted. If more than
50 points are desired, the parameter MAXDAT must be increased. Refer to
Section 7.3.1.3 for the routines involved.

ERROR: OVER LIMIT ON NUMBER OF RELATED DATA SETS
   Fatal The materials characterization model allows up to 5 related data sets.
   Check file RELATD to determine if more than 5 related data sets were
   specified. The parameter MAXSET must be increased. Refer to Section
   7.3.1.3 for the routines involved.

ERROR: OVER NUMBER OF POINTS LIMIT IN SPECIFIC MATERIAL
   Fatal The materials characterization model cannot accept more than 50 S/N
   points in the specific material data set. Check file DCTHCD for the total
   number of points in the specific data set declared, or there may be more
   than 50 S/N points with an incorrect total declaration. If more than 50 points
   are desired, the parameter MAXDAT must be increased. Refer to Section
   7.3.1.3 for the routines involved.

ERROR: OVER REGION LIMIT IN RELATED MATERIAL 'J'
   Fatal No more than 3 life regions are allowed, and an attempt has been
   made to place some S/N data in a region number greater than 3. Check file
   RELATD for an invalid region number immediately following the stress ratio
   value in the data set indicated.

ERROR: OVER REGION LIMIT IN SPECIFIC DATA SET
   Fatal No more than 3 life regions are allowed, and an attempt has been made
   to place some S/N data in a region number greater than 3. Check file DCTHCD
   for an invalid region number immediately following the stress ratio value.

ERROR: POSTERIOR INTERVAL IN REGION 'L' IS INCONSISTENT WITH POINT
   POSTERIOR IN REGION 'L-1'
   Fatal Check file DUMP to verify that the point posterior value of m in region
   'L-1' is greater than the upper bound of the posterior credibility range in
   region 'L'. This error indicates a violation of the concavity assumption.

ERROR: POSTERIOR INTERVAL IN REGION 'L' IS INCONSISTENT WITH THE
   POSTERIOR INTERVAL IN REGION 'L-1'
   Fatal Check file DUMP to verify that the lower bound of the posterior
   credibility range of m in region 'L-1' is greater than the upper bound of the
posterior credibility range of $m$ in region 'L'. The data should be checked for consistency.

ERROR: PRIOR ON M INCORRECTLY SPECIFIED IN 'L'
Fatal  The number of points for the specified prior range on $m$ in the indicated region has been incorrectly specified. Check file DCTHCD to verify that the number of points indicated for each range has an integer value of 0, 1, or 2.

ERROR: STRESS-TIME HISTORY TOO LARGE
Fatal  No more than 24,000 points are allowed for a reference time history, and an attempt has been made to use a larger history. Check file DCTHCD for a value of NRAN larger than 24,000.

ERROR: SXY > = 0 IN REGION 'L'
Fatal  During the linear regression calculations for the region indicated, the resulting value of the sample covariance $S_{xy}$ was found to be non-negative. This suggests that the data is specified erroneously or is inadequate for analysis, since life increasing with increasing stress contradicts the true fatigue behavior of materials.

ERROR: TOO FEW POINTS FOR REGRESSION IN REGION 'L'
Fatal  The materials characterization model does not have the required minimum number of points in the region indicated to perform a linear regression. If there are no related data sets, then there must be at least 3 points in each region. If there are $N$ related data sets, then the total number of points in each region (specific and related combined) must be at least $N + 3$.

IMPOSSIBLE M RANGE IN REGION 'L'
Fatal  Concavity constraints during the random $m$ selection have required an impossible range on $m$ for the region indicated. Take note of all input parameters for this run, and consult Sections 4.1.5.1, 4.1.5.2, and 7.3 to aid in identification of the cause of this error.

NOTE: E(m) IS NOT IN THE POSTERIOR RANGE ON m IN REGION 'L'
Warning  This means that the estimate of $m$ based on the S/N data only, in the region indicated, is outside the range indicated by the specified constraints on $m$ and $C$.

PROGRAM EXECUTION TERMINATED
Fatal  This message is produced by routine TRMNAT and follows all other fatal messages.
WARNING: LAMBDA < .16 DURING OVAlITY CALCULATIONS

Warning During the ovality effect calculations, the resulting value of \( \lambda \), Equations 2-74 through 2-77, was found to be less than 0.16. This suggests that the following stress calculations may be invalid.

6.1.7 Summary of Input/Output Files

Input Files

DCTHCD
This file is opened in DCTHCF. It contains all parameters for the run options; driver distributions; engineering analysis parameters; and the specific and exogenous materials input, including yield and ultimate strengths (psi), stress ratio, S/N data points, life (cycles) boundaries, region information, coefficient of variation constraint, \( C \), and prior ranges on the materials shape parameter \( m \) for each region.

RELATD
This file is opened in subroutine INFAGG. It contains the related material data input, including yield and ultimate strengths (psi), stress ratio, S/N data points, and region information.

User Specified
These are the reference time history files and are opened in DCTHCF. They contain the time histories generated by program NBSIN.

Output Files

DCTHC0
This file is opened in DCTHCF. It contains the echo of the information contained in DCTHCD, and provides the simulated failure distribution B-life information.\(^\text{13}\)

RELATO
This file is opened in subroutine INFAGG. It contains the echo of the information contained in RELATD.

DUMP
This file is opened in DCTHCF. It contains the results of the information aggregation portion of the materials model calculations, such as \( I_o \) and \( J_o \); the point estimates of

\(^{13}\) A B-life is the value of accumulated operating time to failure at a failure probability specified as a percent; e.g., B.1 is the failure time at a probability of 0.001 or 0.1%.
and $C$; posterior credibility ranges for $m$; and a list of the estimated values for all S/N curve parameters. See Section 4.1.

IOUTPR
This file is opened in DCTHCF. It contains information on the particular run that is not echoed to DCTHCO and the data dump provided when the variable IOUT is equal to 10 (materials characterization calculations), 15 (Monte Carlo simulation and driver transformation calculations), 20 (rainflow cycle counting and damage accumulation calculations), or 25 (stress analysis calculations).

LOWLIF
This file is opened in DCTHCF. It contains the first one percent of the calculated lives used by the software described in Section 4.2 to calculate $\alpha$, $\beta$, and $\theta$, the parameters of the Bayesian prior failure distribution.

6.1.8 HEXHCF Program
The HEXHCF program was used to analyze high cycle fatigue failure of the HPOTP heat exchanger coil small tube outlet. The dynamic load input for the program consists of narrow-band, sinusoidal, and aerodynamic reference time histories. These reference time histories are generated using the program NBSIN. The output of HEXHCF includes the simulated B-lives and a list of the lowest one percent of lives. The list of lives may be used as input to the regression programs of Section 4.2 to compute the parameters of the Bayesian prior failure distribution. This prior distribution and success/failure data are used as input to the Bayesian updating program BAYES to derive a posterior failure distribution.

6.1.9 How To Use Program HEXHCF
The program HEXHCF is intended to be run in batch (i.e., background) mode. HEXHCF requires two input data files: HEXHCD and RELATD. The materials characterization model portion of the program requires both files for all runs, even when no related S/N data is used. HEXHCF also uses a set of load data files containing the reference time histories. The names of the load data files must be defined by the user. The file HEXHCD contains the analysis control parameters, driver distributions, engineering analysis parameters, and specific and exogenous materials information. The file RELATD contains the related materials information. A complete description of the input data for the HEXHCD and RELATD data files is given in Section 6.1.10.

The results from the HEXHCF program are written to five output files: HEXHCO, RELATO, DUMP, IOUTPR, and LOWLIF. HEXHCO contains the echo of the information in HEXHCD, the results of any stress ratio transformations performed on specific materials data, and the results of the simulation. RELATO contains the echo of the information in RELATD and the results of any stress ratio transformations performed
on related materials data. The results of the materials characterization calculations are primarily given in DUMPR. These calculations include point and interval estimates for S/N curve parameters \( m \) and \( C \), posterior credibility ranges for \( m \), and an estimate of the median S/N curve. File IOUTPR contains an echo of the analysis parameters and, if requested, a dump of intermediate calculations. If the program terminates prematurely, an error message will be printed in the IOUTPR file. A list of error messages and possible remedies for the problems is given in Section 6.1.13. LOWLIF contains the first one percent of the lives of the simulated failure distribution.

6.1.10 Description of Input Data Files

Annotated examples of the complete data file format structure for HEXHCD and RELATD are presented in Figures 6-5 and 6-2, respectively. The data lines of the input files are given in boxes, with a description of each data line located adjacent to each box. The specific input parameters of Figure 6-5 are individually defined in Section 6.1.10.1. Input parameter values given in Figures 6-2 and 6-5 are not necessarily those used in the application case study of Section 3.2.

The input data is read by free format statements from files HEXHCD and RELATD. Thus, the numbers may be provided sequentially on a line up to 80 characters in length, with each number separated by a blank character or comma. Each number may also be on a separate line in the file. However, it is recommended that the input format suggested in Figure 6-5 be followed whenever possible.

6.1.10.1 Input File HEXHCD

The required data for the HEXHCD file is divided into the four blocks shown in Figure 6-3: analysis parameters, driver information, load and geometry, and materials information. The analysis parameters block contains the analysis parameters and the keys to select the program options. The driver information block contains the parameters that define the driver distributions. The number of dynamic loads, the magnitudes of the dynamic loads, the load file names, the static loads, and duct geometry are given in the load and geometry block. The materials information block contains the specific material S/N data, including the yield and ultimate strengths, stress ratio, S/N data points, life region boundaries, and materials characterization model parameter constraints.

The input parameters are described below by using the following convention: the input variable names are indicated by **BOLD UPPERCASE** letters; the variable types are specified as character [CHR], integer [INT], real [RE], and double precision real [DRE]; the function of the variable is underlined and followed by a description and a list of options, when appropriate; the program and file names are indicated by **UPPERCASE** letters. A consistent set of units is given in parentheses for specifying dimension, load, and stress input parameters. All character strings must be enclosed
<table>
<thead>
<tr>
<th>675</th>
<th>Random number seed</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Output dump controller</td>
</tr>
<tr>
<td>1</td>
<td>Inner loop size</td>
</tr>
<tr>
<td>20000</td>
<td>Outer loop size</td>
</tr>
<tr>
<td>2</td>
<td>Type of S/N variation</td>
</tr>
<tr>
<td>0</td>
<td>Request for truncated Normal median S/N curve</td>
</tr>
<tr>
<td>0</td>
<td>Controls materials process variation</td>
</tr>
<tr>
<td>5</td>
<td>Number of B-lives</td>
</tr>
</tbody>
</table>

Decimal equivalent of percentages for B-lives

| 0.0001 | 0.0005 | 0.001 | 0.005 | 0.01 |

Weld offset two Beta distribution information

| 0.06 | 0.06 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 |

Outer diameter weld axial stress concentration factor Beta distribution information

| 1.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 |

Inner diameter weld axial stress concentration factor Beta distribution information

| 1.20 | 3.50 | 0.1304 | 0.5652 | 10.00 | 10.00 |

Duct inside diameter Beta distribution Information

| 0.1885 | 0.1915 | 0.50 | 0.50 | 0.50 | 20.00 |

Wall thickness Beta distribution information

| 0.0113 | 0.0157 | 0.27273 | 0.27273 | 0.50 | 20.00 |

| 2.00 | 2.00 | 0.15 | 1.00 | Narrow-band random load scale factor |
| 2.00 | 2.00 | 0.20 | 1.00 | Sinusoidal load scale factor |
| 486.66 | 666.29 | 56.5 | Inner wall temperature Normal distribution information |
| 799.908 | 908.495 | 48. | Outer wall temperature Normal distribution information |
| 3808.4177 | 69.69 | Internal pressure Normal distribution information |

Figure 6-5 Format for File HEXHCD
| 0.50 | 1.50 | Dynamic aerodynamic load scale factor |
| 0.80 | 1.20 | Static aerodynamic load scale factor |
| 0.80 | 1.20 | Dynamic stress analysis accuracy factor |
| 0.90 | 1.10 | Aerodynamic stress analysis accuracy factor |
| 0.80 | 1.20 | Weld offset accuracy factor |
| 0.60 | 1.40 | Neuber’s rule accuracy factor |
| -1.38629 | 0.95166 | Damage accumulation model accuracy factor |

Number of dynamic loads

Static aerodynamic load: \( P, M_x, M_y, M_z, V_y, V_z \)

| 0.00 | 0.00 | -0.07214 | 0.00 | 0.00 | 0.00 |

Dynamic loads: file name, load type, \( P, M_x, M_y, M_z, V_y, V_z \)

| 'NBM3' | 1 | 0.00 | 0.00 | 0.00 | 0.355475 | 0.00 | 0.00 |
| 'SIN1' | 2 | 0.027374 | 0.000451 | 0.001621 | 0.082116 | 0.205288 | 0.005789 |
| 'AERO1' | 3 | 0.00 | 0.00 | 0.00 | 0.07179 | 0.00 | 0.00 |

1.0 1.0 1.0 1.0

Other fatigue stress concentration factors

3640.

2

180.

1.0

0.0

20001

29000000. 8.8E-06 0.30

0.615 2.00

0.693 4.80

0.753 7.20

0.813 9.60

0.873 12.50

0.933 15.80

0.993 20.00

1.029 24.00

1.053 30.00

1.053 200.00

6

21.95 0.001

55.77 0.002

144.85 0.005

322.73 0.010

1945.90 0.050

50688.0 0.660

Figure 6-5 Format for File HEXHCD (Cont’d)
Description of specific material S/N data set

'70 F, 321 STAINLESS STEEL ALLOY - WELDED'

Specific materials information: yield and ultimate strengths, number of data divisions, and total number of points in data set

27900. 76800. 1 13

Specific materials information for each data division: number of points in data division, stress ratio, and life region

<table>
<thead>
<tr>
<th>Stress tensile point</th>
<th>Number of life regions with and without data</th>
<th>Life boundary</th>
<th>C constraint</th>
<th>Prior information m</th>
</tr>
</thead>
<tbody>
<tr>
<td>40000. 1000.</td>
<td>S1, N1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40000. 2000.</td>
<td>S2, N2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40000. 3000.</td>
<td>S3, N3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40000. 4000.</td>
<td>S4, N4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40000. 5000.</td>
<td>S5, N5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40000. 6000.</td>
<td>S6, N6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30000. 23000.</td>
<td>S7, N7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30000. 66000.</td>
<td>S8, N8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25000. 72000.</td>
<td>S9, N9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25000. 190000</td>
<td>S10, N10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20000. 789000</td>
<td>S11, N11</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20000. 1070000</td>
<td>S12, N12</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20000. 1450000</td>
<td>S13, N13</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

0.00 1 0 1.0E+36 0.00 0.00 0.00

Bayesian prior distribution information

Materials process variation information

Figure 6-5 Format for File HEXHCD (Cont'd)
by 'single quotes'. The user is reminded about the difference between the number "0" and the letter "O" when preparing the input files.

Analysis Parameters Block

RAND
[DRE]

Random number seed
Needed by HEXHCF's built-in random number generator.

IOUT
[INT]

Output dump controller
HEXHCF has the ability to write intermediate calculations to file IOUTPR. The following integer values control the "dump" of HEXHCF's calculation.

<table>
<thead>
<tr>
<th>IOUT</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>no intermediate calculation output</td>
</tr>
<tr>
<td>10</td>
<td>materials characterization model calculations</td>
</tr>
<tr>
<td>15</td>
<td>driver sampling</td>
</tr>
<tr>
<td>20</td>
<td>cycle counting and damage accumulation calculations</td>
</tr>
<tr>
<td>25</td>
<td>stress analysis calculations</td>
</tr>
</tbody>
</table>

NLIFE
[INT]

Inner loop number
Size of the inner loop of the Monte Carlo (MC) simulation. A positive value is required.

NHYPER
[INT]

Outer loop number
Size of the outer loop of the MC simulation. The program requires a positive value.

VARY
[INT]
Type of S/N variation\textsuperscript{14}
Controls the type of stochastic variation to be included in the materials characterization model S/N curve.

- \texttt{VARY = 0} no variation will be included
- \texttt{VARY = 1} allows only intrinsic materials variation
- \texttt{VARY = 2} allows Uniform variation of the materials model shape parameter \( m \) and intrinsic materials variation
- \texttt{VARY = 3} allows truncated Normal variation of the materials model shape parameter \( m \) and intrinsic materials variation

\textbf{NMED} [\texttt{INT}]

Request for truncated Normal median S/N curve\textsuperscript{15}

If \texttt{VARY = 3}, then \texttt{NMED} controls the calculation of the empirical median S/N curve.

- \texttt{NMED = 0} no median curve calculation is required
- \texttt{NMED = 1} median curve calculation is required

\textbf{MPROC} [\texttt{INT}]

Controls materials process variation

Controls the inclusion of materials process variation (heat-to-heat variation). Process variation in materials is discussed in Section 2.1.2.3.

- \texttt{MPROC = 0} no variation to be included
- \texttt{MPROC = 1} variation is to be included

\textbf{NBLIFE} [\texttt{INT}]

Number of B-lives

The number of B-lives to be provided from the simulated distribution of life. A B-life is the value of accumulated operating time to failure at a failure probability specified as a percentage; e.g., B.1 is the failure time at a probability of 0.001 or 0.1\%. \texttt{NBLIFE} must be non-negative and cannot exceed 10.

\textsuperscript{14} A discussion of the possible stochastic specifications of the materials model shape parameter \( m \) is given in Pages 2-13 through 2-14.

\textsuperscript{15} The median S/N curve for the truncated Normal distribution is discussed on Page 2-15.
**BLFPER(1)  BLFPER(2) ...  BLFPER(NBLIFE)**

**[RE]  [RE]  [RE]**

**B-life percentages**
The decimal equivalent of the percentages at which the B-lives are required; e.g., if the B.1 life is desired, then $\text{BLFPER} = 0.001$. A total of $\text{NBLIFE}$ percentages must be provided. The percentage cannot exceed 50% ($\text{BLFPER} \leq 0.50$).

**Driver Information Block**

<table>
<thead>
<tr>
<th>WOFFA</th>
<th>WOFFB</th>
<th>WOFFR1</th>
<th>WOFFR2</th>
<th>WOFFT1</th>
<th>WOFFT2</th>
</tr>
</thead>
<tbody>
<tr>
<td>[RE]</td>
<td>[RE]</td>
<td>[RE]</td>
<td>[RE]</td>
<td>[RE]</td>
<td>[RE]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>WOFFC</th>
<th>WOFFD</th>
<th>WOFFR3</th>
<th>WOFFR4</th>
<th>WOFFT3</th>
<th>WOFFT4</th>
</tr>
</thead>
<tbody>
<tr>
<td>[RE]</td>
<td>[RE]</td>
<td>[RE]</td>
<td>[RE]</td>
<td>[RE]</td>
<td>[RE]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>WOFFE</th>
</tr>
</thead>
<tbody>
<tr>
<td>[RE]</td>
</tr>
</tbody>
</table>

**Weld offset Beta distribution information**

$W_{off}$ in *Equation 2-73* is the weld offset and may be characterized by two Beta distributions. The first two lines are the two Beta distributions, one per line. See *Section 2.1.3.1* and *Equation 2-54* for defining parameters for setting up a Beta driver distribution. The first two parameters are the lower and upper bounds, respectively, for $W_{off}$. The next two parameters are the lower and upper bounds for the Uniform distribution on $p$. Similarly, the last two parameters describe the Uniform distribution on $\theta$. The third line is the decimal equivalent percentage weight for the first Beta distribution and must be between 0.00 and 1.00.

<table>
<thead>
<tr>
<th>WOFFA</th>
<th>$W_{off}$ lower bound of Beta distribution 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>WOFFB</td>
<td>$W_{off}$ upper bound of Beta distribution 1</td>
</tr>
<tr>
<td>WOFFR1</td>
<td>$p$ Uniform distribution lower bound of Beta distribution 1 of $W_{off}$</td>
</tr>
<tr>
<td>WOFFR2</td>
<td>$p$ Uniform distribution upper bound of Beta distribution 1 of $W_{off}$</td>
</tr>
<tr>
<td>WOFFT1</td>
<td>$\theta$ Uniform distribution lower bound of Beta distribution 1 of $W_{off}$</td>
</tr>
<tr>
<td>WOFFT2</td>
<td>$\theta$ Uniform distribution upper bound of Beta distribution 1 of $W_{off}$</td>
</tr>
<tr>
<td>WOFFC</td>
<td>$W_{off}$ lower bound of Beta distribution 2</td>
</tr>
<tr>
<td>WOFFD</td>
<td>$W_{off}$ upper bound of Beta distribution 2</td>
</tr>
</tbody>
</table>
Outer diameter weld axial stress concentration factor Beta distribution information

The outer diameter weld axial stress concentration factor is characterized by a Beta distribution. See Section 2.1.3.1 and Equation 2-54 for defining parameters for setting up a Beta driver distribution. The first two parameters are the lower and upper bounds, respectively, for the outer diameter weld axial stress concentration factor. The next two parameters are the lower and upper bounds for the Uniform distribution on $\rho$. Similarly, the last two parameters describe the Uniform distribution on $\theta$. The outer diameter weld axial stress concentration factor is used to calculate $K_{T1}$ in Equation 2-68.

KWODA  outer diameter weld axial stress concentration factor lower bound of Beta distribution
KWODB  outer diameter weld axial stress concentration factor upper bound of Beta distribution
KWODR1 $\rho$ Uniform distribution lower bound of Beta distribution of outer diameter weld axial stress concentration factor
KWODR2 $\rho$ Uniform distribution upper bound of Beta distribution of outer diameter weld axial stress concentration factor
KWODT1 $\theta$ Uniform distribution lower bound of Beta distribution of outer diameter weld axial stress concentration factor
KWODT2 $\theta$ Uniform distribution upper bound of Beta distribution of outer diameter weld axial stress concentration factor

Inner diameter weld axial stress concentration factor Beta distribution information

The inner diameter weld axial stress concentration factor is characterized by a Beta distribution. See Section 2.1.3.1 and Equation 2-54 for defining parameters for setting
up a Beta driver distribution. The first two parameters are the lower and upper bounds, respectively, for the inner diameter weld axial stress concentration factor. The next two parameters are the lower and upper bounds for the Uniform distribution on $p$. Similarly, the last two parameters describe the Uniform distribution on $\theta$. The inner diameter weld axial stress concentration factor is used to calculate $K_{T_1}$ in Equation 2-68.

**KWIDA** inner diameter weld axial stress concentration factor lower bound of Beta distribution

**KWIDB** inner diameter weld axial stress concentration factor upper bound of Beta distribution

**KWIDR1** $p$ Uniform distribution lower bound of Beta distribution of inner diameter weld axial stress concentration factor

**KWIDR2** $p$ Uniform distribution upper bound of Beta distribution of inner diameter weld axial stress concentration factor

**KWIDT1** $\theta$ Uniform distribution lower bound of Beta distribution of inner diameter weld axial stress concentration factor

**KWIDT2** $\theta$ Uniform distribution upper bound of Beta distribution of inner diameter weld axial stress concentration factor

**DIA** $D_i$ lower bound of Beta distribution

**DIB** $D_i$ upper bound of Beta distribution

**DIR1** $p$ Uniform distribution lower bound of Beta distribution of $D_i$

**DIR2** $p$ Uniform distribution upper bound of Beta distribution of $D_i$

**DIT1** $\theta$ Uniform distribution lower bound of Beta distribution of $D_i$

**DIT2** $\theta$ Uniform distribution upper bound of Beta distribution of $D_i$
Wall thickness Beta distribution information

The duct wall thickness is used to calculate the area and calculate $R_o$ in Equation 2-68 and is characterized by a Beta distribution. See Section 2.1.3.1 and Equation 2-54 for defining parameters for setting up a Beta driver distribution. The first two parameters are the lower and upper bounds, respectively, for the wall thickness. The next two parameters are the lower and upper bounds for the Uniform distribution on $\theta$. Similarly, the last two parameters describe the Uniform distribution on $\theta$.

- **THICA**: $t$ lower bound of Beta distribution
- **THICB**: $t$ upper bound of Beta distribution
- **THICR1**: $\rho$ Uniform distribution lower bound of Beta distribution of $t$
- **THICR2**: $\rho$ Uniform distribution upper bound of Beta distribution of $t$
- **THICT1**: $\theta$ Uniform distribution lower bound of Beta distribution of $t$
- **THICT2**: $\theta$ Uniform distribution upper bound of Beta distribution of $t$

Narrow-band random load scale factor distribution information

This line contains the parameters to define the narrow-band random load scale factor $\lambda_{P_{\text{random}}}$ in Equation 2-81. See Section 2.1.3.2 on load scale factors for a detailed description of the parameters $k$, coefficient of variation $C$, and strain gage factor $d$.

- **LAMNA**: lower bound of Uniform distribution of $k$ for the narrow-band random load scale factor
- **LAMNB**: upper bound of Uniform distribution of $k$ for the narrow-band random load scale factor
- **LAMNC**: coefficient of variation $C$ for the narrow-band random load scale factor
- **LAMND**: strain gage factor $d$ for the narrow-band random load scale factor
Sinusoidal load scale factor distribution information
This line contains the parameters to define the sinusoidal load scale factor $\lambda_{D_{\text{SINUSOIDAL}}}$ in Equation 2-81. See Section 2.1.3.2 on load scale factors for a detailed description of the parameters $k$, coefficient of variation $C$, and strain gage factor $d$.

- LAMSA: lower bound of Uniform distribution of $k$ for the sinusoidal load scale factor
- LAMSB: upper bound of Uniform distribution of $k$ for the sinusoidal load scale factor
- LAMSC: coefficient of variation $C$ for the sinusoidal load scale factor
- LAMSD: strain gage factor $d$ for the sinusoidal load scale factor

TIMUA TIMUB TISIGA TISIGB
[RE] [RE] [RE] [RE]

Inner wall temperature Normal distribution information
$T_i$ (°R) the inner wall temperature is used to calculate the temperature difference across the wall of the duct, $\Delta T$ (°R) in Equation 2-70, and is characterized by a Normal distribution.

- TIMUA: $\mu$ Uniform distribution lower bound of Normal distribution of $T_i$
- TIMUB: $\mu$ Uniform distribution upper bound of Normal distribution of $T_i$
- TISIGA: $\sigma$ Uniform distribution lower bound of Normal distribution of $T_i$
- TISIGB: $\sigma$ Uniform distribution upper bound of Normal distribution of $T_i$

TOMUA TOMUB TOSIGA TOSIGB
[RE] [RE] [RE] [RE]

Outer wall temperature Normal distribution information
$T_o$ (°R) the outer wall temperature is used to calculate the temperature difference across the wall of the duct, $\Delta T$ (°R) in Equation 2-70, and is characterized by a Normal distribution.

- TOMUA: $\mu$ Uniform distribution lower bound of Normal distribution of $T_o$
- TOMUB: $\mu$ Uniform distribution upper bound of Normal distribution of $T_o$
- TOSIGA: $\sigma$ Uniform distribution lower bound of Normal distribution of $T_o$
- TOSIGB: $\sigma$ Uniform distribution upper bound of Normal distribution of $T_o$
Inner wall pressure Normal distribution information $p_i$ (psi) in Equation 2-68. This is the inner wall pressure and it is characterized by a Normal distribution.

PCMUA $\mu$ Uniform distribution lower bound of Normal distribution of $p_i$
PCMUB $\mu$ Uniform distribution upper bound of Normal distribution of $p_i$
PCSIGA $\sigma$ Uniform distribution lower bound of Normal distribution of $p_i$
PCSIGB $\sigma$ Uniform distribution upper bound of Normal distribution of $p_i$

AERDA AERDB

Dynamic aerodynamic load scale factor distribution information $\lambda_{D_{AERO}}$ in Equation 2-81. This is the dynamic aerodynamic load scale factor and it is characterized by a Uniform distribution.

AERDA dynamic aerodynamic load scale factor Uniform distribution lower bound
AERDB dynamic aerodynamic load scale factor Uniform distribution upper bound

AERSA AERSB

Static aerodynamic load scale factor distribution information $\lambda_{ST_{AERO}}$ in Equation 2-81. This is the static aerodynamic load scale factor and it is characterized by a Uniform distribution.

AERSA static aerodynamic load scale factor Uniform distribution lower bound
AERSB static aerodynamic load scale factor Uniform distribution upper bound

DSTRA DSTRB

6 - 56
The dynamic stress analysis accuracy factor Uniform distribution information \( \lambda_{\text{DYN}} \) in Equation 2-81. This is the dynamic stress analysis accuracy factor and it is characterized by a Uniform distribution.

- **DSTRA**: Dynamic stress analysis accuracy factor Uniform distribution lower bound
- **DSTRB**: Dynamic stress analysis accuracy factor Uniform distribution upper bound

Aerodynamic stress analysis accuracy factor Uniform distribution information \( \lambda_{\text{AERO}} \) in Equation 2-81. This is the aerodynamic stress analysis accuracy factor and it is characterized by a Uniform distribution.

- **ASTRA**: Aerodynamic stress analysis accuracy factor Uniform distribution lower bound
- **ASTRB**: Aerodynamic stress analysis accuracy factor Uniform distribution upper bound

Weld offset accuracy factor Uniform distribution information \( \lambda_{\text{OFF}} \) in Equation 2-73. This is the weld offset eccentricity stress concentration accuracy factor and it is characterized by a Uniform distribution.

- **LAMWA**: Weld offset accuracy factor Uniform distribution lower bound
- **LAMWB**: Weld offset accuracy factor Uniform distribution upper bound

Neuber's Rule accuracy factor Uniform distribution information \( \lambda_{\text{neu}} \) in Equation 2-89. This is the Neuber's Rule accuracy factor and it is characterized by a Uniform distribution.

- **NEUBA**: Neuber's Rule accuracy factor Uniform distribution lower bound
- **NEUBB**: Neuber's Rule accuracy factor Uniform distribution upper bound

R - 6
Damage accumulation model accuracy factor distribution information
This line contains the Uniform distribution bounds in loge space for the damage accumulation model accuracy factor $\lambda_{\text{dam}}$ in Equation 2-91. See Section 2.2.1.4 for a discussion of the damage accumulation calculations.

- **GAMA**: lower bound on damage accumulation accuracy factor
- **GAMB**: upper bound on damage accumulation accuracy factor

Load and Geometry block

**NLOAD**

[Int]

Number of dynamic loads
Total number of dynamic or time-varying loads. **NLOAD** cannot exceed 16.

**PSTAT**  **TSTAT**  **MSTAT(1)**  **MSTAT(2)**  **VSTAT(1)**  **VSTAT(2)**

[RE]  [RE]  [RE]  [RE]  [RE]  [RE]

Static loads
This line contains the six beam-end force components due to static aerodynamic loads.

- **PSTAT**: $P$ (lbs) in Equation 2-68, the static axial load component
- **TSTAT**: $M_x$ (in.-lbs) in Equation 2-72, the static torsional load component
- **MSTAT(1)**: $M_y$ (in.-lbs) in Equation 2-68, the static moment load component about the $y$ axis
- **MSTAT(2)**: $M_z$ (in.-lbs) in Equation 2-68, the static moment load component about the $z$ axis
- **VSTAT(1)**: $V_y$ (lbs) in Equation 2-72, the static shear load component along the $y$ axis
- **VSTAT(2)**: $V_z$ (lbs) in Equation 2-72, the static shear load component along the $z$ axis
<table>
<thead>
<tr>
<th>LDNAME(I)</th>
<th>TYPE(I)</th>
<th>P(I)</th>
<th>T(I)</th>
<th>M(1,I)</th>
<th>M(2,I)</th>
<th>V(1,I)</th>
<th>V(2,I)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[CHR]</td>
<td>[INT]</td>
<td>[RE]</td>
<td>[RE]</td>
<td>[RE]</td>
<td>[RE]</td>
<td>[RE]</td>
<td>[RE]</td>
</tr>
</tbody>
</table>

**Dynamic loads**

This line contains the dynamic load file names, load types, and the six components of the beam-end force magnitudes. A total of NLOAD lines must be specified (i.e., the value of I goes from 1 to NLOAD).

- **LDNAME(I)**: File names containing the reference time history for load I. The file name cannot be more than six characters long and must be enclosed by single quotes.
- **TYPE(I)**: Load-type of load I, used to assign the appropriate load scale factor
  - TYPE(I) = 1 Narrow-band random load
  - TYPE(I) = 2 Sinusoidal load
  - TYPE(I) = 3 Dynamic aerodynamic load
- **P(I)**: \( P \, (\text{lbs}) \) in Equation 2-68, the dynamic axial load magnitude for load I
- **T(I)**: \( M_x \, (\text{in.-lbs}) \) in Equation 2-72, the dynamic torsional load magnitude for load I
- **M(1,I)**: \( M_y \, (\text{in.-lbs}) \) in Equation 2-68, the dynamic moment load magnitude about the y axis for load I
- **M(2,I)**: \( M_z \, (\text{in.-lbs}) \) in Equation 2-68, the dynamic moment load magnitude about the z axis for load I
- **V(1,I)**: \( V_y \, (\text{lbs}) \) in Equation 2-72, the dynamic shear load magnitude along the y axis for load I
- **V(2,I)**: \( V_z \, (\text{lbs}) \) in Equation 2-72, the dynamic shear load magnitude along the z axis for load I

<table>
<thead>
<tr>
<th>KGOD</th>
<th>KGID</th>
<th>KT(2,1)</th>
<th>KT(2,2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[RE]</td>
<td>[RE]</td>
<td>[RE]</td>
<td>[RE]</td>
</tr>
</tbody>
</table>

**Fatigue stress concentration factors**

Geometric axial and hoop fatigue stress concentration factors. The geometric axial stress concentration factors are used to calculate the total axial stress concentration factor, \( K_{T1} \) in Equation 2-68, by the multiplication of the geometric factors KGOD and KGID, and the weld factors KWOD and KWID, specified above.

- **KGOD**: outer diameter axial geometric stress concentration factor
- **KGID**: inner diameter axial geometric stress concentration factor
- **KT(2,1)**: outer diameter hoop stress concentration factor, \( K_{T2} \) in Equation 2-69
- **KT(2,2)**: inner diameter hoop stress concentration factor, \( K_{T2} \) in Equation 2-69
PCO

(RE)

External pressure
$p_o$ (psi) in Equation 2-68. This is the outer wall pressure.

LOCAT

(INT)

Critical location
Critical location of interest on the duct wall.

$\text{LOCAT} = 1$ outer wall

$\text{LOCAT} = 2$ inner wall

ANGLE

(RE)

Critical angle
$\phi$ (degrees) in Equation 2-68. This is the angle measured counterclockwise from the Z-direction to the critical circumferential location of the duct.

PERIOD

(RE)

Period
$T$ (sec) in Equation 2-91. This is the period of the reference time histories, and it is required so that life may be provided in seconds.

TRUNC

(RE)

Noise filter
Value (psi) used to filter out the insignificant cycles in the composite stress-time history during rainflow cycle counting.

NRAN

(RE)

Number of history points
Number of points in the reference time history files for the dynamic loads. NRAN cannot exceed 24,000.
EM  COEXP  NU
[RE]  [RE]  [RE]

Materials information
This line contains the elastic modulus, thermal expansion, and Poisson's ratio.

EM
$E$ (psi) in Equation 2-70, Young's modulus of elasticity

COEXP
$\alpha$ ($^\circ$R) in Equation 2-70, the coefficient of thermal expansion

NU
$\nu$ in Equation 2-70, the materials Poisson's ratio

FK(I)  RT(I)
[RE]  [RE]

$F_k$ versus $R/t$ curve
$F_k$ versus $R/t$ points for each segment of the curve are used by Equation 2-73 in the weld offset eccentricity stress concentration calculations. A block of 10 segments must be provided (i.e., the value of $I$ goes from 1 to 10). Both $FK$ and $RT$ must be positive and increase with increasing $I$ (i.e., $I = 1$ is the lower bound of the first segment and $I = 10$ is the upper bound of the last segment).

FK(I)  $F_k(R/t)$ value
RT(I)  $R/t$ value

NUMSEG
[INT]

Number of segments
The number of piecewise linear segments in the stress-strain versus strain curve required by Equation 2-88.

SE(J)  E(J)
[RE]  [RE]

Stress-strain versus strain curve
$\sigma\epsilon$ versus $\epsilon$ points for each segment of the $\sigma$ vs. $\epsilon$ curve are used in the Neuber's Rule calculations in Equations 2-88 and 2-89. A block of NUMSEG lines must be provided (i.e., the value of $J$ goes from 1 to NUMSEG). Both SE and E must be positive and increase with increasing $J$ as HEXHCF assumes that the $J = 0$ point is at the origin.
\[ SE(J) \quad \text{value of the product of stress and strain, } \sigma e, \text{ at the upper end of the } \]
\[ E(J) \quad \text{value of the strain } \epsilon \text{ at the upper end of the } J \text{th segment of the stress-strain versus strain curve} \]

**Materials Information Block**

**DESCRP(0)**

[CHR]

Description of specific material S/N data set

Name and test environment for the specific material S/N data. This is a character string no more than 40 characters long, enclosed by single quotes.

**FTY**  **FTU**  **NDIV**  **NPTS(0)**

[RE]  [RE]  [INT]  [INT]

Specific materials information

Yield strength, ultimate strength, number of divisions of data, number of points in S/N data set. The data may be divided when they are assigned to a different life region or have different stress ratios. **NPTS (0)** cannot exceed fifty. The next two data sets have to be provided for each data division.

**NUM**  **RATIO**  **REG**

[INT]  [RE]  [INT]

Materials information for each data division of the specific S/N data set

Number of points, stress ratio, and the life region of interest for each data division. This line must be provided for each data division.

**NUM**  **RATIO**  **REG**

number of S/N data points in the data division

stress ratio for the data in the data division

life region number to be assigned to the data in the data division

6 - 62
Specific material S/N data points
Stress versus fatigue life data points for each data division. A block of NUM lines must be specified (i.e., the value of I goes from 1 to NUM). This block must be provided for each data division.

\[
\text{RAWSTR}(I,0) \quad \text{stress value (psi)} \\
\text{RAWNF}(I,0) \quad \text{fatigue life value (cycles)} 
\]

SZERO

Tensile point
Stress tensile point \(S_o\) (psi). Must be non-negative. A value of zero indicates no tensile point. For HCF applications, this aspect of the materials model has been disabled, however, a value of SZERO must be provided.

NUMREG NNODAT

Data regions
Number of life regions that are data-determined and not data-determined. NUMREG + NNODAT cannot exceed three. NUMREG must be 1, 2, or 3, and NNODAT must be non-negative, and should be 0 or 1.

\[
\begin{align*}
\text{NUMREG} & \quad \text{number of life regions determined by data} \\
\text{NNODAT} & \quad \text{number of life regions (to the right) not determined by data}
\end{align*}
\]

NBND(L)

Life Boundaries
The upper boundaries of the life regions are specified (cycles). The value of L goes from ZROREG to the total number of regions (equal to NUMREG + NNODAT). If a

---

16 Extension of the S/N curve to the left is discussed on Page 2-17.
17 Extension of the S/N curve to the right is discussed on Page 2-17.
18 Life region boundaries are discussed on Page 2-15.
non-zero tensile point is specified, then ZROREG = 0 else ZROREG = 1. The program expects the upper bound of the last life region to be $10^{36}$, a proxy for $\infty$.

CZERO

Prior information on coefficient of variation of fatigue strength

Information in the form of a constraint on the coefficient of variation of fatigue strength $C$ for the specific material S/N data set. Value must be non-negative and a value of zero indicates that CZERO is not in use.

**MPNT(L) MZERO(1,L) MZERO(2,L)**

Prior information on the materials shape parameter $m$

The number of MZERO values in each life region, and the lower and upper bound for the range of $m$. The value of L goes from 1 to (NUMREG + NNODAT). If VARY = 3 is specified (truncated Normal distribution on $m$), then a prior range of $m$ must be specified for each region.

**DELTA(L) MO(L) SIGMA2(L)**

Information on the Bayesian prior distribution for the truncated Normal distribution

If VARY = 3, then the materials model uses the truncated Normal distribution. The truncated Normal distribution requires some prior information on the Normal distribution parameters because a Bayesian analysis is performed. The information is required for each life region. The value of L goes from 1 to (NUMREG + NNODAT).

---

19 The implicit constraint on the materials shape parameter provided by prior information on the coefficient of variation of fatigue strength is discussed on Pages 2-12 through 2-13.

20 The explicit constraint on the materials shape parameter provided by prior information on the materials shape parameter is discussed on Page 2-12.

21 Specification of the Bayesian prior distribution for the truncated Normal case is discussed on Page 2-14.
DELTA(L)  The shape parameter $\delta$ of the Bayesian prior distribution is used to compute the Bayesian posterior distribution parameters. Value must be non-negative, a value of zero indicates a diffuse prior distribution.

MO(L)  Location parameter $m_0$ of the Bayesian prior distribution of the shape parameter $m$. Must be positive. Required when DELTA(L) is non-zero.

SIGMA2(L)  $\sigma^2$, the known variance of $\ln(fatigue\ life)$, $V(\ln N | \ln S)$. Must be non-negative.

KRATIO  LAMN  
[RE]  [RE]

Materials process variation information
If MPROC = 1, then specification of KRATIO and LAMN is required. KRATIO is $\lambda_K^*$, the ratio $\text{MED} K'/\text{MED} K$ where $\text{MED} K^*$ is the median value over all heats for the stress (psi) at a life of one cycle, and $\text{MED} K$ is the median value for the specific S/N data for the stress (psi) at a life of one cycle. LAMN is the ratio of the variance of $\ln(life)$ conditional on stress over all heats to the intrinsic materials variation for the given S/N data conditional on stress. Process variation in materials is discussed in Section 2.1.2.3.

6.1.10.2 Input File RELATD
The input data for file RELATD, which contains the related materials information, is given below. The data format is similar to that used to specify the S/N data in the specific materials information block in the HEXHCD file.

NSETS  
[INT]

Number of related data sets
Number of related material S/N data sets. The following data groups have to be repeated as a block for each data set. The value of J varies from 1 to NSETS. If there is no related data, then file RELATD will only contain the number "0". NSETS cannot exceed five.

DESCRP(J)  
[CHR]

---

22 Related S/N data is discussed on Page 2-7.
Description of related material S/N data set

Name and test environment for related material S/N data set J. This is a character string no more than 40 characters long, enclosed by single quotes.

<table>
<thead>
<tr>
<th>FTY</th>
<th>FTU</th>
<th>NDIV</th>
<th>NPTS(J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[RE]</td>
<td>[RE]</td>
<td>[INT]</td>
<td>[INT]</td>
</tr>
</tbody>
</table>

Related materials information

Yield strength, ultimate strength, number of divisions of data, number of points in S/N data set. The data may be divided when they are assigned to a different life region or have different stress ratios. If all data has a stress ratio of \(-1.0\), then the yield and ultimate strengths are not required, but zero values must be specified as placeholders. \(\text{NPTS}(J)\) cannot exceed fifty. The next two data sets have to be provided for each data division.

<table>
<thead>
<tr>
<th>FTY</th>
<th>yield strength corresponding to related material data set J (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FTU</td>
<td>ultimate strength corresponding to related material data set J (psi)</td>
</tr>
<tr>
<td>NDIV</td>
<td>number of data divisions for related material data set J</td>
</tr>
<tr>
<td>NPTS(J)</td>
<td>total number of points in related material S/N data set J</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>NUM</th>
<th>RATIO</th>
<th>REG</th>
</tr>
</thead>
<tbody>
<tr>
<td>[INT]</td>
<td>[RE]</td>
<td>[INT]</td>
</tr>
</tbody>
</table>

Materials information for each data division of the related S/N data set

Number of points, stress ratio, and the life region of interest for each data division. This line must be provided for each data division.

<table>
<thead>
<tr>
<th>NUM</th>
<th>number of S/N data points in the data division</th>
</tr>
</thead>
<tbody>
<tr>
<td>RATIO</td>
<td>stress ratio for the data in the data division</td>
</tr>
<tr>
<td>REG</td>
<td>life region number to be assigned to the data in the data division</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>RAWSTR(I,J)</th>
<th>RAWNF(I,J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[RE]</td>
<td>[RE]</td>
</tr>
</tbody>
</table>

Related material S/N data points

Stress versus fatigue life data points for each data division. A block of NUM lines must be specified (i.e., the value of \(I\) goes from 1 to \(\text{NUM}\)). This block must be provided for each data division.

<table>
<thead>
<tr>
<th>RAWSTR(I,J)</th>
<th>stress value (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAWNF(I,J)</td>
<td>fatigue life value (cycles)</td>
</tr>
</tbody>
</table>
6.1.10.3 Reference Time History Files

The data format for the reference time history files is given below. There must be NLOAD files with the same names, as specified by LDNAME(I) in file HEXHCD. Reference time histories are typically generated by program NBSIN described in Sections 4.5, 6.6, and 7.7.

STRHIS(I,J)
[RE]

The points of the Ith reference time history
The points of the time history specified by LDNAME(I). The data is entered one point per line for J = 1, ..., NRAN.

6.1.11 Options and Capabilities

HEXHCF is a Monte Carlo simulation program which generates a sequence of component lives for a particular failure mode, where life is defined as the accumulated operating time at failure. The simulation has a double-loop structure with NHYPER outer loops and NLIFE inner loops. The simulation size is dependent on the failure probability at which a life estimate is desired and the precision desired. For the HEX application, single-loop runs with NHYPER = 20,000 and NLIFE = 1 were used to characterize component reliability, and single-loop runs with NHYPER = 1000 and NLIFE = 1 were used for the marginal analysis to assess the importance of drivers.

During a run, it may be desirable to “hold” a driver at a fixed value. This may be the nominal or median value of the driver. This is done for drivers with a Beta or a Uniform distribution by merely specifying both the upper and lower bounds to be the desired value. For drivers with a Normal distribution, the standard deviation \( \sigma \), or coefficient of variation \( C \), is set at zero and the mean \( \mu \) is set at the desired value.

The procedure of holding certain drivers at fixed values while letting the other drivers vary according to their probability distributions may be used for driver variation sensitivity studies. That is, the effect on life of driver variation may be evaluated by letting it vary while holding other drivers at fixed values. Each driver variation sensitivity was determined in the case studies of this report with the intrinsic variation of the fatigue life of the material included (VARY = 1).

A printout of intermediate calculations in various parts of the program may be obtained via the IOUT option. This output will be printed in the IOUTPR file. It is recommended that such output not be requested when the simulation size is large.
since the information will be dumped during every simulation loop. The NMED option provides for calculation of an empirical median S/N curve if the truncated Normal distribution is employed.\textsuperscript{23} In this case, the median S/N curve is based on the empirical median $m$ from all the shape parameters used in the simulation. The MPROC option activates the computations for the process variation feature of the materials characterization model, as discussed in Section 2.1.2.3.

### 6.1.12 Code Execution Example

The following example run of the HCF analysis code HEXHCF was carried out with random variation of all drivers for the HPOTP heat exchanger coil small tube outlet. In this example run, 1000 lives were simulated ($\text{NLIFE} = 1 \times \text{NHYPHER} = 1000$) by using Uniform shape parameter variation, $\text{VARY} = 2$ and $\text{NMED} = 0$; and no materials process variation, $\text{MPROC} = 0$. The B-lives\textsuperscript{24} to be provided are B.1, B.2, B.3, B.4, B.5, B.6, B.7, B.8, B.9, and B1 ($\text{NBLIFE} = 10, \text{BLFPER}(1) = 0.001, \text{BLFPER}(2) = 0.002, \text{BLFPER}(3) = 0.003, \text{BLFPER}(4) = 0.004, \text{BLFPER}(5) = 0.005, \text{BLFPER}(6) = 0.006, \text{BLFPER}(7) = 0.007, \text{BLFPER}(8) = 0.008, \text{BLFPER}(9) = 0.009, \text{BLFPER}(10) = 0.01$). The user may refer to Section 2.2.1.5 for additional information on the engineering analysis and to Section 3.2 for the results of the case study for this component.

Figure 6-6 shows the component in detail and the location of the critical weld, designated as $\Delta$. The external pressure $\text{PCO}$ is 3640 psi. All geometric axial and

\textsuperscript{23} The truncated Normal distribution for the materials model shape parameter $m$ is discussed on Page 2-14.

\textsuperscript{24} A B-life is the value of accumulated operating time to failure at a failure probability specified as a percent; e.g., B.1 is the failure time at a probability of 0.001 or 0.1%.
hoop stress concentration factors are one, \( KGOD = KGID = KT(2,1) = KT(2,2) = 1.0 \). The elastic modulus \( EM \) is \( 2.9 \times 10^7 \), the coefficient of thermal expansion \( COEXP \) is \( 8.8 \times 10^{-6} \), and Poisson’s ratio \( \nu \) is 0.30 for the material.

The drivers for the HCF failure of weld 3 are as follows:

<table>
<thead>
<tr>
<th>DRIVER</th>
<th>DISTRIBUTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Weld Offset</td>
<td>Beta</td>
</tr>
<tr>
<td>2. ( K_T ) Weld Factors</td>
<td>Beta</td>
</tr>
<tr>
<td>3. Inner Diameter</td>
<td>Beta</td>
</tr>
<tr>
<td>4. Wall Thickness</td>
<td>Beta</td>
</tr>
<tr>
<td>5. Random &amp; Sine Load Scale Factors</td>
<td>Normal</td>
</tr>
<tr>
<td>6. Flow Conditions</td>
<td>Normal</td>
</tr>
<tr>
<td>7. ( K_T ) Weld Offset Eccentricity Accuracy</td>
<td>Uniform</td>
</tr>
<tr>
<td>8. Neuber’s Rule Accuracy</td>
<td>Uniform</td>
</tr>
<tr>
<td>9. Dynamic Aerodynamic Load Scale Factor</td>
<td>Uniform</td>
</tr>
<tr>
<td>10. Static Aerodynamic Load Scale Factor</td>
<td>Uniform</td>
</tr>
<tr>
<td>11. Dynamic Stress Analysis Accuracy Factor</td>
<td>Uniform</td>
</tr>
<tr>
<td>12. Aerodynamic Stress Analysis Accuracy Factor</td>
<td>Uniform</td>
</tr>
<tr>
<td>13. Damage Accumulation Model Accuracy</td>
<td>Uniform</td>
</tr>
</tbody>
</table>

The rationale for the specification of the driver distributions is given in Section 3.2.2. The weld offset was held at 6% by fixing the upper and lower bounds of the distribution at \( WOFFA = WOFFB = 0.06 \).

In addition to the static loads, there were one narrow-band random load, one sinusoidal load, and one dynamic aerodynamic load. The three dynamic loads (\( NLOAD = 3 \)) used here are a subset of the significant loads for this component. The procedure for identifying the significant loads is described in Sections 2.2.1.5, 2.3.7, and 3.A.2.5. The three reference time histories are in the files named NBM3, SIN1, and AERO1, and the contents of these input files are given below. The reference time histories have five points (\( NRAN = 5 \)) and represent 0.00025 seconds (\( PERIOD = 0.00025 \)) of the loading. The reference time histories used for the case studies of the HEX coil small tube outlet given in Section 3.2 consisted of 17,800 points. Shorter histories are used here to permit their inclusion in this example. The critical location is the inner wall (\( LOCAT = 2 \)) at a circumferential position of \( \text{ANGLE} = 85^\circ \).

Thirteen S/N data points, \( \text{NUM} = 13 \) with a stress ratio of \( -1.0 \) (\( \text{RATIO} = -1.0 \)) are provided. The number of regions with data, \( \text{NUMREG} \), is 1, and there are no regions to the right without data, \( \text{NNODAT} = 0 \). The data is in one division, \( \text{NDIV} = 1 \), and the total number of points is thirteen, \( \text{NPTS(0)} = 13 \). No related data is provided. Thus, the
The input file HEXHCD is empty, except for a single entry to indicate NSETS = 0. If further explanation of file HEXHCD is required, refer to Section 6.1.10.1 and Figure 6-5.

The echo of the input data is in the output file HEXHCO. The simulated B-lives are also given for the component. For instance, the B.1 life is 4.5x10^9 seconds. This value is different from the B.1 life obtained during the case study of this component as given in Section 3.2.4 because the number and size of the reference time histories and the number of simulation trials have been reduced to facilitate the example run. There are only three time histories with just five points each used here, and therefore they do not properly represent the loads. Also, the F_k versus R/t curve is only an example curve.

The IOUTPR file gives an echo of the analysis parameters. The dump parameter IOUT is zero; therefore, no other output is in this file. The LOWLIF file contains the lowest one percent of the 1000 simulation lives. Finally, the DUMP file contains the results of the materials characterization model information aggregation calculations.

Input File - HEXHCD

```
675
0
1
1000
2
0
10
0.001
0.002
0.003
0.004
0.005
0.006
0.007
0.008
0.009
0.01
0.06  0.06  0.00  0.00  0.0  0.0
0.00  0.00  0.00  0.00  0.0  0.0
1.00
1.00  1.00  0.00  0.00  0.0  0.0
1.20  3.50  0.1304  0.5652  10.  10.
0.1885  0.1915  0.50  0.50  0.5  20.
0.0113  0.0157  0.27273  0.27273  0.5  20.
```

The information aggregation calculations are discussed on Pages 2-6 through 2-14.
2.00 2.00 0.15 1.00
2.00 2.00 0.20 1.00
486. 666. 29. 56.5
799. 908. 49.5 48.
3808. 4177. 69. 69.
0.50 1.50
0.80 1.20
0.80 1.20
0.90 1.10
0.80 1.20
0.60 1.40
-1.38629 0.95166
3
0.00 0.00 -0.07214 0.00 0.00 0.00
'NBM3' 1 0.00 0.00 0.00 0.355475 0.00 0.00
'SIN1' 2 0.027374 0.000451 0.001621 0.082116 0.205288 0.005789
'AERO1' 3 0.00 0.00 0.00 0.07179 0.00 0.00
1.0 1.0 1.0 1.0
3640.
2
85.
0.00025
0.0
5
29000000. 8.8E-06 0.30
0.615 2.00
0.693 4.80
0.753 7.20
0.813 9.60
0.873 12.50
0.933 15.80
0.993 20.00
1.029 24.00
1.053 30.00
1.053 200.00
6
21.95 0.001
55.77 0.002
144.85 0.005
322.73 0.010
1945.90 0.050
50688.0 0.660
'70 F, 321 STAINLESS STEEL ALLOY - WELDED'
27900. 76800. 1 13
13 -1.0 1
40000. 1000.
40000. 3000.
40000. 4000.
40000. 5000.
<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>40000</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>30000</td>
<td>23000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30000</td>
<td>66000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25000</td>
<td>72000</td>
<td></td>
<td></td>
</tr>
<tr>
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<td>190000</td>
<td>789000</td>
<td></td>
</tr>
<tr>
<td>20000</td>
<td>107000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20000</td>
<td>145000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.00</td>
<td>1.0E+36</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.00</td>
<td>0.000</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Input File - RELATD**

0

**Input File - NBM3**

- 0.9396865670744
- 0.9325857187916
- 1.132583595703
- 1.378186790842
- 1.546197891515

**Input File - SIN1**

-0.9766760261059
-0.9310621841538
-0.8625225012037
-0.7727446517203
-0.6639392643142

**Input File - AERO1**

-1.202208564616
-2.176975899958
-2.250379923423
-1.314959553996
-0.5704567649678

6 - 72
Output File - HEXHCO

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## INPUT DATA

<table>
<thead>
<tr>
<th>DRIVERS</th>
<th>PARAMETER DISTRIBUTIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>WELD OFFSET (%)</td>
<td>RHO</td>
</tr>
<tr>
<td>Be(0.06, 0.06)</td>
<td>U(0.00000, 0.00000)</td>
</tr>
<tr>
<td>Be(0.00, 0.00)</td>
<td>U(0.00000, 0.00000)</td>
</tr>
<tr>
<td>K WELD (OD)</td>
<td></td>
</tr>
<tr>
<td>Be(1.00, 1.00)</td>
<td>U(0.00000, 0.00000)</td>
</tr>
<tr>
<td>K WELD (ID)</td>
<td></td>
</tr>
<tr>
<td>Be(1.20, 3.50)</td>
<td>U(0.13040, 0.56520)</td>
</tr>
<tr>
<td>INNER DIAMETER</td>
<td></td>
</tr>
<tr>
<td>Be(0.1885, 0.1915)</td>
<td>U(0.50000, 0.50000)</td>
</tr>
<tr>
<td>WALL THICKNESS</td>
<td></td>
</tr>
<tr>
<td>Be(0.0113, 0.0157)</td>
<td>U(0.27273, 0.27273)</td>
</tr>
</tbody>
</table>

### LAMBDA RANDOM

- **k**: U(2.00000, 2.00000)
- COEFFICIENT OF VARIATION: 0.150
- STRAIN GAGE FACTOR: 1.0000000

### LAMBDA SINE

- **k**: U(2.00000, 2.00000)
- COEFFICIENT OF VARIATION: 0.200
- STRAIN GAGE FACTOR: 1.0000000

<table>
<thead>
<tr>
<th>MU</th>
<th>SIGMA</th>
</tr>
</thead>
<tbody>
<tr>
<td>INNER TEMPERATURE</td>
<td>NORMAL: U(486.0, 666.0)</td>
</tr>
<tr>
<td>OUTER TEMPERATURE</td>
<td>NORMAL: U(799.0, 908.0)</td>
</tr>
<tr>
<td>INNER PRESSURE</td>
<td>NORMAL: U(3808.0, 4177.0)</td>
</tr>
<tr>
<td>DYNAMIC AERO LOAD FACTOR</td>
<td>U(0.50000, 1.50000)</td>
</tr>
<tr>
<td>STATIC AERO LOAD FACTOR</td>
<td>U(0.80000, 1.20000)</td>
</tr>
<tr>
<td>DYNAMIC STRESS ANALYSIS</td>
<td>U(0.80000, 1.20000)</td>
</tr>
</tbody>
</table>
AERO STRESS ANALYSIS

LAMBDA KOFF

NEUBERS RULE

DAMAGE MODEL ACCURACY

U( 0.90000, 1.10000)

U( 0.80000, 1.20000)

U( 0.60000, 1.40000)

U(ln 0.25000, ln 2.59001)

LOADS INPUT

<table>
<thead>
<tr>
<th>P LOADS</th>
<th>T LOADS</th>
<th>M2 LOADS</th>
<th>M3 LOADS</th>
<th>V2 LOADS</th>
<th>V3 LOADS</th>
</tr>
</thead>
<tbody>
<tr>
<td>(LBS)</td>
<td>(IN.-LBS)</td>
<td>(IN.-LBS)</td>
<td>(IN.-LBS)</td>
<td>(LBS)</td>
<td>(LBS)</td>
</tr>
<tr>
<td>STATIC AERO</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
</tr>
<tr>
<td>NBM3</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.355475</td>
<td>0.000000</td>
</tr>
<tr>
<td>SIN1</td>
<td>0.027374</td>
<td>0.000451</td>
<td>0.001621</td>
<td>0.082116</td>
<td>0.205288</td>
</tr>
<tr>
<td>AERO1</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.071790</td>
<td>0.000000</td>
</tr>
</tbody>
</table>

GEOMETRIC AND OTHER INPUT

| K GEOM (OD) | 1.00 |
| K GEOM (ID) | 1.00 |
| K HOOP (OD) | 1.00 |
| K HOOP (ID) | 1.00 |

EXTERNAL PRESSURE, PSI

3640.

ANALYSIS LOCATION

2

ANGLE THETA (DEGREES)

85.0

STRESS-TIME HISTORY PERIOD, SEC

0.00

STRESS-TIME HISTORY NOISE FILTER, PSI

0.0
NUMBER OF TIME-VARYING LOADS 3
NUMBER OF POINTS IN HISTORIES 5
ANGLE THETA (RADIANS) 1.48
ELASTIC MODULUS, PSI 0.290E+08
COEFF OF THERMAL EXPANSION 0.88000000E-05
POISSONS RATIO 0.300

STRESS-STRAIN CURVE INPUT

MAXIMUM NUMBER OF SEGMENTS 6

<table>
<thead>
<tr>
<th>STRESS-STRAIN PRODUCT</th>
<th>STRAIN VALUES</th>
</tr>
</thead>
<tbody>
<tr>
<td>21.95</td>
<td>0.00100</td>
</tr>
<tr>
<td>55.77</td>
<td>0.00200</td>
</tr>
<tr>
<td>144.85</td>
<td>0.00500</td>
</tr>
<tr>
<td>322.73</td>
<td>0.01000</td>
</tr>
<tr>
<td>1945.90</td>
<td>0.05000</td>
</tr>
<tr>
<td>50688.00</td>
<td>0.66000</td>
</tr>
</tbody>
</table>

MATERIAL INPUT

DESCRIPTION: 70 F, 321 STAINLESS STEEL ALLOY - WELDED

YIELD STRENGTH 0.27900E+05
ULTIMATE STRENGTH 0.76800E+05
NUMBER OF POINTS 13

ORIGINAL S/N STRESS TRANSFORMED S/N

6 - 75
<table>
<thead>
<tr>
<th>STRESS</th>
<th>LIFE</th>
<th>RATIO</th>
<th>REGION</th>
<th>STRESS</th>
<th>LIFE</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.40000E+05</td>
<td>1000.</td>
<td>-1.00</td>
<td>1</td>
<td>0.40000E+05</td>
<td>1000.</td>
</tr>
<tr>
<td>0.40000E+05</td>
<td>2000.</td>
<td>-1.00</td>
<td>1</td>
<td>0.40000E+05</td>
<td>2000.</td>
</tr>
<tr>
<td>0.40000E+05</td>
<td>3000.</td>
<td>-1.00</td>
<td>1</td>
<td>0.40000E+05</td>
<td>3000.</td>
</tr>
<tr>
<td>0.40000E+05</td>
<td>4000.</td>
<td>-1.00</td>
<td>1</td>
<td>0.40000E+05</td>
<td>4000.</td>
</tr>
<tr>
<td>0.40000E+05</td>
<td>5000.</td>
<td>-1.00</td>
<td>1</td>
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<td>5000.</td>
</tr>
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<td>0.40000E+05</td>
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<td>1</td>
<td>0.40000E+05</td>
<td>6000.</td>
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<tr>
<td>0.30000E+05</td>
<td>23000.</td>
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<td>1</td>
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<td>23000.</td>
</tr>
<tr>
<td>0.30000E+05</td>
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<td>-1.00</td>
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<td>66000.</td>
</tr>
<tr>
<td>0.25000E+05</td>
<td>72000.</td>
<td>-1.00</td>
<td>1</td>
<td>0.25000E+05</td>
<td>72000.</td>
</tr>
<tr>
<td>0.25000E+05</td>
<td>190000.</td>
<td>-1.00</td>
<td>1</td>
<td>0.25000E+05</td>
<td>190000.</td>
</tr>
<tr>
<td>0.20000E+05</td>
<td>789000.</td>
<td>-1.00</td>
<td>1</td>
<td>0.20000E+05</td>
<td>789000.</td>
</tr>
<tr>
<td>0.20000E+05</td>
<td>1070000.</td>
<td>-1.00</td>
<td>1</td>
<td>0.20000E+05</td>
<td>1070000.</td>
</tr>
<tr>
<td>0.20000E+05</td>
<td>1450000.</td>
<td>-1.00</td>
<td>1</td>
<td>0.20000E+05</td>
<td>1450000.</td>
</tr>
</tbody>
</table>

There is 1 region(s) with data
And 0 region(s) to the right without data
The upper bound(s) of the region(s) are (cycles):

0.100E+37

Exogenous Information

Constraint on coefficient of variation, C: 0.0000

Explicit constraint on m for each region:

<table>
<thead>
<tr>
<th>REGION</th>
<th># OF POINTS</th>
<th>LOWER BOUND</th>
<th>UPPER BOUND</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

B lives: Empirical

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00100</td>
<td>0.447327E+10</td>
</tr>
<tr>
<td>0.00200</td>
<td>0.104092E+11</td>
</tr>
<tr>
<td>0.00300</td>
<td>0.191086E+11</td>
</tr>
<tr>
<td>0.00400</td>
<td>0.208025E+11</td>
</tr>
<tr>
<td>0.00500</td>
<td>0.398571E+11</td>
</tr>
<tr>
<td>0.00600</td>
<td>0.662463E+11</td>
</tr>
<tr>
<td>0.00700</td>
<td>0.824330E+11</td>
</tr>
<tr>
<td>0.00800</td>
<td>0.959502E+11</td>
</tr>
</tbody>
</table>

6 - 76
0.00900 0.983484E+11
0.01000 0.103062E+12
0.50000 0.374265E+15

Output File - RELATO

NUMBER OF DATA SETS: 0

NOTE: ALL Kt ASSUMED TO BE 1.0

TRANSFORMED DATA

Output File - DUMP

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RESULTS OF INFORMATION AGGREGATION CALCULATIONS

95% CONFIDENCE INTERVALS ON C AND m FOR EACH REGION

REGION: 1  \( \text{Io} = (0.047421050, 0.113658400) \)
\( \text{Jo} = (7.136659000, 9.595363000) \)

POINT ESTIMATES OF C AND m FOR EACH REGION

\[
\begin{array}{ccc}
\text{REGION} & \text{E(C)} & \text{E(m)} \\
1 & 0.066941450 & 8.366011 \\
\end{array}
\]

POSTERIOR CREDIBILITY RANGE ON m FOR EACH REGION

\[
\begin{array}{ccc}
\text{REGION} & \text{LOWER Bound} & \text{UPPER Bound} \\
1 & 7.1367 & 9.5954 \\
\end{array}
\]

PARAMETER VALUES FOR MEDIAN S/N CURVE
NUMBER OF REGIONS: 1

\[
E(\beta_0) = 19.5380 \\
E(k) = 11.5536
\]

<table>
<thead>
<tr>
<th>REGION</th>
<th>m</th>
<th>K</th>
<th>LIFE BOUND</th>
<th>STRESS BOUND</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.36601</td>
<td>0.10528E+06</td>
<td>0.100E+37</td>
<td>0.000000E+00</td>
</tr>
</tbody>
</table>

Output File - IOUTPR

RANDOM NUMBER SEED = 675.000000000000

IOUT (MATCHR = 10, HEXHCF = 15, THWELD = 25) = 0
INNER LOOP SIZE = 1
OUTER LOOP SIZE = 1000

TYPE OF S/N VARIATION DESIRED = 2
NORMAL MEDIAN CURVE (0 - NO, 1 - YES) = 0
MATERIALS PROCESS VARIATION DESIRED (0 - NO, 1 - YES) = 0

Output File - LOWLIF

1 0.100000E-02 0.447327E+10
2 0.200000E-02 0.104092E+11
3 0.300000E-02 0.191086E+11
4 0.400000E-02 0.208025E+11
5 0.500000E-02 0.398571E+11
6 0.600000E-02 0.662463E+11
7 0.700000E-02 0.824330E+11
8 0.800000E-02 0.959502E+11
9 0.900000E-02 0.983484E+11
10 0.100000E-01 0.103062E+12

6.1.13 Error Messages and Possible Remedies

The following messages, when applicable, will appear in file IOUTPR. These messages are primarily generated by the materials characterization model (MATCHR) portion of HEXHCF. An error message stating that a limit has been exceeded will require that the user increase those limits, as directed, and reviewing or consulting Section 7.3.1.3 is desirable. The messages are listed in alphabetical order for the convenience of the user.

ERROR: BAD VALUE FOR DELTA OR VALUE OF MO INCONSISTENT WITH DELTA IN REGION 'L'

Fatal This error can occur during the use of the truncated Normal variation option of the materials characterization model for two reasons. First, the value of \( \delta \) may be negative. Second, a value of \( \delta \) was specified, but the value for \( m_0 \) is not positive. Check file HEXHCD.
ERROR: CANNOT OPEN FILE, 'filename' DOES NOT EXIST
Fatal  HEXHCF attempted to open the indicated file, however the file did not exist. Check the directory for existence of the file and also check file HEXHCD for correct spelling of the filename.

ERROR: Co TOO LOW
Fatal  The constraint, \( C_o \), imposed on the coefficient of variation of fatigue strength is inconsistent with the observed S/N data.

ERROR: EXCEEDED LIMIT ON DEGREES OF FREEDOM IN CHI-SQUARE TABLE, IN REGION 'L'
Fatal  As implemented, the credibility interval calculations can handle no more than 150 degrees of freedom, and the amount of data in the region indicated requires more. The \( \chi^2 \) tables of routine INTRVL must be increased. See Sections 4.1.3.6 and 7.3.1.3 for more information.

ERROR: EXCEEDED LIMIT ON NUMBER OF REGIONS
Fatal  The materials characterization model can handle no more than 3 life regions. Check file HEXHCD because the sum of the number of regions with data and the number of regions without data is greater than 3.

ERROR: INVALID LOCATION SPECIFICATION
Fatal  LOCAT can only have the integer value 1 or 2. Check file HEXHCD for the value used.

ERROR: INVALID RESPONSE TO NORMAL MEDIAN CURVE QUESTION
Fatal  NMED can only have the integer value 0 or 1. Check file IOUTPR for the value used.

ERROR: INVALID TYPE OF MATERIALS PROCESS VARIATION DESIRED
Fatal  MPROC can only have the integer value 0 or 1. Check file IOUTPR for the value used.

ERROR: INVALID TYPE OF S/N VARIATION DESIRED
Fatal  VARY can only have the integer value 0, 1, 2, or 3. Check file IOUTPR for the value used.

ERROR: INVALID VALUE FOR RATIO: 'RATIO'
Fatal  An invalid value for the stress ratio has been declared for the specific material data set. Only values between \(-1.0\) and \(+1.0\) inclusive, are possible. Check file HEXHCD.
ERROR: INVALID VALUE OF RATIO: 'RATIO'

Fatal   An invalid value for the stress ratio has been declared for a related material data set. Only values between -1.0 and +1.0 inclusive, are possible. Check file RELATD.

ERROR: LOAD INCORRECTLY TYPED

Fatal   TYPE(I) can only have the integer value 1, 2 or 3. Check file HEXHCD for the value used.

ERROR: NO INTERSECTION BETWEEN Jo AND Mc
ERROR: NO INTERSECTION BETWEEN Jo AND Mo
ERROR: NO INTERSECTION BETWEEN Jo, Mo, AND Mc

Fatal   These errors indicate that the specified C constraint and/or prior credibility range on m do not agree with each other and/or the observed S/N data.

ERROR: NORMAL VARIATION REQUIRES A PRIOR RANGE ON M

Fatal   The truncated Normal variation option of the materials characterization model requires a prior range on m. The number of points for the prior range on m has been incorrectly specified. Check file HEXHCD to verify that the number of points indicated for each range has an integer value of 1 or 2.

ERROR: NUMBER OF POINTS PER DIVISION INCORRECTLY SPECIFIED IN SET 'J'

Fatal   The materials characterization model has been given conflicting information about the number of points in one of the related S/N data sets. Check file RELATD to compare for each related data set the total number of points declared with the sum of the numbers of points in each data division.

ERROR: NUMBER OF POINTS PER DIVISION INCORRECTLY SPECIFIED IN SPECIFIC DATA SET

Fatal   The materials characterization model has been given conflicting information about the number of points in the specific S/N data set. Check file HEXHCD, since the total number of points in the specific data set declared and the sum of the numbers of points in each data division do not agree.

ERROR: OVERALL PRIOR RANGE INCORRECTLY SPECIFIED IN REGION WITHOUT DATA

Fatal   The prior credibility range on m in one of the regions without data has been incorrectly specified. Check file HEXHCD to verify that either more regions without data have been indicated than intended or that the number
of points in the prior on \( m \) in a region without data has been incorrectly specified. Only the integer value 0, 1, or 2 is acceptable.

**ERROR: OVER LIMIT ON NUMBER OF POINTS IN SET 'J'**

*Fatal* The materials characterization model cannot accept more than 50 S/N points in any related material data set. Check file RELATD for the total number of points in each related data set declared, or there may be more than 50 S/N points with an incorrect total declaration. It is suggested that the number of S/N data points in each related set be recounted. If more than 50 points are desired, the parameter **MAXDAT** must be increased. Refer to Section 7.3.1.3 for the routines involved.

**ERROR: OVER LIMIT ON NUMBER OF RELATED DATA SETS**

*Fatal* The materials characterization model allows up to 5 related data sets. Check file RELATD to determine if more than 5 related data sets were specified. The parameter **MAXSET** must be increased. Refer to Section 7.3.1.3 for the routines involved.

**ERROR: OVER NUMBER OF POINTS LIMIT IN SPECIFIC MATERIAL**

*Fatal* The materials characterization model cannot accept more than 50 S/N points in the specific material data set. Check file HEXHCD for the total number of points in the specific data set declared, or there may be more than 50 S/N points with an incorrect total declaration. If more than 50 points are desired, the parameter **MAXDAT** must be increased. Refer to Section 7.3.1.3 for the routines involved.

**ERROR: OVER REGION LIMIT IN RELATED MATERIAL 'J'**

*Fatal* No more than 3 life regions are allowed, and an attempt has been made to place some S/N data in a region number greater than 3. Check file RELATD for an invalid region number immediately following the stress ratio value in the data set indicated.

**ERROR: OVER REGION LIMIT IN SPECIFIC DATA SET**

*Fatal* No more than 3 life regions are allowed, and an attempt has been made to place some S/N data in a region number greater than 3. Check file HEXHCD for an invalid region number immediately following the stress ratio value.

**ERROR: POSTERIOR INTERVAL IN REGION 'L' IS INCONSISTENT WITH POINT POSTERIOR IN REGION 'L-1'**

*Fatal* Check file DUMP to verify that the point posterior value of \( m \) in region 'L-1' is greater than the upper bound of the posterior credibility range in region 'L'. This error indicates a violation of the concavity assumption.
ERROR: POSTERIOR INTERVAL IN REGION 'L' IS INCONSISTENT WITH THE POSTERIOR INTERVAL IN REGION 'L-1'

Fatal  Check file DUMP to verify that the lower bound of the posterior credibility range of \( m \) in region 'L-1' is greater than the upper bound of the posterior credibility range of \( m \) in region 'L'. The data should be checked for consistency.

ERROR: PRIOR ON M INCORRECTLY SPECIFIED IN 'L'

Fatal  The number of points for the specified prior range on \( m \) in the indicated region has been incorrectly specified. Check file HEXHCD to verify that the number of points indicated for each range has an integer value of 0, 1, or 2.

ERROR: STRESS-TIME HISTORY TOO LARGE

Fatal  No more than 24,000 points are allowed for a reference time history, and an attempt has been made to use a larger history. Check file HEXHCD for a value of \( NRAN \) larger than 24,000.

ERROR: \( S_{XY} > 0 \) IN REGION 'L'

Fatal  During the linear regression calculations for the region indicated, the resulting value of the sample covariance \( S_{xy} \) was found to be non-negative. This suggests that the data is specified erroneously or is inadequate for analysis, since life increasing with increasing stress contradicts the true fatigue behavior of materials.

ERROR: TOO FEW POINTS FOR REGRESSION IN REGION 'L'

Fatal  The materials characterization model does not have the required minimum number of points in the region indicated to perform a linear regression. If there are no related data sets, then there must be at least 3 points in each region. If there are \( N \) related data sets, then the total number of points in each region (specific and related combined) must be at least \( N + 3 \).

IMPOSSIBLE M RANGE IN REGION 'L'

Fatal  Concavity constraints during the random \( m \) selection have required an impossible range on \( m \) for the region indicated. Take note of all input parameters for this run, and consult Sections 4.1.5.1, 4.1.5.2, and 7.3 to aid in identification of the cause of this error.

NOTE: \( E(m) \) IS NOT IN THE POSTERIOR RANGE ON \( m \) IN REGION 'L'

Warning  This means that the estimate of \( m \) based on the S/N data only, in the region indicated, is outside the range indicated by the specified constraints on \( m \) and \( C \).
PROGRAM EXECUTION TERMINATED

Fatal  This message is produced by routine TRMNAT and follows all other fatal messages.

THE VALUE PRODCT EXCEEDED STRESS-STRAIN CURVE

Warning  The maximum stress has exceeded the stress-strain curve provided for the Neuber's rule calculation. The program has assumed the curve to end at the ultimate strength and hence assigned a value of unity for damage (the part has failed). If this message is believed to be in error, check the stress-strain curve provided in file HEXHCD, and/or check that all units for stress, strain, elastic modulus, geometric parameters, etc., are consistent.

6.1.14 Summary of Input/Output Files

Input Files

HEXHCD
This file is opened in HEXHCF. It contains all parameters for the run options; driver distributions; engineering analysis parameters; and the specific and exogenous materials input, including yield and ultimate strengths (psi), stress ratio, S/N data points, life (cycles) boundaries, region information, coefficient of variation constraint, C, and prior ranges on the materials shape parameter m for each region.

RELATD
This file is opened in subroutine INFAGG. It contains the related material data input, including yield and ultimate strengths (psi), stress ratio, S/N data points, and region information.

User Specified
These are the reference time history files and are opened in HEXHCF. They contain the time histories generated by program NBSIN.

Output Files

HEXHCO
This file is opened in HEXHCF. It contains the echo of the information contained in HEXHCD, and provides the simulated failure distribution B-life information.26

---

26 A B-life is the value of accumulated operating time to failure at a failure probability specified as a percent; e.g., B.1 is the failure time at a probability of 0.001 or 0.1%.
RELATO
This file is opened in subroutine INFAGG. It contains the echo of the information contained in RELATD.

DUMP
This file is opened in HEXHCF. It contains the results of the information aggregation portion of the materials model calculations, such as $I_o$ and $J_o$; the point estimates of $m$ and $C$; posterior credibility ranges for $m$; and a list of the estimated values for all S/N curve parameters. See Section 4.1.

IOUTPR
This file is opened in HEXHCF. It contains information on the particular run that is not echoed to HEXHCO and the data dump provided when the variable IOUT is equal to 10 (materials characterization calculations), 15 (Monte Carlo simulation and driver transformation calculations), 20 (rainflow cycle counting and damage accumulation calculations), or 25 (stress analysis calculations).

LOWLIF
This file is opened in HEXHCF. It contains the first one percent of the calculated lives used by the software described in Section 4.2 to calculate $\alpha$, $\beta$, and $\theta$, the parameters of the Bayesian prior failure distribution.
Section 6.2
Low Cycle Fatigue Analysis User’s Guide

6.2.1 TRBPWA Program

A user’s guide for running the low cycle fatigue (LCF) analysis code TRBPWA is given here. The LCF analysis for the ATD Disk is discussed in Section 2.2.2.2, the program description and flowcharts are presented in Section 5.2, and the code structure and listing are provided in Section 7.2.

The TRBPWA program was used to analyze the low cycle fatigue failure of the ATD-HPFTP second stage turbine disk. The output of TRBPWA includes the simulated B-lives and a list of the lowest one percent of lives. The list of lives may be used as input to the regression programs of Section 4.2 to compute the parameters of the Bayesian prior failure distribution. This prior distribution and success/failure data are used as input to the Bayesian updating program BAYES to obtain a posterior failure distribution.

6.2.2 How To Use Program TRBPWA

The program TRBPWA is intended to be run in batch (i.e., background) mode. TRBPWA requires two input data files: TRBPWD and RELATD. The materials characterization model portion of the program requires both files for all runs, even when no related S/N data is used. The file TRBPWD contains the analysis control parameters, driver distributions, engineering analysis parameters, and specific and exogenous materials information. The file RELATD contains the related materials information. A complete description of the input data for the TRBPWD and RELATD data files is given in Section 6.2.3.

The results from the TRBPWA program are written to five output files: TRBPWO, RELATO, DUMP, IOUTPR, and LOWLIF. TRBPWO contains the echo of the information in TRBPWD, the results of any stress ratio transformations performed on specific materials data, and the results of the simulation. RELATO contains the echo of the information in RELATD and the results of any stress ratio transformations performed on related materials data. The results of the materials characterization calculations are primarily given in DUMP. These calculations include point and interval estimates for S/N curve parameters $m$ and $C$, posterior credibility ranges for $m$, and an estimate of the median S/N curve. File IOUTPR contains an echo of the analysis parameters and, if requested, a dump of intermediate calculations. If the program terminates prematurely, an error message will be printed in the IOUTPR file. A list of error messages and possible remedies for the problems is given in Section 6.2.6. LOWLIF contains the first one percent of the lives of the simulated failure distribution.
6.2.3 Description of Input Data Files

Annotated examples of the complete data file format structure for TRBPWD and RELATD are presented in Figures 6-7 and 6-2, respectively. The data lines of the input files are given in boxes, with a description of each data line located adjacent to each box. The specific input parameters of Figure 6-7 are individually defined in Section 6.2.3.1. Input parameter values given in Figures 6-2 and 6-7 are not necessarily those used in the application case study of Section 3.3.

The input data is read by free format statements from files TRBPWD and RELATD. Thus, the numbers may be provided sequentially on a line up to 80 characters in length, with each number separated by a blank character or comma. Each number may also be on a separate line in the file. However, it is recommended that the input format suggested in Figure 6-7 be followed whenever possible.

6.2.3.1 Input File TRBPWD

The required data for the TRBPWD file is divided into the four blocks shown in Figure 6-3: analysis parameters, driver information, load and geometry, and materials information. The analysis parameters block contains the analysis parameters and the keys to select the program options. The driver information block contains the parameters that define the driver distributions. The parametric sensitivity information, the stress concentration factors, and the nominal stresses are given in the load and geometry block. The materials information block contains the specific material S/N data, including the yield and ultimate strengths, stress ratio, the S/N data points, life region boundaries, and materials characterization model parameter constraints.

The input parameters are described below by using the following convention: the input variable names are indicated by BOLD UPPERCASE letters; the variable types are specified as character [CHR], integer [INT], real [RE], and double precision real [DRE]; the function of the variable is underlined and followed by a description and a list of options, when appropriate; the program and file names are indicated by UPPERCASE letters. A consistent set of units is given in parentheses for specifying dimension, load, and stress input parameters. All character strings must be enclosed by 'single quotes'. The user is reminded about the difference between the number "0" and the letter "O" when preparing the input files.
675 Random number seed
0 Value of output dump controller
100 Inner loop size
200 Outer loop size
50 Symmetry number
2 Type of S/N variation
0 Request for truncated Normal median S/N curve
0 Controls materials process variation
5 Number of B-lives

Decimal equivalent of percentages for B-lives

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0001</td>
<td>0.0005</td>
<td>0.001</td>
<td>0.005</td>
<td>0.01</td>
<td></td>
</tr>
</tbody>
</table>

\( \Delta \tau \) two Beta distribution information

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>-200</td>
<td>200</td>
<td>0.50</td>
<td>0.50</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>200</td>
<td>500</td>
<td>0.00</td>
<td>0.00</td>
<td>10.0</td>
<td>10.0</td>
</tr>
<tr>
<td>0.95</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

37592 507 Rotational speed Normal distribution information
0.80000 1.20000 Uniform distribution bounds for \( \lambda_{K_d} \)
0.95000 1.05000 Uniform distribution bounds for \( \lambda_{K_1} \)

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.41</td>
<td>2.18</td>
<td>159807</td>
<td>38600</td>
</tr>
<tr>
<td>1915</td>
<td>0.91325</td>
<td>4.4435</td>
<td></td>
</tr>
<tr>
<td>14749</td>
<td>0.04</td>
<td>0.07</td>
<td>101.72</td>
</tr>
</tbody>
</table>

Description of specific material S/N data set

"PWA HPFTP 2ND TURBINE DISK"

Specific materials information: yield and ultimate strengths, number of data divisions, and total number of points in data set

00000 198000 1 9

Figure 6-7 Format for File TRBPWD
Specific materials information for each data division: number of points in data division, stress ratio, and life region

<table>
<thead>
<tr>
<th>9</th>
<th>-1.0</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>160000.</td>
<td>600.</td>
<td>$S_1, N_1$</td>
</tr>
<tr>
<td>160000.</td>
<td>700.</td>
<td>$S_2, N_2$</td>
</tr>
<tr>
<td>160000.</td>
<td>1000.</td>
<td>$S_3, N_3$</td>
</tr>
<tr>
<td>140000.</td>
<td>4800.</td>
<td>$S_4, N_4$</td>
</tr>
<tr>
<td>130000.</td>
<td>3700.</td>
<td>$S_5, N_5$</td>
</tr>
<tr>
<td>130000.</td>
<td>4300.</td>
<td>$S_6, N_6$</td>
</tr>
<tr>
<td>120000.</td>
<td>3800.</td>
<td>$S_7, N_7$</td>
</tr>
<tr>
<td>120000.</td>
<td>11000.</td>
<td>$S_8, N_8$</td>
</tr>
<tr>
<td>110000.</td>
<td>40000.</td>
<td>$S_9, N_9$</td>
</tr>
<tr>
<td>198000.</td>
<td></td>
<td>Stress tensile point</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>Number of life regions with and without data</td>
</tr>
<tr>
<td>500.</td>
<td></td>
<td>Life boundary of region 0</td>
</tr>
<tr>
<td>1.0E + 36</td>
<td></td>
<td>Life boundary of region 1</td>
</tr>
<tr>
<td>0.00</td>
<td></td>
<td>C constraint</td>
</tr>
<tr>
<td>0</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Bayesian prior distribution information

Materials process variation information

Figure 6-7  Format for File TRBPWD (Cont’d)
Analysis Parameters Block

RAND
[DRE]

Random number seed
Needed by TRBPWA's built-in random number generator.

IOUT
[INT]

Output dump controller
TRBPWA has the ability to write intermediate calculations to file IOUTPR. The following integer values control the "dump" of TRBPWA's calculations.

IOUT = 0  no intermediate calculation output
IOUT = 10 materials characterization model calculations
IOUT = 15 driver sampling and driver transformation calculations

NLIFE
[INT]

Inner loop number
Size of the inner loop of the Monte Carlo (MC) simulation. A positive value is required.

NHYPER
[INT]

Outer loop number
Size of the outer loop of the MC simulation. The program requires a positive value.

NSYM
[INT]

Symmetry number
The number of modeling units in the component. A positive value is required.

VARY
[INT]
Type of S/N variation

Controls the type of stochastic variation to be included in the materials characterization model S/N curve.

<table>
<thead>
<tr>
<th>VARY</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>no variation will be included</td>
</tr>
<tr>
<td>1</td>
<td>allows only intrinsic materials variation</td>
</tr>
<tr>
<td>2</td>
<td>allows Uniform variation of the materials model shape parameter $m$ and intrinsic materials variation</td>
</tr>
<tr>
<td>3</td>
<td>allows truncated Normal variation of the materials model shape parameter $m$ and intrinsic materials variation</td>
</tr>
</tbody>
</table>

NMED [INT]

Request for truncated Normal median S/N curve

If VARY = 3, then NMED controls the calculation of the empirical median S/N curve.

<table>
<thead>
<tr>
<th>NMED</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>no median curve calculation is required</td>
</tr>
<tr>
<td>1</td>
<td>median curve calculation is required</td>
</tr>
</tbody>
</table>

MPROC [INT]

Controls materials process variation

Controls the inclusion of materials process variation (heat-to-heat variation). Process variation in materials is discussed in Section 2.1.2.3.

<table>
<thead>
<tr>
<th>MPROC</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>no variation to be included</td>
</tr>
<tr>
<td>1</td>
<td>variation is to be included</td>
</tr>
</tbody>
</table>

NBLIFE [INT]

Number of B-lives

The number of B-lives to be provided from the simulated distribution of life. A B-life is the value of accumulated operating time to failure at a failure probability specified as a percentage; e.g., B.1 is the failure time at a probability of 0.001 or 0.1%. NBLIFE must be non-negative and cannot exceed 10.

---

27 A discussion of the possible stochastic specifications of the materials model shape parameter $m$ is given in Pages 2-13 through 2-14.

28 The median S/N curve for the truncated Normal distribution is discussed on Page 2-15.
**BLFPER(1)  BLFPER(2) ...  BLFPER(NBLIFE)**

[RE]  [RE]  [RE]

**B-life percentages**
The decimal equivalent of the percentages at which the B-lives are required; e.g., if the B.1 life is desired, then BLFPER = 0.001. A total of NBLIFE percentages must be provided. The percentage cannot exceed 50% (BLFPER ≤ 0.50).

**Driver Information Block**

<table>
<thead>
<tr>
<th>DELTA</th>
<th>DELTB</th>
<th>DELTR1</th>
<th>DELTR2</th>
<th>DELTT1</th>
<th>DELTT2</th>
</tr>
</thead>
<tbody>
<tr>
<td>[RE]</td>
<td>[RE]</td>
<td>[RE]</td>
<td>[RE]</td>
<td>[RE]</td>
<td>[RE]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>DELTC</th>
<th>DELTD</th>
<th>DELTR3</th>
<th>DELTR4</th>
<th>DELTT3</th>
<th>DELTT4</th>
</tr>
</thead>
<tbody>
<tr>
<td>[RE]</td>
<td>[RE]</td>
<td>[RE]</td>
<td>[RE]</td>
<td>[RE]</td>
<td>[RE]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>DELTE</th>
</tr>
</thead>
<tbody>
<tr>
<td>[RE]</td>
</tr>
</tbody>
</table>

**ΔTᵣ**, two Beta distribution information

ΔTᵣ (°F) in *Equation 2-95* is the deviation from the nominal coolant fluid temperature and is characterized by two Beta probability distributions. The first two lines are the two Beta distributions, one per line. See *Section 2.1.3.1* and *Equation 2-54* for defining parameters for setting up a Beta driver distribution. The Beta distribution format consists of six parameters. The first two parameters are the lower and upper bounds, respectively, for ΔTᵣ. The next two parameters are the lower and upper bounds for the Uniform distribution on p. Similarly, the last two parameters describe the Uniform distribution on θ. The third line is the decimal equivalent percentage weight for the first Beta distribution and must be between 0.00 and 1.00.

<table>
<thead>
<tr>
<th>DELTA</th>
<th>ΔTᵣ lower bound of Beta distribution 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>DELTB</td>
<td>ΔTᵣ upper bound of Beta distribution 1</td>
</tr>
<tr>
<td>DELTR1</td>
<td>p Uniform distribution lower bound of Beta distribution 1 of ΔTᵣ</td>
</tr>
<tr>
<td>DELTR2</td>
<td>p Uniform distribution upper bound of Beta distribution 1 of ΔTᵣ</td>
</tr>
<tr>
<td>DELTT1</td>
<td>θ Uniform distribution lower bound of Beta distribution 1 of ΔTᵣ</td>
</tr>
<tr>
<td>DELTT2</td>
<td>θ Uniform distribution upper bound of Beta distribution 1 of ΔTᵣ</td>
</tr>
<tr>
<td>DELTC</td>
<td>ΔTᵣ lower bound of Beta distribution 2</td>
</tr>
</tbody>
</table>
DELTD \quad \Delta T_f \text{ upper bound of Beta distribution 2}

DELTR3 \quad \rho \text{ Uniform distribution lower bound of Beta distribution 2 of } \Delta T_f

DELTR4 \quad \rho \text{ Uniform distribution upper bound of Beta distribution 2 of } \Delta T_f

DELTT3 \quad \theta \text{ Uniform distribution lower bound of Beta distribution 2 of } \Delta T_f

DELTT4 \quad \theta \text{ Uniform distribution upper bound of Beta distribution 2 of } \Delta T_f

DELTE \quad \text{decimal equivalent percentage weight occurring in Beta distribution 1}
\quad \text{of the deviation from nominal coolant fluid temperature, } \Delta T_f

SPDMU \quad \text{SPDSIG}
[RE] \quad [RE]

Rotational speed Normal distribution information
The rotational speed variation is characterized by a Normal(\mu, \sigma^2) distribution. The mean \mu is equal to the expected operating speed of the turbopump, and the standard deviation \sigma is obtained from the engine performance balance. Both the mean and standard deviation are in rpm.

SPDMU \quad \text{mean } \mu \text{ of Normally distributed speed}

SPDSIG \quad \text{standard deviation } \sigma \text{ of Normally distributed speed}

LAMKDA \quad LAMKDB
[RE] \quad [RE]

K_d \text{ accuracy factor Uniform distribution information}
lam{K_d} \text{ in Equation 2-103. This is the } K_d \text{ accuracy factor, and it is characterized by a Uniform distribution.}

LAMKDA \quad K_d \text{ accuracy factor Uniform distribution lower bound}

LAMKDB \quad K_d \text{ accuracy factor Uniform distribution upper bound}

LAMKTA \quad LAMKTB
[RE] \quad [RE]

K_t \text{ accuracy factor Uniform distribution information}
lam{K_t} \text{ in Equation 2-103. This is the } K_t \text{ accuracy factor, and it is characterized by a Uniform distribution.}
LAMKTA $K_t$ accuracy factor Uniform distribution lower bound
LAMKTB $K_t$ accuracy factor Uniform distribution upper bound

Load and Geometry Block

<table>
<thead>
<tr>
<th>KD</th>
<th>KT</th>
<th>SMM</th>
<th>REFSPD</th>
</tr>
</thead>
<tbody>
<tr>
<td>[RE]</td>
<td>[RE]</td>
<td>[RE]</td>
<td>[RE]</td>
</tr>
</tbody>
</table>

Stress concentration factors and parametric sensitivity analysis information for the mechanical stress
The line contains the two stress concentration factors from the engineering analysis: $K_d$ in Equation 2-102 is the adjustment factor for the 2-D analyses; $K_t$ in Equation 2-92 is the local stress concentration factor; $S_{M_o}$ (psi) in Equation 2-94 is the nominal mechanical stress due to rotor speed effects only; and $\omega_o$ is the nominal or reference speed (rpm) corresponding to all nominal stress values.

<table>
<thead>
<tr>
<th>STM</th>
<th>CMF</th>
<th>CM</th>
</tr>
</thead>
<tbody>
<tr>
<td>[RE]</td>
<td>[RE]</td>
<td>[RE]</td>
</tr>
</tbody>
</table>

Parametric sensitivity analysis information for the thermal stress due to metal temperature
The line contains $S_{M_o}$ (psi) in Equation 2-97, the nominal stress due to metal temperature only (at the nominal speed and nominal coolant fluid temperature); $C_{mf}$ in Equation 2-95, the sensitivity of metal temperature to deviation from the nominal coolant fluid temperature; and $C_m$ (psi°F) in Equation 2-97, the sensitivity of stress to variation of metal temperature $\Delta T_m$ in Equation 2-95 due to deviation from nominal coolant fluid temperature.

<table>
<thead>
<tr>
<th>SG</th>
<th>CG1</th>
<th>CG2</th>
<th>CG</th>
</tr>
</thead>
<tbody>
<tr>
<td>[RE]</td>
<td>[RE]</td>
<td>[RE]</td>
<td>[RE]</td>
</tr>
</tbody>
</table>

Parametric sensitivity analysis information for the thermal stress due to thermal gradient
The line contains $S_{G_o}$ (psi) in Equation 2-98, the nominal stress due to the thermal gradient only (at the nominal speed, nominal coolant fluid temperature, and nominal thermal gradient); $C_{G1}$ and $C_{G2}$ in Equation 2-96 are coefficients characterizing the sensitivity of the thermal gradient to deviation from nominal coolant fluid temperature; and $C_{G}$ (psi°F) in Equation 2-98 is the sensitivity of stress to variation of thermal gradient due to deviation from nominal coolant fluid temperature.
Materials Information Block

DESCRIPT(0)
[CHR]

Description of specific material S/N data set
Name and test environment for the specific material S/N data. This is a character string no more than 40 characters long, enclosed by single quotes.

FTY  FTU  NDIV  NPTS(0)
[RE]  [RE]  [INT]  [INT]

Specific materials information
Yield strength, ultimate strength, number of divisions of data, number of points in S/N data set. The data may be divided when they are assigned to a different life region or have different stress ratios. If all data has a stress ratio of -1.0, then the yield and ultimate strengths are not required, but zero values must be specified as placeholders. NPTS(0) cannot exceed fifty. The next two data sets have to be provided for each data division.

NUM  RATIO  REG
[INT]  [RE]  [INT]

Materials information for each data division of the specific S/N data set
Number of points, stress ratio, and the life region of interest for each data division. This line must be provided for each data division.

RAWSTR(I,0)  RAWNF(I,0)
[RE]  [RE]
Specific material S/N data points
Stress versus fatigue life data points for each data division. A block of NUM lines must be specified (i.e., the value of I goes from 1 to NUM). This block must be provided for each data division.

RAWSTR(I,0) stress value (psi)
RAWNF(I,0) fatigue life value (cycles)

SZERO
[RE]

Tensile point [29]
Stress tensile point \( S_o \) (psi). Must be non-negative. A value of zero indicates no tensile point.

NUMREG [INT] NNODAT [INT]

Data regions [30]
Number of life regions that are data-determined and not data-determined. NUMREG + NNODAT cannot exceed three. NUMREG must be 1, 2, or 3, and NNODAT must be non-negative, and should be 0 or 1.

NUMREG number of life regions determined by data
NNODAT number of life regions (to the right) not determined by data

NBND(L) [RE]

Life Boundaries [31]
The upper boundaries of the life regions are specified (cycles). The value of L goes from ZROREG to the total number of regions (equal to NUMREG + NNODAT). If a non-zero tensile point is specified, then ZROREG = 0 else ZROREG = 1. The program expects the upper bound of the last life region to be \( 10^{36} \), a proxy for \( \infty \).

---

[29] Extension of the S/N curve to the left is discussed on Page 2-17.
[30] Extension of the S/N curve to the right is discussed on Page 2-17.
[31] Life region boundaries are discussed on Page 2-15.
CZERO
[RE]

Prior information on coefficient of variation of fatigue strength

Information in the form of a constraint on the coefficient of variation of fatigue strength $C$ for the specific material S/N data set. Value must be non-negative and a value of zero indicates that CZERO is not in use.

MPNT(L)  MZERO(1,L)  MZERO(2,L)  [INT]  [RE]  [RE]

Prior information on the materials shape parameter $m$

The number of MZERO values in each life region, and the lower and upper bound for the range of $m$. The value of $L$ goes from 1 to $(\text{NUMREG} + \text{NNODAT})$. If VARY $= 3$ is specified (truncated Normal distribution on $m$), then a prior range of $m$ must be specified for each region.

MPNT(L) The number of points, 0, 1, or 2 (no prior on $m$, a point prior on $m$, or a prior over a range of $m$, respectively), in MZERO() for each region.

MZERO(1,L) The lower bound on the range of $m$ or the value of the point prior for $m$.

MZERO(2,L) The upper bound on the range of $m$. Program requires that the value be zero if a point prior for $m$ is specified.

DELTA(L)  MO(L)  SIGMA2(L)  [RE]  [RE]  [RE]

Information on the Bayesian prior distribution for the truncated Normal distribution

If VARY $= 3$, then the materials model uses the truncated Normal distribution. The truncated Normal distribution requires some prior information on the Normal distribution parameters because a Bayesian analysis is performed. The information is required for each life region. The value of $L$ goes from 1 to $(\text{NUMREG} + \text{NNODAT})$.

DELTA(L) The shape parameter $\delta$ of the Bayesian prior distribution is used to compute the Bayesian posterior distribution parameters. Value must be non-negative, a value of zero indicates a diffuse prior distribution.

---

32 The implicit constraint on the materials shape parameter provided by prior information on the coefficient of variation of fatigue strength is discussed on Pages 2-12 through 2-13.

33 The explicit constraint on the materials shape parameter provided by prior information on the materials shape parameter is discussed on Page 2-12.

34 Specification of the Bayesian prior distribution for the truncated Normal case is discussed on Page 2-14.
MO(L) Location parameter \( m_0 \) of the Bayesian prior distribution of the shape parameter \( m \). Must be positive. Required when \( \text{DELTA}(L) \) is non-zero.

SIGMA2(L) \( \sigma^2 \), the known variance of \( \ln(\text{fatigue life}) \), \( V(\ln N | \ln S) \). Must be non-negative.

\[ \text{KRATIO} \quad \text{LAMN} \]

[RE] [RE]

Materials process variation information

If \( \text{MPROC} = 1 \), then specification of \( \text{KRATIO} \) and \( \text{LAMN} \) is required. \( \text{KRATIO} \) is \( \lambda^*_K \), the ratio \( \text{MED} K^* / \text{MED} K \) where \( \text{MED} K^* \) is the median value over all heats for the stress (psi) at a life of one cycle, and \( \text{MED} K \) is the median value for the specific S/N data for the stress (psi) at a life of one cycle. \( \text{LAMN} \) is the ratio of the variance of \( \ln(\text{life})\) conditional on stress over all heats to the intrinsic materials variation for the given S/N data conditional on stress. Process variation in materials is discussed in Section 2.1.2.3.

6.2.3.2 Input File RELATD

The input data for file RELATD, which contains the related materials information, is given below. The data format is similar to that used to specify the S/N data in the specific materials information block in the TRBPWD file.

\( \text{NSETS} \)

[INT]

Number of related data sets

Number of related material S/N data sets. The following data groups have to be repeated as a block for each data set. The value of \( J \) varies from 1 to \( \text{NSETS} \). If there is no related data, then file RELATD will only contain the number "0". \( \text{NSETS} \) cannot exceed five.

\( \text{DESCRIPT}(J) \)

[CHR]

Description of related material S/N data set

Name and test environment for related material S/N data set \( J \). This is a character string no more than 40 characters long, enclosed by single quotes.

\[ ^{35} \text{Related S/N data is discussed on Page 2-7.} \]
Related materials information
Yield strength, ultimate strength, number of divisions of data, number of points in S/N data set. The data may be divided when they are assigned to a different life region or have different stress ratios. If all data has a stress ratio of -1.0, then the yield and ultimate strengths are not required, but zero values must be specified as placeholders. NPTS(J) cannot exceed fifty. The next two data sets have to be provided for each data division.

<table>
<thead>
<tr>
<th>FTY</th>
<th>FTU</th>
<th>NDIV</th>
<th>NPTS(J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[RE]</td>
<td>[RE]</td>
<td>[INT]</td>
<td>[INT]</td>
</tr>
</tbody>
</table>

Yield strength corresponding to related material data set J (psi)
Ultimate strength corresponding to related material data set J (psi)
Number of data divisions for related material data set J
Total number of points in related material S/N data set J

<table>
<thead>
<tr>
<th>NUM</th>
<th>RATIO</th>
<th>REG</th>
</tr>
</thead>
<tbody>
<tr>
<td>[INT]</td>
<td>[RE]</td>
<td>[INT]</td>
</tr>
</tbody>
</table>

Number of S/N data points in the data division
Stress ratio for the data in the data division
Life region number to be assigned to the data in the data division

<table>
<thead>
<tr>
<th>RAWSTR(I,J)</th>
<th>RAWNF(I,J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[RE]</td>
<td>[RE]</td>
</tr>
</tbody>
</table>

Stress versus fatigue life data points for each data division. A block of NUM lines must be specified (i.e., the value of I goes from 1 to NUM). This block must be provided for each data division.

Stress value (psi)
Fatigue life value (cycles)
6.2.4 Options and Capabilities

TRBPWA is a Monte Carlo simulation program which generates a sequence of component lives for a particular failure mode, where life is defined as the accumulated operating time at failure. The simulation has a double-loop structure with NHYPER outer loops and NLIFE inner loops. The simulation size is dependent on the failure probability at which a life estimate is desired and the precision desired. For the ATD Disk application, single-loop runs with NHYPER = 20,000 and NLIFE = 1 were used to characterize component reliability, and single-loop runs with NHYPER = 1000 and NLIFE = 1 were used for the marginal analysis to assess the importance of drivers.

During a run, it may be desirable to "hold" a driver at a fixed value. This may be the nominal or median value of the driver. This is done for drivers with a Beta or a Uniform distribution by merely specifying both the upper and lower bounds to be the desired value. For drivers with a Normal distribution, the standard deviation $\sigma$ is set at zero, and the mean $\mu$ is set at the desired value.

The procedure of holding certain drivers at fixed values while letting the other drivers vary according to their probability distributions may be used for driver variation sensitivity studies. That is, the effect on life of driver variation may be evaluated by letting it vary while holding other drivers at fixed values. Each driver variation sensitivity was determined in the case studies of this report with the intrinsic variation of the fatigue life of the material included (VARY = 1).

A printout of intermediate calculations in various parts of the program may be obtained via the IOUT option. This output will be printed in the IOUTPR file. It is recommended that such output not be requested when the simulation size is large since the information will be dumped during every simulation loop. The NMED option provides for calculation of an empirical median S/N curve if the truncated Normal distribution is employed.\footnote{The truncated Normal distribution for the materials model shape parameter $m$ is discussed on Page 2-14.} In this case, the median S/N curve is based on the empirical median $m$ from all the shape parameters used in the simulation. The MPROC option activates the calculations for the process variation feature of the materials characterization model, as discussed in Section 2.1.2.3.
6.2.5 Code Execution Example

The following example run of the LCF analysis code for the ATD-HPFTP second stage turbine disk was carried out with random variation of all drivers. In this example run, 20,000 lives were simulated (NLIFE = 1 times NHYPER = 20,000) by using Uniform shape parameter variation, VARY = 2 and NMED = 0; no materials process variation, MPROC = 0, and a symmetry number of NSYM = 50. The B-lives\textsuperscript{37} to be provided are B.1, B.2, B.3, B.4, B.5, B.6, B.7, B.8, B.9, and B1 (NBLIFE = 10, BLFPER(1) = 0.001, BLFPER(2) = 0.002, BLFPER(3) = 0.003, BLFPER(4) = 0.004, BLFPER(5) = 0.005, BLFPER(6) = 0.006, BLFPER(7) = 0.007, BLFPER(8) = 0.008, BLFPER(9) = 0.009, BLFPER(10) = 0.01). The user may refer to Section 2.2.2 for additional information on the engineering analysis and to Section 3.3 for the results of the case study for this component.

The drivers for LCF failure of the disk are as follows:

<table>
<thead>
<tr>
<th>DRIVER</th>
<th>DISTRIBUTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. $\Delta T_f$</td>
<td>Two Betas</td>
</tr>
<tr>
<td>2. $\omega$</td>
<td>Normal</td>
</tr>
<tr>
<td>3. $\lambda_{K_d}$</td>
<td>Uniform</td>
</tr>
<tr>
<td>4. $\lambda_{K_i}$</td>
<td>Uniform</td>
</tr>
</tbody>
</table>

The rationale for the specification of the driver distributions is given in Section 3.3.2.

The materials information consists of nine S/N data points, NUM = 9. The S/N data has a stress ratio of 0.05, but no stress ratio correction is required for use with the driver transformation so a stress RATIO of -1.0 has been indicated. The number of regions with data, NUMREG, is 1, and there are no regions to the right without data, NNODAT = 0. The data is in one division, NDIV = 1, and the total number of points is nine, NPTS(0) = 9. No related data is provided. Thus, the RELATD file is empty, except for a single entry to indicate NSETS = 0. No stress tensile point is used, SZERO = 0, so only one life region upper boundary must be defined, NBND(0) = 1.0E36. If further explanation of file TRBPWD is required, refer to Section 6.2.3.1 and Figure 6-7.

The echo of the input data is in the output file TRBPWO. The simulated B-lives are also given for the component. For instance, the B.1 life is 121 cycles. The IOUTPR file gives an echo of the analysis parameters. The dump parameter IOUT is zero;

\textsuperscript{37} A B-life is the value of accumulated operating time to failure at a failure probability specified as a percent; e.g., B.1 is the failure time at a probability of 0.001 or 0.1%.
therefore, no other output is in this file. The LOWLIF file contains the lowest one percent of the 20,000 simulation lives. Finally, the DUMP file contains the results of the materials characterization model information aggregation calculations.\textsuperscript{38}

**Input File - TRBPWD**

```
675
0
1
20000
50
2
0
0
10
0.001
0.002
0.003
0.004
0.005
0.006
0.007
0.008
0.009
0.010
-200. 200. 0.50 0.50 0.0 0.0
200. 500. 0.00 0.00 10.0 10.0
0.95
37592. 507.
0.80000 1.20000
0.95000 1.05000
1.41 2.18 159807. 38600.
1915. 0.91325 4.4435
14749. 0.04 0.07 101.72
'PWA HPFTP 2ND TURBINE DISK'
00000. 198000. 1 9
9 -1.0 1
160000. 636.
160000. 677.
160000. 1019.
140000. 4743.
130000. 3824.
130000. 4163.
120000. 3749.
120000. 11349.
110000. 39600.
```

\textsuperscript{38} The information aggregation calculations are discussed on Pages 2-6 through 2-14.
INPUT DATA

DRIVERS          PARAMETER DISTRIBUTIONS

DELTA Tf
  Be(-200.0, 200.0)  U(0.50000, 0.50000)  U( 0.0,  0.0)
  Be( 200.0, 500.0)  U(0.00000, 0.00000)  U(10.0, 10.0)
  TEST = 0.95

SPEED (RPM)      NORMAL: MEAN = 37592.  STAND. DEV. = 507.

LAMBDA Kd         U( 0.80000, 1.20000)

LAMBDA Kt         U( 0.95000, 1.05000)

OTHER LOADS INPUT

STRESS ADJUSTMENT, Kd         1.410

STRESS CONCENTRATION, Kt      2.180

MECHANICAL STRESS (PSI)        159807.0

ROTATIONAL SPEED (RPM)         38600.
STRESS DUE TO METAL TEMPERATURE (PSI) 1915.0
SENSITIVITY OF METAL TEMPERATURE TO DELTA Tf 0.91325
SENSITIVITY OF STRESS DUE TO Tmetal (PSI/F) 4.44

STRESS DUE TO THERMAL GRADIENT (PSI) 14749.0
SENSITIVITY OF THERMAL GRADIENT TO DELTA Tf
FOR DELTA Tf < 0 0.040
FOR DELTA Tf >= 0 0.070
SENSITIVITY OF STRESS DUE TO THERM. GRAD. (PSI/F) 101.72

MATERIAL INPUT

DESCRIPTION: PWA HPFTP 2ND TURBINE DISK

YIELD STRENGTH 0.00000E+00
ULTIMATE STRENGTH 0.19800E+06

NUMBER OF POINTS 9

<table>
<thead>
<tr>
<th>ORIGINAL S/N</th>
<th>STRESS LIFE</th>
<th>STRESS RATIO</th>
<th>REGION</th>
<th>TRANSFORMED S/N STRESS</th>
<th>TRANSFORMED S/N LIFE</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.16000E+06</td>
<td>636.</td>
<td>-1.00</td>
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<td>636.</td>
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<td>-1.00</td>
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<td>677.</td>
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<tr>
<td>0.16000E+06</td>
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<td>-1.00</td>
<td>1</td>
<td>0.16000E+06</td>
<td>1019.</td>
</tr>
<tr>
<td>0.14000E+06</td>
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<td>4743.</td>
</tr>
<tr>
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<td>3824.</td>
</tr>
<tr>
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<td>4163.</td>
<td>-1.00</td>
<td>1</td>
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</tr>
<tr>
<td>0.12000E+06</td>
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<td>-1.00</td>
<td>1</td>
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<td>3749.</td>
</tr>
<tr>
<td>0.12000E+06</td>
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<td>-1.00</td>
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<td>-1.00</td>
<td>1</td>
<td>0.11000E+06</td>
<td>39600.</td>
</tr>
</tbody>
</table>

THERE IS 1 REGION(S) WITH DATA
AND 0 REGION(S) TO THE RIGHT WITHOUT DATA
THE UPPER BOUND(S) OF THE REGION(S) ARE (CYCLES):

6 - 103
EXOGENOUS INFORMATION

CONSTRAINT ON COEFFICIENT OF VARIATION, C: 0.0000

EXPLICIT CONSTRAINT ON m FOR EACH REGION:

<table>
<thead>
<tr>
<th>REGION</th>
<th># OF POINTS</th>
<th>LOWER BOUND</th>
<th>UPPER BOUND</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

B LIVES: EMPIRICAL

<table>
<thead>
<tr>
<th>Value</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00100</td>
<td>0.121108E+03</td>
</tr>
<tr>
<td>0.00200</td>
<td>0.155309E+03</td>
</tr>
<tr>
<td>0.00300</td>
<td>0.180471E+03</td>
</tr>
<tr>
<td>0.00400</td>
<td>0.200357E+03</td>
</tr>
<tr>
<td>0.00500</td>
<td>0.214710E+03</td>
</tr>
<tr>
<td>0.00600</td>
<td>0.230961E+03</td>
</tr>
<tr>
<td>0.00700</td>
<td>0.251356E+03</td>
</tr>
<tr>
<td>0.00800</td>
<td>0.263503E+03</td>
</tr>
<tr>
<td>0.00900</td>
<td>0.281120E+03</td>
</tr>
<tr>
<td>0.01000</td>
<td>0.288462E+03</td>
</tr>
<tr>
<td>0.50000</td>
<td>0.411175E+04</td>
</tr>
</tbody>
</table>

Output File - RELATO

NUMBER OF DATA SETS: 0

NOTE: ALL Kt ASSUMED TO BE 1.0

TRANSFORMED DATA

Output File - DUMP

Copyright (C) 1990, California Institute of Technology. U.S. Government Sponsorship under NASA Contract NAS7-918 is acknowledged.
RESULTS OF INFORMATION AGGREGATION CALCULATIONS

95% CONFIDENCE INTERVALS ON C AND m FOR EACH REGION

REGION: 1

\[ \begin{align*}
I_o & = (0.036692030, 0.112948100) \\
J_o & = (5.734418000, 11.972310000)
\end{align*} \]

POINT ESTIMATES OF C AND m FOR EACH REGION

<table>
<thead>
<tr>
<th>REGION</th>
<th>( \bar{E}(C) )</th>
<th>( \bar{E}(m) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.055495330</td>
<td>8.853366</td>
</tr>
</tbody>
</table>

POSTERIOR CREDIBILITY RANGE ON m FOR EACH REGION

<table>
<thead>
<tr>
<th>REGION</th>
<th>LOWER BOUND</th>
<th>UPPER BOUND</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.7344</td>
<td>11.9723</td>
</tr>
</tbody>
</table>

PARAMETER VALUES FOR MEDIAN S/N CURVE

NUMBER OF REGIONS: 1

\[ \begin{align*}
E(\beta_0) & = 22.9860 \\
E(k) & = 12.7338
\end{align*} \]

<table>
<thead>
<tr>
<th>REGION</th>
<th>( m )</th>
<th>( k )</th>
<th>LIFE BOUND</th>
<th>STRESS BOUND</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.85337</td>
<td>0.34214E+06</td>
<td>0.100E+37</td>
<td>0.00000E+00</td>
</tr>
</tbody>
</table>

Output File - IOUTPR

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<thead>
<tr>
<th>RANDOM NUMBER SEED</th>
<th>675.0000000000000</th>
</tr>
</thead>
<tbody>
<tr>
<td>IOUT (MATCHR = 10, TRBFWA = 15)</td>
<td>0</td>
</tr>
<tr>
<td>INNER LOOP SIZE</td>
<td>1</td>
</tr>
<tr>
<td>OUTER LOOP SIZE</td>
<td>20000</td>
</tr>
<tr>
<td>SYMMETRY NUMBER</td>
<td>50</td>
</tr>
<tr>
<td>TYPE OF S/N VARIATION DESIRED</td>
<td>2</td>
</tr>
<tr>
<td>NORMAL MEDIAN CURVE (0 - NO, 1 - YES)</td>
<td>0</td>
</tr>
<tr>
<td>MATERIALS PROCESS VARIATION DESIRED (0 - NO, 1 - YES)</td>
<td>0</td>
</tr>
</tbody>
</table>
## Output File - LOWLIF

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
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</thead>
<tbody>
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<tr>
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<td></td>
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<tr>
<td>7</td>
<td>0.350000E-03</td>
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6.2.6 Error Messages and Possible Remedies

The following messages, when applicable, will appear in file IOUTPR. These messages are primarily generated by the materials characterization model (MATCHR) portion of TRBPWA. An error message stating that a limit has been exceeded will require that the user increase those limits, as directed, and reviewing or consulting Section 7.3.1.3 is desirable. The messages are listed in alphabetical order for the convenience of the user.

ERROR: BAD VALUE FOR DELTA OR VALUE OF MO INCONSISTENT WITH DELTA IN REGION 'L'

Fatal This error can occur during the use of the truncated Normal variation option of the materials characterization model for two reasons. First, the value of δ may be negative. Second, a value of δ was specified, but the value of mo is not positive. Check file TRBPWD.

ERROR: CO TOO LOW

Fatal The constraint, C_o, imposed on the coefficient of variation of fatigue strength is inconsistent with the observed S/N data.

ERROR: EXCEEDED LIMIT ON DEGREES OF FREEDOM IN CHI-SQUARE TABLE, IN REGION 'L'

Fatal As implemented, the credibility interval calculations can handle no more than 150 degrees of freedom, and the amount of data in the region indicated requires more. The χ² tables of routine INTRVL must be increased. See Sections 4.1.3.6 and 7.3.1.3 for more information.

ERROR: EXCEEDED LIMIT ON NUMBER OF REGIONS

Fatal The materials characterization model can handle no more than 3 life regions. Check file TRBPWD because the sum of the number of regions with data and the number of regions without data is greater than 3.

ERROR: INVALID RESPONSE TO NORMAL MEDIAN CURVE QUESTION

Fatal NMED can only have the integer value 0 or 1. Check file IOUTPR for the value used.
ERROR: INVALID TYPE OF MATERIALS PROCESS VARIATION DESIRED
   Fatal MPROC can only have the integer value 0 or 1. Check file IOUTPR for the value used.

ERROR: INVALID TYPE OF S/N VARIATION DESIRED
   Fatal VARY can only have the integer value 0, 1, 2, or 3. Check file IOUTPR for the value used.

ERROR: INVALID VALUE FOR RATIO: 'RATIO'
   Fatal An invalid value for the stress ratio has been declared for the specific material data set. Only values between -1.0 and +1.0 inclusive, are possible. Check file TRBPWD.

ERROR: INVALID VALUE OF RATIO: 'RATIO'
   Fatal An invalid value for the stress ratio has been declared for a related material data set. Only values between -1.0 and +1.0 inclusive, are possible. Check file RELATD.

ERROR: NO INTERSECTION BETWEEN Jo AND Mc
ERROR: NO INTERSECTION BETWEEN Jo AND Mo
ERROR: NO INTERSECTION BETWEEN Jo, Mo, AND Mc
   Fatal These errors indicate that the specified C constraint and/or prior credibility range on m do not agree with each other and/or the observed S/N data.

ERROR: NORMAL VARIATION REQUIRES A PRIOR RANGE ON M
   Fatal The truncated Normal variation option of the materials characterization model requires a prior range on m. The number of points for the prior range on m has been incorrectly specified. Check file TRBPWD to verify that the number of points indicated for each range has an integer value of 1 or 2.

ERROR: NUMBER OF POINTS PER DIVISION INCORRECTLY SPECIFIED IN SET 'J'
   Fatal The materials characterization model has been given conflicting information about the number of points in one of the related S/N data sets. Check file RELATD to compare for each related data set the total number of points declared with the sum of the numbers of points in each data division.

ERROR: NUMBER OF POINTS PER DIVISION INCORRECTLY SPECIFIED IN SPECIFIC DATA SET
   Fatal The materials characterization model has been given conflicting information about the number of points in the specific S/N data set. Check file
TRBPWD, since the total number of points in the specific data set declared and the sum of the numbers of points in each data division do not agree.

ERROR: OVERALL PRIOR RANGE INCORRECTLY SPECIFIED IN REGION WITHOUT DATA

Fatal The prior credibility range on \( m \) in one of the regions without data has been incorrectly specified. Check file TRBPWD to verify that either more regions without data have been indicated than intended or that the number of points in the prior on \( m \) in a region without data has been incorrectly specified. Only the integer value 0, 1, or 2 is acceptable.

ERROR: OVER LIMIT ON NUMBER OF POINTS IN SET 'J'

Fatal The materials characterization model cannot accept more than 50 S/N points in any related material data set. Check file RELATD for the total number of points in each related data set declared, or there may be more than 50 S/N points with an incorrect total declaration. It is suggested that the number of S/N data points in each related set be recounted. If more than 50 points are desired, the parameter MAXDAT must be increased. Refer to Section 7.3.1.3 for the routines involved.

ERROR: OVER LIMIT ON NUMBER OF RELATED DATA SETS

Fatal The materials characterization model allows up to 5 related data sets. Check file RELATD to determine if more than 5 related data sets were specified. The parameter MAXSET must be increased. Refer to Section 7.3.1.3 for the routines involved.

ERROR: OVER NUMBER OF POINTS LIMIT IN SPECIFIC MATERIAL

Fatal The materials characterization model cannot accept more than 50 S/N points in the specific material data set. Check file TRBPWD for the total number of points in the specific data set declared, or there may be more than 50 S/N points with an incorrect total declaration. If more than 50 points are desired, the parameter MAXDAT must be increased. Refer to Section 7.3.1.3 for the routines involved.

ERROR: OVER REGION LIMIT IN RELATED MATERIAL 'J'

Fatal No more than 3 life regions are allowed, and an attempt has been made to place some S/N data in a region number greater than 3. Check file RELATD for an invalid region number immediately following the stress ratio value in the data set indicated.
ERROR: OVER REGION LIMIT IN SPECIFIC DATA SET
  Fatal  No more than 3 life regions are allowed, and an attempt has been made to place some S/N data in a region number greater than 3. Check file TRBPWD for an invalid region number immediately following the stress ratio value.

ERROR: POSTERIOR INTERVAL IN REGION 'L' IS INCONSISTENT WITH POINT POSTERIOR IN REGION 'L-1'
  Fatal  Check file DUMP to verify that the point posterior value of $m$ in region 'L-1' is greater than the upper bound of the posterior credibility range in region 'L'. This error indicates a violation of the concavity assumption.

ERROR: POSTERIOR INTERVAL IN REGION 'L' IS INCONSISTENT WITH THE POSTERIOR INTERVAL IN REGION 'L-1'
  Fatal  Check file DUMP to verify that the lower bound of the posterior credibility range of $m$ in region 'L-1' is greater than the upper bound of the posterior credibility range of $m$ in region 'L'. The data should be checked for consistency.

ERROR: PRIOR ON M INCORRECTLY SPECIFIED IN 'L'
  Fatal  The number of points for the specified prior range of $m$ in the indicated region has been incorrectly provided. Check file TRBPWD to verify that the number of points indicated for each range has an integer value of 0, 1, or 2.

ERROR: SXY $\geq$ 0 IN REGION 'L'
  Fatal  During the linear regression calculations for the region indicated, the resulting value of the sample covariance $S_{xy}$ was found to be non-negative. This suggests that the data is specified erroneously or is inadequate for analysis, since life increasing with increasing stress contradicts the true fatigue behavior of materials.

ERROR: TOO FEW POINTS FOR REGRESSION IN REGION 'L'
  Fatal  The materials characterization model does not have the required minimum number of points in the region indicated to perform a linear regression. If there are no related data sets, then there must be at least 3 points in each region. If there are $N$ related data sets, then the total number of points in each region (specific and related combined) must be at least $N + 3$.

IMPOSSIBLE M RANGE IN REGION 'L'
  Fatal  Concavity constraints during the random $m$ selection have required an impossible range on $m$ for the region indicated. Take note of all input.
parameters for this run, and consult Sections 4.1.5.1, 4.1.5.2, and 7.3 to aid in identification of the cause of this error.

NOTE: E(m) IS NOT IN THE POSTERIOR RANGE ON m IN REGION 'L'

Warning  This means that the estimate of m based on the S/N data only, in the region indicated, is outside the range indicated by the specified constraints on m and C.

PROCESS EXECUTION TERMINATED

Fatal  This message is produced by routine TRMNAT and follows all other fatal messages.

6.2.7 Summary of Input/Output Files

Input Files

TRBPWD
This file is opened in TRBPWA. It contains all parameters for the run options; driver distributions; values for nominal stresses and their associated parametric sensitivity coefficients; and the specific and exogenous materials input, including yield and ultimate strengths (psi), stress ratio, S/N data points, life (cycles) boundaries, region information, coefficient of variation constraint, C, and prior ranges on the materials shape parameter m for each region.

RELATD
This file is opened in subroutine INFAGG. It contains the related material data input, including yield and ultimate strengths (psi), stress ratio, S/N data points, and region information.

Output Files

TRBPWO
This file is opened in TRBPWA. It contains the echo of the information contained in TRBPWD, and provides the simulated failure distribution B-life information.39

RELATO
This file is opened in subroutine INFAGG. It contains the echo of the information contained in RELATD.

39 A B-life is the value of accumulated operating time to failure at a failure probability specified as a percent; e.g., B.1 is the failure time at a probability of 0.001 or 0.1%.
**DUMP**
This file is opened in TRBPWA. It contains the results of the information aggregation portion of the materials model calculations, such as $l_0$ and $J_0$; the point estimates of $m$ and $C$; posterior credibility ranges for $m$; and a list of the estimated values for all S/N curve parameters. See Section 4.1.

**IOUTPR**
This file is opened in TRBPWA. It contains information on the particular run that is not echoed to TRBPWO and the data dump provided when the variable IOUT is equal to 10 (materials characterization calculations), or 15 (Monte Carlo simulation and driver transformation calculations).

**LOWLIF**
This file is opened in TRBPWA. It contains the first one percent of the calculated lives used by the software described in Section 4.2 to calculate $\alpha$, $\beta$, and $\theta$, the parameters of the Bayesian prior failure distribution.
Section 6.3
Materials Characterization User's Guide

The user's guide for running the materials characterization model code MATCHR is given here. The materials characterization model is discussed in Section 2.1.2, the program description and flowcharts are presented in Section 4.1, and the code structure and listing are provided in Section 7.3.

6.3.1 MATCHR Program

The MATCHR program is used to facilitate the characterization of a materials data set before performing probabilistic failure modeling. The output of MATCHR includes point and interval estimates of various S/N curve parameters and posterior credibility ranges for m.

The application case studies of Section 3 used the stress formulation of the materials characterization model. The strain formulation is included here for completeness.

6.3.2 How To Use the Stress Formulation Option of Program MATCHR

The program MATCHR is intended to be run in batch (i.e., background) mode. MATCHR requires two input data files: SPECFD and RELATD. The program requires both files for all runs, even when no related S/N data is used. The file SPECFD contains the analysis control parameters and specific and exogenous materials information. The file RELATD contains the related materials information. A complete description of the input data for the SPECFD and RELATD data files is given in Section 6.3.3.

The results from the MATCHR program are written to four output files: SPECFO, RELATO, DUMP, and IOUTPR. SPECFO contains the echo of the information in SPECFD and the results of any stress ratio transformations performed on specific materials data. RELATO contains the echo of the information in RELATD and the results of any stress ratio transformations performed on related materials data. The results of the materials characterization calculations are primarily given in DUMP. These calculations include point and interval estimates for S/N curve parameters m and C, posterior credibility ranges for m, and an estimate of the median S/N curve. File IOUTPR contains an echo of the analysis parameters, the randomly selected S/N curve, the resulting life at the user-provided stress level and, if requested, a dump of intermediate calculations. If the program terminates prematurely, an error message will be printed in the IOUTPR file. A list of error messages and possible remedies for the problems is given in Section 6.3.10.
6.3.3 Description of the Stress Formulation Input Data Files

Annotated examples of the complete data file format structure for SPECFD and RELATD are presented in Figures 6-8 and 6-9, respectively. The data lines of the input files are given in boxes, with a description of each data line located adjacent to each box. The specific input parameters of Figures 6-8 and 6-9 are individually defined in Sections 6.3.3.1 and 6.3.3.2. Input parameter values given in Figures 6-8 and 6-9 are not necessarily those used in the application case studies of Section 3.

The input data is read by free format statements from files SPECFD and RELATD. Thus, the numbers may be provided sequentially on a line up to 80 characters in length, with each number separated by a blank character or comma. Each number may also be on a separate line in the file. However, it is recommended that the input format suggested in Figures 6-8 and 6-9 be followed whenever possible.

6.3.3.1 Input File SPECFD

The required data for the SPECFD file is divided into the two blocks shown in Figure 6-10: analysis parameters and materials information. The analysis parameters block contains the analysis parameters and the keys to select the program options. The materials information block contains the specific material S/N data, including the yield and ultimate strengths, stress ratio, the S/N data points, life region boundaries, and materials characterization model parameter constraints.

The input parameters are described below by using the following convention: the input variable names are indicated by **BOLD UPPERCASE** letters; the variable types are specified as character [CHR], integer [INT], real [RE], and double precision real [DRE]; the function of the variable is **underlined** and followed by a description and a list of options, when appropriate; the program and file names are indicated by **UPPERCASE** letters. A consistent set of units is given in parentheses for specifying dimension, load, and stress input parameters. All character strings must be enclosed by 'single quotes'. The user is reminded about the difference between the number "0" and the letter "O" when preparing the input files.

**Analysis Parameters Block**

**RAND**

[DRE]

Random number seed
Needed by MATCHR's built-in random number generator.
Random number seed
Output dump controller
Stress formulation is to be used
Type of S/N variation
Request for truncated Normal median S/N curve
Controls materials process variation
Value of stress used in life calculation

Description of specific material S/N data set

```
-HOURGLASS + STRAIGHT-
```

Specific materials information: yield and ultimate strengths, number of data divisions, and total number of points in data set

```
178600. 220400. 1 20
```

Specific materials information for each data division: number of points in data division, stress ratio, and life region

```
20 0.05 1
```

Figure 6-8 Format for File SPECFD
| 150000. | 65000. | $S_1, N_1$ |
| 140000. | 261000. | $S_2, N_2$ |
| 120000. | 265000. | $S_3, N_3$ |
| 160000. | 377000. | $S_4, N_4$ |
| 130000. | 694000. | $S_5, N_5$ |
| 110000. | 2175000. | $S_6, N_6$ |
| 100000. | 4198000. | $S_7, N_7$ |
| 105000. | 5053000. | $S_8, N_8$ |
| 92000. | 9210000. | $S_9, N_9$ |
| 95000. | 9667000. | $S_{10}, N_{10}$ |
| 150000. | 418000. | $S_{11}, N_{11}$ |
| 140000. | 732000. | $S_{12}, N_{12}$ |
| 130000. | 740000. | $S_{13}, N_{13}$ |
| 120000. | 859000. | $S_{14}, N_{14}$ |
| 110000. | 1181000. | $S_{15}, N_{15}$ |
| 100000. | 4020000. | $S_{16}, N_{16}$ |
| 92000. | 5917000. | $S_{17}, N_{17}$ |
| 94000. | 6522000. | $S_{18}, N_{18}$ |
| 90000. | 6891000. | $S_{19}, N_{19}$ |
| 88000. | 4460000. | $S_{20}, N_{20}$ |

0.00 Stress tensile point
1 0 Number of life regions with and without data
1.0E + 36 Life boundary
0.00 $C$ constraint
2 3.596 5.874 Prior information on $m$

---

0.0 0.0 0.0 Bayesian prior distribution information

---

0.0 0.0 Materials process variation information

---

*Figure 6-8 Format for File SPECFD (Cont’d)*
Number of related data sets

Description of related material S/N data set

TITANIUM, -423F, 0.14 Fe

Related materials information: yield and ultimate strengths, number of data divisions, and total number of points in data set

\begin{verbatim}
201700. 215300. 2 10
\end{verbatim}

Related materials information for data division 1: number of points in data division, stress ratio, and life region

\begin{verbatim}
4 0.10 1
140000. 38000. S_1, N_1
130000. 30000. S_2, N_2
130000. 713000. S_3, N_3
130000. 310000. S_4, N_4
\end{verbatim}

Figure 6-9 Format for File RELATD

\begin{verbatim}
6 0.10 2
120000. 72000. S_5, N_5
110000. 3224000. S_6, N_6
100000. 910000. S_7, N_7
100000. 3230000. S_8, N_8
120000. 665000. S_9, N_9
110000. 56000. S_{10}, N_{10}
\end{verbatim}

Figure 6-10 Data Blocks for input File

Figure 6-9 Format for File RELATD
IOUT
[INT]

Output dump controller
MATCHR has the ability to write intermediate calculations to file IOUTPR. The following
integer values control the "dump" of MATCHR's calculations.

IOUT = 0    no intermediate calculation output
IOUT = 10   materials characterization model calculations

NCOMPS
[INT]

Controls materials characterization formulation
MATCHR has the ability to produce stochastic realizations of both stress/life and
strain/life curves. The materials information block described below depends on the
value of NCOMPS chosen. This section describes the NCOMPS = 1 case.

NCOMPS = 1    stress formulation
NCOMPS = 2    strain formulation

VARY
[INT]

Type of S/N variation
Controls the type of stochastic variation to be included in the materials characterization model S/N curve.

VARY = 0    no variation will be included
VARY = 1    allows only intrinsic materials variation
VARY = 2    allows Uniform variation of the materials model shape parameter m
            and intrinsic materials variation
VARY = 3    allows truncated Normal variation of the materials model shape
            parameter m and intrinsic materials variation

NMED
[INT]

---

40 A discussion of the possible stochastic specifications of the materials model shape
parameter m is given in Pages 2-13 through 2-14.
Request for truncated Normal median S/N curve

If \( \text{VARY} = 3 \), then \( \text{NMED} \) controls the calculation of the empirical median S/N curve.

\[\begin{align*}
\text{NMED} = 0 & \quad \text{no median curve calculation is required} \\
\text{NMED} = 1 & \quad \text{median curve calculation is required}
\end{align*}\]

\textbf{MPROC} \\
[\text{INT}]

Controls materials process variation

Controls the inclusion of materials process variation (heat-to-heat variation). Process variation in materials is discussed in Section 2.1.2.3.

\[\begin{align*}
\text{MPROC} = 0 & \quad \text{no variation to be included} \\
\text{MPROC} = 1 & \quad \text{variation is to be included}
\end{align*}\]

\textbf{STRESS} \\
[\text{RE}]

\textbf{Value of stress}

MATCHR will provide a value of life (cycles) corresponding to the user-provided value of stress (psi). The life value will be calculated from the stochastic S/N curve resulting from the value of \( \text{RAND} \) provided. \( \text{STRESS} \) must be a positive number.

\textbf{Materials Information Block}

\textbf{DESCRP(0)} \\
[\text{CHR}]

\textbf{Description of specific material S/N data set}

Name and test environment for the specific material S/N data. This is a character string no more than 40 characters long, enclosed by single quotes.

\textbf{FTY FTU NDIV NPTS(0)} \\
[\text{RE}] [\text{RE}] [\text{INT}] [\text{INT}]

\[\text{41 The median S/N curve for the truncated Normal distribution is discussed on Page 2-15.}\]
Specific materials information

Yield strength, ultimate strength, number of divisions of data, number of points in S/N data set. The data may be divided when they are assigned to a different life region or have different stress ratios. If all the data has a stress ratio of -1.0, then the yield and ultimate strengths are not required, but zero values must be specified as placeholders. **NPTS(0)** cannot exceed fifty. The next two data sets have to be provided for each data division.

- **FTY**: yield strength corresponding to the specific material data set (psi)
- **FTU**: ultimate strength corresponding to the specific material data set (psi)
- **NDIV**: number of data divisions for the specific material data set
- **NPTS(0)**: total number of points in the specific material S/N data set

**NUM** | **RATIO** | **REG**
---|---|---
[INT] | [RE] | [INT]

Materials information for each data division of the specific S/N data set

Number of points, stress ratio, and the life region of interest for each data division. This line must be provided for each data division.

- **NUM**: number of S/N data points in the data division
- **RATIO**: stress ratio for the data in the data division
- **REG**: life region number to be assigned to the data in the data division

**RAWSTR(I,0)** | **RAWNF(I,0)**
---|---
[RE] | [RE]

Specific material S/N data points

Stress versus fatigue life data points for each data division. A block of **NUM** lines must be specified (i.e., the value of I goes from 1 to **NUM**). This block must be provided for each data division.

- **RAWSTR(I,0)**: stress value (psi)
- **RAWNF(I,0)**: fatigue life value (cycles)

**SZERO**
[RE]
Tensile point\textsuperscript{42} Stress tensile point $S_o$ (psi). Must be non-negative. A value of zero indicates no tensile point.

\textbf{NUMREG} \hspace{1cm} \textbf{NNODAT}  \\
\texttt{[INT]} \hspace{1cm} \texttt{[INT]} \\

Data regions\textsuperscript{43} Number of life regions that are data-determined and not data-determined. \texttt{NUMREG + NNODAT} cannot exceed three. \texttt{NUMREG} must be 1, 2, or 3, and \texttt{NNODAT} must be non-negative, and should be 0 or 1.

\begin{itemize}
  \item \texttt{NUMREG} number of life regions determined by data
  \item \texttt{NNODAT} number of life regions (to the right) not determined by data
\end{itemize}

\textbf{NBND(L)}  \\
\texttt{[RE]} \\

Life Boundaries\textsuperscript{44} The upper boundaries of the life regions are specified (cycles). The value of \texttt{L} goes from \texttt{ZROREG} to the total number of regions (equal to \texttt{NUMREG + NNODAT}). If a non-zero tensile point is specified, then \texttt{ZROREG} = 0 else \texttt{ZROREG} = 1. The program expects the upper bound of the last life region to be 10\textsuperscript{36}, a proxy for $\infty$.

\textbf{CZERO}  \\
\texttt{[RE]} \\

Prior information on coefficient of variation of fatigue strength\textsuperscript{45} Information in the form of a constraint on the coefficient of variation of fatigue strength $C$ for the specific material S/N data set. Value must be non-negative and a value of zero indicates that \texttt{CZERO} is not in use.

\begin{itemize}
  \item \textsuperscript{42} Extension of the S/N curve to the left is discussed on Page 2-17.
  \item \textsuperscript{43} Extension of the S/N curve to the right is discussed on Page 2-17.
  \item \textsuperscript{44} Life region boundaries are discussed on Page 2-15.
  \item \textsuperscript{45} The implicit constraint on the materials shape parameter provided by prior information on the coefficient of variation of fatigue strength is discussed on Pages 2-12 through 2-13.
\end{itemize}
MPNT(L)  MZERO(1,L)  MZERO(2,L)
(INT)   (RE)      (RE)

Prior information on the materials shape parameter $m$\textsuperscript{46}

The number of MZERO values in each life region, and the lower and upper bound for the range of $m$. The value of L goes from 1 to (NUMREG + NNODAT). If VARY = 3 is specified (truncated Normal distribution on $m$), then a prior range of $m$ must be specified for each region.

MPNT(L)  The number of points, 0, 1, or 2 (no prior on $m$, a point prior on $m$, or a prior over a range of $m$, respectively), in MZERO( ) for each region.

MZERO(1,L)  The lower bound on the range of $m$ or the value of the point prior for $m$.

MZERO(2,L)  The upper bound on the range of $m$. Program requires that the value be zero if a point prior for $m$ is specified.

DELTA(L)  MO(L)  SIGMA2(L)
(RE)      (RE)      (RE)

Information on the Bayesian prior distribution for the truncated Normal distribution\textsuperscript{47} If VARY = 3, then the materials model uses the truncated Normal distribution. The truncated Normal distribution requires some prior information on the Normal distribution parameters because a Bayesian analysis is performed. The information is required for each life region. The value of L goes from 1 to (NUMREG + NNODAT).

DELTA(L)  The shape parameter $\delta$ of the Bayesian prior distribution is used to compute the Bayesian posterior distribution parameters. Value must be non-negative, a value of zero indicates a diffuse prior distribution.

MO(L)  Location parameter $m_0$ of the Bayesian prior distribution of the shape parameter $m$. Must be positive. Required when DELTA(L) is non-zero.

SIGMA2(L)  $\sigma^2$, the known variance of $\ln(fatigue\,life)$, $V(\ln N | \ln S)$. Must be non-negative.

KRATIO  LAMN
(RE)      (RE)

\textsuperscript{46} The explicit constraint on the materials shape parameter provided by prior information on the materials shape parameter is discussed on Page 2-12.

\textsuperscript{47} Specification of the Bayesian prior distribution for the truncated Normal case is discussed on Page 2-14.
Materials process variation information
If MPROC = 1, then specification of KRATIO and LAMN is required. KRATIO is \( \lambda_K \), the ratio \( MED K^*/MED K \) where \( MED K^* \) is the median value over all heats for the stress (psi) at a life of one cycle, and \( MED K \) is the median value for the specific S/N data for the stress (psi) at a life of one cycle. LAMN is the ratio of the variance of \( \ln(\text{life}) \) conditional on stress over all heats to the intrinsic materials variation for the given S/N data conditional on stress. Process variation in materials is discussed in Section 2.1.2.3.

6.3.3.2 Input File RELATD
The input data for file RELATD, which contains the related materials information, is given below. The data format is similar to that used to specify the S/N data in the specific materials information block in the SPECFD file.

NSETS
[INT]
Number of related data sets
Number of related material S/N data sets. The following data groups have to be repeated as a block for each data set. The value of \( J \) varies from 1 to NSETS. If there is no related data, then file RELATD will only contain the number "0". NSETS cannot exceed five.

DESCRP(J)
[CHR]
Description of related material S/N data set
Name and test environment for related material S/N data set \( J \). This is a character string no more than 40 characters long, enclosed by single quotes.

FTY FTU NDIV NPTS(J)
[RE] [RE] [INT] [INT]
Related materials information
Yield strength, ultimate strength, number of divisions of data, number of points in S/N data set. The data may be divided when they are assigned to a different life region or have different stress ratios. If all the data has a stress ratio of \(-1.0\), then the yield and ultimate strengths are not required, but zero values must be specified as placeholders.

---

48 Related S/N data is discussed on Page 2-7.
NPTS(J) cannot exceed fifty. The next two data sets have to be provided for each data division.

- **FTY**: yield strength corresponding to related material data set J (psi)
- **FTU**: ultimate strength corresponding to related material data set J (psi)
- **NDIV**: number of data divisions for related material data set J
- **NPTS(J)**: total number of points in related material S/N data set J

<table>
<thead>
<tr>
<th>NUM</th>
<th>RATIO</th>
<th>REG</th>
</tr>
</thead>
<tbody>
<tr>
<td>[INT]</td>
<td>[RE]</td>
<td>[INT]</td>
</tr>
</tbody>
</table>

Materials information for each data division of the related S/N data set
Number of points, stress ratio, and the life region of interest for each data division. This line must be provided for each data division.

- **NUM**: number of S/N data points in the data division
- **RATIO**: stress ratio for the data in the data division
- **REG**: life region number to be assigned to the data in the data division

<table>
<thead>
<tr>
<th>RAWSTR(I,J)</th>
<th>RAWNF(I,J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[RE]</td>
<td>[RE]</td>
</tr>
</tbody>
</table>

Related material S/N data points
Stress versus fatigue life data points for each data division. A block of NUM lines must be specified (i.e., the value of I goes from 1 to NUM). This block must be provided for each data division.

- **RAWSTR(I,J)**: stress value (psi)
- **RAWNF(I,J)**: fatigue life value (cycles)

**6.3.4 Options and Capabilities of the Stress Formulation**

MATCHR is a Monte Carlo simulation program which generates a stochastic realization of an S/N curve based on data and exogenous information. A printout of intermediate calculations in various parts of the program may be obtained via the IOUT option. This output will be printed in the IOUTPR file. It is recommended that such output not be requested when the NMED option is used since the information will be dumped during every S/N curve selection. The NMED option provides for
calculation of an empirical median S/N curve if the truncated Normal distribution is employed. In this case, the median S/N curve is based on the empirical median from all the shape parameters used in the simulation. The MPROC option activates the computations for the process variation feature of the materials characterization model, as discussed in Section 2.1.2.3.

6.3.5 Code Execution Example for the Stress Formulation

The following example run of the stress formulation of the materials characterization model code MATCHR was carried out by using Uniform shape parameter variation, VARY = 2, and no process variation MPROC = 0. The data set consists of twenty S/N data points, NUM = 20 with a stress ratio of 0.05 (RATIO = 0.05). No tensile point is used, SZERO = 0. The number of regions with data, NUMREG, is 1, and there are no regions to the right without data, NNODAT = 0. The data is in one division, NDIV = 1, and the total number of points is twenty, NPTS(0) = 20. No constraint on the coefficient of variation of fatigue strength is provided, CZERO = 0. An explicit range on m in region one is included (MPNT(1) = 2, MZERO(1,L) = 3.00, and MZERO(2,L) = 5.00). No related data is provided. Thus, the RELATD file is empty, except for a single entry to indicate NSETS = 0. If further explanation of files SPECFD and RELATD is required, refer to Sections 6.3.3.1 and 6.3.3.2, and Figures 6-8 and 6-9, respectively.

The echo of the input data is in the output file SPECFO. The DUMP file contains the results of the materials characterization model information aggregation calculations. Finally, the IOUTPR file gives an echo of the analysis parameters, the randomly selected S/N curve, and the resulting life at STRESS = 75,000 psi. The dump parameter IOUT is zero; therefore, no other output is in this file.

Input File - SPECFD

675
0
1
2
0
0
75000.
'-320 HOURGLASS + STRAIGHT'
178600. 220400. 1 20
20 0.05 1
150000. 65000.

49 The truncated Normal distribution for the materials model shape parameter m is discussed on Page 2-14.

50 The information aggregation calculations are discussed on Pages 2-6 through 2-15.
\begin{verbatim}
140000.  261000.
120000.  265000.
160000.  377000.
130000.  694000.
110000.  2175000.
100000.  4198000.
105000.  5053000.
 92000.  9210000.
 95000.  9667000.
150000.  418000.
140000.  732000.
130000.  740000.
120000.  859000.
110000.  1181000.
100000.  4020000.
 92000.  5917000.
 94000.  6522000.
 90000.  6891000.
 86000.  4460000.
 0.00
 1  0
 1.0E+36
 0.00
 2  3.00  5.00

Input File - RELATD

0

Output File - SPECFO

Copyright (C) 1990, California Institute of Technology. U.S. Government
Sponsorship under NASA Contract NAS7-918 is acknowledged.

MATERIAL INPUT

DESCRIPTION:   -320 HOURGLASS + STRAIGHT

YIELD STRENGTH   0.17860E+06
ULTIMATE STRENGTH 0.22040E+06
NUMBER OF POINTS  20

6 - 130
\end{verbatim}
THERE IS 1 REGION(S) WITH DATA
AND 0 REGION(S) TO THE RIGHT WITHOUT DATA
THE UPPER BOUND(S) OF THE REGION(S) ARE (CYCLES):

0.100E+37

EXOGENOUS INFORMATION

CONSTRAINT ON COEFFICIENT OF VARIATION, C: 0.0000

EXPLICIT CONSTRAINT ON m FOR EACH REGION:

<table>
<thead>
<tr>
<th>REGION</th>
<th># OF POINTS</th>
<th>LOWER BOUND</th>
<th>UPPER BOUND</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>3.0000</td>
<td>5.0000</td>
</tr>
</tbody>
</table>

Output File - RELATO

NUMBER OF DATA SETS: 0

6 - 131
NOTE: ALL Kt ASSUMED TO BE 1.0

TRANSFORMED DATA

Output File - DUMP

Copyright (C) 1990, California Institute of Technology. U.S. Government Sponsorship under NASA Contract NAS7-918 is acknowledged.

RESULTS OF INFORMATION AGGREGATION CALCULATIONS

95% CONFIDENCE INTERVALS ON C AND m FOR EACH REGION

REGION: 1

\[ \begin{align*}
I_o &= (0.092758540, 0.181539600) \\
J_o &= (3.596348000, 5.874000000)
\end{align*} \]

POINT ESTIMATES OF C AND m FOR EACH REGION

\[
\begin{array}{c|cc}
REGION & E(C) & E(m) \\
\hline
1 & 0.122759400 & 4.735174 \\
\end{array}
\]

POSTERIOR CREDIBILITY RANGE ON m FOR EACH REGION

\[
\begin{array}{c|cc}
REGION & LOWER BOUND & UPPER BOUND \\
\hline
1 & 3.5963 & 5.0000 \\
\end{array}
\]

PARAMETER VALUES FOR MEDIAN S/N CURVE

\[
\begin{align*}
\text{NUMBER OF REGIONS: } & 1 & E(\beta_{ao}) = 8.6103 & E(k) = 14.5351 \\
\text{REGION} & m & K & \text{LIFE BOUND} & \text{STRESS BOUND} \\
\end{align*}
\]

6 - 132
selected values of S/N curve parameters

number of regions: 1  beta = 9.3521

region  m  k  life bound  stress bound
1  4.59492 0.16956E+07 0.100E+37 0.00000E+00

phi = 0.963788

output file - IOUTPR

random number seed: 675.0000000000
output dump controller: 0
number of components: 1
type of S/N variation desired
(0-NONE; 1-INTRINSIC; 2-UNIFORM; 3-NORMAL): 2
median curve for normal type
variation desired (0 NO, 1 YES): 0
materials process variation desired
(0 NO, 1 YES): 0
value of stress: 75000.0

number of regions: 1
phi: 0.963788
region: 1
stress bound: 0.000000
bigk(l): 0.169564E+07 mm(l): 4.59492
stress = 75000.0 life = 0.140987E+07

6.3.6 How To Use the Strain Formulation Option of Program MATCHR

The program MATCHR is intended to be run in batch (i.e., background) mode. MATCHR requires two input data files: SPECFD and RELATD. The program requires both files for all runs, even when no related S/N data is used. The file SPECFD contains the analysis control parameters and specific and exogenous materials information. The file RELATD contains the related materials information. A complete description of the input data for the SPECFD and RELATD data files is given in Section 6.3.7.
The results from the MATCHR program are written to four output files: SPECFO, RELATO, DUMP, and IOUTPR. SPECFO contains the echo of the information in SPECFD. RELATO contains the echo of the information in RELATD. The results of the materials characterization calculations are primarily given in DUMP. These calculations include point and interval estimates for S/N curve parameters \( m_P \) and \( m_E \), posterior credibility ranges for \( m_P \) and \( m_E \), and an estimate of the median S/N curve. File IOUTPR contains an echo of the analysis parameters, the randomly selected S/N curve, the resulting life at the user-provided strain level and, if requested, a dump of intermediate calculations. If the program terminates prematurely, an error message will be printed in the IOUTPR file. A list of error messages and possible remedies for the problems is given in Section 6.3.10.

6.3.7 Description of the Strain Formulation Input Data Files

Annotated examples of the complete data file format structure for SPECFD and RELATD are presented in Figures 6-11 and 6-12, respectively. The data lines of the input files are given in boxes, with a description of each data line located adjacent to each box. The specific input parameters of Figures 6-11 and 6-12 are individually defined in Sections 6.3.7.1 and 6.3.7.2.

The input data is read by free format statements from files SPECFD and RELATD. Thus, the numbers may be provided sequentially on a line up to 80 characters in length, with each number separated by a blank character or comma. Each number may also be on a separate line in the file. However, it is recommended that the input format suggested in Figures 6-11 and 6-12 be followed whenever possible.

6.3.7.1 Input File SPECFD

The required data for the SPECFD file is divided into the two blocks shown in Figure 6-10: analysis parameters and materials information. The analysis parameters block contains the analysis parameters and the keys to select the program options. The materials information block contains the specific material S/N data, including plastic and elastic strain components, the S/N data points, tensile test points, and materials characterization model parameter constraints.

The input parameters are described below by using the following convention: the input variable names are indicated by **BOLD UPPERCASE** letters; the variable types are specified as character [CHR], integer [INT], real [RE], and double precision real [DRE]; the function of the variable is **underlined** and followed by a description and a list of options, when appropriate; the program and file names are indicated by **UPPERCASE** letters. A consistent set of units is given in parentheses for specifying dimension, load, and strain input parameters. All character strings must be enclosed by 'single quotes'. The user is reminded about the difference between the number "0" and the letter "O" when preparing the input files.
Random number seed
Output dump controller
Strain formulation is to be used
Type of S/N variation
Request for truncated Normal median S/N curve
Controls materials process variation
Value of strain used in life calculation

Description of specific material S/N data set

'\text{H2/HIGH PRESSURE/HIGH TEMPERATURE}'

Specific materials information: number of given plastic/elastic decomposed strain points, total number of strain points, and the number of tensile test points

\begin{tabular}{|c|c|c|c|}
\hline
1.8 & 105 & 0.475 & 1.325 \\
1.5 & 260 & 0.27 & 1.23 \\
1.3 & 600 & 0.18 & 1.12 \\
1.0 & 1950 & 0.115 & 0.885 \\
1.49 & 186 & & \\
1.47 & 190 & & \\
2.02 & 55 & & \\
4.17 & & & \\
0 & 0.00 & 0.00 & \\
0 & 0.00 & 0.00 & \\
\hline
\end{tabular}

\begin{itemize}
\item $S_1, N_1, S_{P1}, S_{E1}$
\item $S_2, N_2, S_{P2}, S_{E2}$
\item $S_3, N_3, S_{P3}, S_{E3}$
\item $S_4, N_4, S_{P4}, S_{E4}$
\item $S_5, N_5$
\item $S_6, N_6$
\item $S_7, N_7$
\end{itemize}

Tensile point
Prior information on $m_P$
Prior information on $m_E$

\begin{tabular}{|c|c|c|}
\hline
0.00 & 0.00 & 0.00 \\
0.00 & 0.00 & 0.00 \\
\hline
\end{tabular}

Bayesian prior distribution information on $m_P$
Bayesian prior distribution information on $m_E$

Materials process variation information

Figure 6-11 Format for File SPECFD
Number of related data sets

Description of related material S/N data set

"INERT/MIXED PRESS/HIGH TEMPERATURE"

Related materials information: number of given plastic/elastic decomposed strain points, total number of strain points, and the number of tensile test points

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>S₁, N₁, S₁₂, S₁₅</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>S₂, N₂, S₂₄, S₂₅</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>S₃, N₃</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>S₄, N₄</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>S₅, N₅</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>S₆, N₆</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>S₇, N₇</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>S₈, N₈</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>S₉, N₉</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>S₁₀, N₁₀</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>S₁₁, N₁₁</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>S₁₂, N₁₂</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Tensile point 1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Tensile point 2</td>
</tr>
</tbody>
</table>

Figure 6-12 Format for File RELATD
Analysis Parameters Block

RAND
[DRE]

Random number seed
Needed by MATCHR's built-in random number generator.

IOUT
[INT]

Output dump controller
MATCHR has the ability to write intermediate calculations to file IOUTPR. The following integer values control the "dump" of MATCHR's calculations.

IOUT = 0  no intermediate calculation output
IOUT = 10 materials characterization model calculations

NCOMPS
[INT]

Controls materials characterization formulation
MATCHR has the ability to produce stochastic realizations of both stress/life and strain/life curves. The materials information block described below depends on the value of NCOMPS chosen. This section describes the NCOMPS = 2 case.

NCOMPS = 1  stress formulation
NCOMPS = 2  strain formulation

VARY
[INT]

Type of S/N variation
Controls the type of stochastic variation to be included in the materials characterization model S/N curve.

VARY = 0  no variation will be included
VARY = 1  allows only intrinsic materials variation
VARY = 2  allows Uniform variation of the materials model shape parameters \( m_P \) and \( m_E \) and intrinsic materials variation

---

\(^{51}\) A discussion of the possible stochastic specifications of the materials model shape parameters \( m_P \) and \( m_E \) is given in Pages 2-13 through 2-14.
VARY = 3 allows truncated Normal variation of the materials model shape
parameters \( m_p \) and \( m_E \) and intrinsic materials variation

NMED
[INT]

Request for truncated Normal median S/N curve\(^{52}\)
If VARY = 3, then NMED controls the calculation of the empirical median S/N curve.

- NMED = 0 no median curve calculation is required
- NMED = 1 median curve calculation is required

MPROC
[INT]

Controls materials process variation
Controls the inclusion of materials process variation (heat-to-heat variation). Process
variation in materials is discussed in Section 2.1.2.3.

- MPROC = 0 no variation to be included
- MPROC = 1 variation is to be included

STRAIN
[RE]

Value of strain
MATCHR will provide a value of life (cycles) corresponding to the user-provided value
of strain (%). The life value will be calculated from the stochastic S/N curve resulting
from the value of RAND provided. STRAIN must be a positive number.

Materials Information Block

DESCRP(0)
[CHR]

Description of specific material S/N data set
Name and test environment for the specific material S/N data. This is a character string
no more than 40 characters long, enclosed by single quotes.

NDC(0) NPTS(0) NTENS(0)
[INT] [INT] [INT]

\(^{52}\) The median S/N curve for the truncated Normal distribution is discussed on Page 2-15.
Specific materials information
Number of user-provided plastic/elastic decomposed strain points, number of points in S/N data set, and the number of tensile test points.

$NDC(0)$ Number of strain/life points with user-provided plastic and elastic components. At least three points must be provided to use the strain formulation of the materials characterization model.

$NPTS(0)$ Total number of points in the specific material S/N data set. Cannot exceed fifty.

$NTENS(0)$ Number of tensile test data points. Cannot exceed five.

$RAWSTR(I,0)$ $RAWNF(I,0)$ $SP(I,0)$ $SE(I,0)$

Specific material decomposed S/N data points
Strain versus fatigue life data points with user-provided plastic and elastic strain components. A block of $NDC(0)$ lines must be specified (i.e., the value of $I$ goes from 1 to $NDC(0)$).

$RAWSTR(I,0)$ strain value (%)
$RAWNF(I,0)$ fatigue life value (cycles)
$SP(I,0)$ plastic strain component (%)
$SE(I,0)$ elastic strain component (%)

$RAWSTR(I,0)$ $RAWNF(I,0)$

Specific material S/N data points
Strain versus fatigue life data points. A block of $(NPTS(0) - NDC(0))$ lines must be specified.

$RAWSTR(I,0)$ strain value (%)
$RAWNF(I,0)$ fatigue life value (cycles)

$TNSILE(0,M)$

Tensile points
Plastic strain tensile points $S_p$ (%). A block of $NTENS(0)$ lines must be specified (i.e., the value of $M$ goes from 1 to $NTENS(0)$). Inclusion of the tensile data is discussed in Section 2.1.2.2.
Prior information on the materials shape parameters $m_P$ and $m_E$\textsuperscript{53}

The number of \texttt{MZERO} values for the plastic component, the lower and upper bound for the range of $m_P$, the number of \texttt{MZEROE} values for the elastic component, and the lower and upper bound for the range of $m_E$. If \texttt{VARY} = 3 is specified (truncated Normal distribution on $m_P$ and $m_E$), then prior ranges of $m_P$ and $m_E$ must be specified.

<table>
<thead>
<tr>
<th>MPNTP(1)</th>
<th>MZEROE(1)</th>
<th>MZEROE(2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[INT]</td>
<td>[RE]</td>
<td>[RE]</td>
</tr>
</tbody>
</table>

MPNTP(1) The number of points, 0, 1, or 2 (no prior on $m_P$, a point prior on $m_P$, or a prior over a range of $m_P$, respectively), in \texttt{MZEROE()} for the plastic strain component.

MZEROE(1) The lower bound on the range of $m_E$ or the value of the point prior for $m_E$.

MZEROE(2) The upper bound on the range of $m_E$. Program requires that the value be zero if a point prior for $m_E$ is specified.

\texttt{DELTAP(1)} \texttt{MOP(1)} \texttt{SIG2P(1)}

\texttt{DELTAE(1)} \texttt{MOE(1)} \texttt{SIG2E(1)}

\textsuperscript{53} The explicit constraint on the materials shape parameter provided by prior information on the materials shape parameter is discussed on Page 2-12.
Information on the Bayesian prior distributions for the truncated Normal distribution

If \( \text{VARY} = 3 \), then the materials model uses the truncated Normal distribution. The truncated Normal distribution requires some prior information on the Normal distribution parameters because a Bayesian analysis is performed. The information is required for both plastic and elastic strain components.

**DELTAP(1)**  
The shape parameter \( \delta_p \) of the Bayesian prior distribution is used to compute the Bayesian posterior distribution parameters. Value must be non-negative, a value of zero indicates a diffuse prior distribution.

**MOP(1)**  
Location parameter \( m_{op} \) of the Bayesian prior distribution of the shape parameter \( m_p \). Must be positive. Required when \( \text{DELTAP(1)} \) is non-zero.

**SIG2P(1)**  
\( \sigma_p^2 \), the known variance of \( \ln(\text{fatigue life}) \), \( V(\ln N | \ln S_p) \), for the plastic strain components. Must be non-negative.

**DELTAE(1)**  
The shape parameter \( \delta_E \) of the Bayesian prior distribution is used to compute the Bayesian posterior distribution parameters. Value must be non-negative, a value of zero indicates a diffuse prior distribution.

**MOE(1)**  
Location parameter \( m_{oE} \) of the Bayesian prior distribution of the shape parameter \( m_E \). Must be positive. Required when \( \text{DELTAE(1)} \) is non-zero.

**SIG2E(1)**  
\( \sigma_E^2 \), the known variance of \( \ln(\text{fatigue life}) \), \( V(\ln N | \ln S_E) \), for the elastic strain components. Must be non-negative.

**KRATIO**  
\( [\text{RE}] \)

**LAMN**  
\( [\text{RE}] \)

Materials process variation information  
If \( \text{MPROC} = 1 \), then specification of \( \text{KRATIO} \) and \( \text{LAMN} \) is required. \( \text{KRATIO} \) is \( \lambda^* \), the ratio \( \text{MED} K^* / \text{MED} K \) where \( \text{MED} K^* \) is the median value over all heats for the strain (\%) at a life of one cycle, and \( \text{MED} K \) is the median value for the specific S/N data for the strain (\%) at a life of one cycle. \( \text{LAMN} \) is the ratio of the variance of \( \ln(\text{life}) \) conditional on strain over all heats to the intrinsic materials variation for the given S/N data conditional on strain. Process variation in materials is discussed in Section 2.1.2.3.

---

54 Specification of the Bayesian prior distribution for the truncated Normal case is discussed on Page 2-14.
6.3.7.2 Input File RELATD

The input data for file RELATD, which contains the related materials information, is given below. The data format is similar to that used to specify the S/N data in the specific materials information block in the SPECFD file.

**NSETS**

[INT]

Number of related data sets

Number of related material S/N data sets. The following data groups have to be repeated as a block for each data set. The value of J varies from 1 to NSETS. If there is no related data, then file RELATD will only contain the number “0”. NSETS cannot exceed five.

**DESCRI(J)**

[CHR]

Description of related material S/N data set

Name and test environment for related material S/N data set J. This is a character string no more than 40 characters long, enclosed by single quotes.

**NDC(J) NPTS(J) NTENS(J)**

[INT] [INT] [INT]

Related materials information

Number of user-provided plastic/elastic decomposed strain points, number of points in S/N data set, and the number of tensile test points.

**NDC(J)**

Number of strain/life points with user-provided plastic and elastic components for related material data set J.

**NPTS(J)**

Total number of points in related material S/N data set J. Cannot exceed fifty.

**NTENS(J)**

Number of tensile test data points for related material data set J. Cannot exceed five.

**RAWSTR(I,J) RAWNF(I,J) SP(I,J) SE(I,J)**

[RE] [RE] [RE] [RE]

55 Related S/N data is discussed on Page 2-7.
Related material decomposed S/N data points
Strain versus fatigue life data points with user-provided plastic and elastic strain components. A block of $NDC(J)$ lines must be specified, i.e., the value of $I$ goes from 1 to $NDC(J)$.

RAWSTR(I,J) strain value (%)
RAWNF(I,J) fatigue life value (cycles)
SP(I,J) plastic strain component (%)
SE(I,J) elastic strain component (%)

RAWSTR(I,J) RAWNF(I,J) [RE] [RE]

Related material S/N data points
Strain versus fatigue life data points. A block of $(NPTS(J) - NDC(J))$ lines must be specified.

RAWSTR(I,J) strain value (%)
RAWNF(I,J) fatigue life value (cycles)

TNSILE(J,M) [RE]

Tensile points
Plastic strain tensile points $S_p$ (%). A block of $NTENS(J)$ lines must be specified, i.e., the value of $M$ goes from 1 to $NTENS(J)$. Inclusion of tensile data is discussed in Section 2.1.2.2.

6.3.8 Options and Capabilities of the Strain Formulation

MATCHR is a Monte Carlo simulation program which generates a stochastic realization of an S/N curve based on data and exogenous information. A printout of intermediate calculations in various parts of the program may be obtained via the IOUT option. This output will be printed in the IOUTPR file. It is recommended that such output not be requested when the NMED option is used since the information will be dumped during every S/N curve selection. The NMED option provides for calculation of an empirical median S/N curve if the truncated Normal distribution is employed.\footnote{The truncated Normal distribution for the materials model shape parameters $m_p$ and $m_e$ is discussed on Page 2-14.} In this case, the median S/N curve is based on the empirical median
$m_p$ and $m_e$ from all the shape parameters used in the simulation. The MPROC option activates the computations for the process variation feature of the materials characterization model, as discussed in Section 2.1.2.3.

### 6.3.9 Code Execution Example for the Strain Formulation

The following example run of the strain formulation of the materials characterization model code MATCHR was carried out by using Uniform shape parameter variation, \texttt{VARY} = 2, and no process variation \texttt{MPROC} = 0. The data set consists of four data points with given plastic and elastic strain components, \texttt{NDC(0)} = 4, the total number of strain/life points is seven, \texttt{NPTS(0)} = 7, and the number of tensile points, \texttt{NTENS(0)}, is one. No explicit ranges on $m_p$ and $m_e$ are provided (\texttt{MPNTP = MZEROP(1) = MZEROP(2) = MPNTE = MZEROE(1) = MZEROE(2) = 0}). No related data is provided. Thus, the RELATD file is empty except for a single entry to indicate \texttt{NSETS = 0}. If further explanation of files \texttt{SPECFD} and \texttt{RELATD} is required, refer to Sections 6.3.7.1 and 6.3.7.2, and Figures 6-11 and 6-12.

The echo of the input data is in the output file \texttt{SPECFO}. The DUMP file contains the results of the plastic/elastic strain decomposition and the materials characterization model information aggregation calculations. Finally, the IOUTPR file gives an echo of the analysis parameters, the randomly selected S/N curve, and the resulting life at \texttt{STRAIN = 1.5%}. The dump parameter $\texttt{IOUT}$ is zero; therefore, no other output is in this file.

**Input File - SPECFD**

```
675
0
2
2
0
0
1.5
'H2/HIGH PRESSURE/HIGH TEMPERATURE'
4 7 1
1.8 105 0.475 1.325
1.5 260 0.27 1.23
1.3 600 0.18 1.12
1.0 1950 0.115 0.885
1.49 186
1.47 190
2.02 55
4.17
```

\textsuperscript{57} The information aggregation calculations are discussed on Pages 2-6 through 2-14.
MATERIAL INPUT

DESCRIPTION:  H2/HIGH PRESSURE/HIGH TEMPERATURE

NUMBER OF DECOMPOSED STRAIN POINTS:  4
NUMBER OF POINTS IN SPECIFIC DATA SET:  7
NUMBER OF TENSILE TEST POINTS:  1

<table>
<thead>
<tr>
<th>TOTAL STRAIN</th>
<th>LIFE</th>
<th>PLASTIC STRAIN</th>
<th>ELASTIC STRAIN</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.8000</td>
<td>105</td>
<td>0.47500</td>
<td>1.32500</td>
</tr>
<tr>
<td>1.5000</td>
<td>260</td>
<td>0.27000</td>
<td>1.23000</td>
</tr>
<tr>
<td>1.3000</td>
<td>600</td>
<td>0.18000</td>
<td>1.12000</td>
</tr>
<tr>
<td>1.0000</td>
<td>1950</td>
<td>0.11500</td>
<td>0.88500</td>
</tr>
<tr>
<td>1.4900</td>
<td>186</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.4700</td>
<td>190</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.0200</td>
<td>55</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

TENSILE DATA

4.17000

EXOGENOUS INFORMATION
EXPLICIT CONSTRAINT ON $mp$
NUMBER OF POINTS IN RANGE: 0

<table>
<thead>
<tr>
<th>LOWER BOUND</th>
<th>UPPER BOUND</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0000</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

EXPLICIT CONSTRAINT ON $me$
NUMBER OF POINTS IN RANGE: 0

<table>
<thead>
<tr>
<th>LOWER BOUND</th>
<th>UPPER BOUND</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0000</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

Output File - RELATO

NUMBER OF DATA SETS: 0

Output File - DUMP

Copyright (C) 1990, California Institute of Technology. U.S. Government Sponsorship under NASA Contract NAS7-918 is acknowledged.

RESULTS OF STRAIN DECOMPOSITION AND INFORMATION AGGREGATION CALCULATIONS

95% CONFIDENCE INTERVAL AND POINT ESTIMATE OF $mp$
FOR GIVEN PLASTIC COMPONENTS

$$J_{op} = \left( 1.300915000, \ 2.791690000 \right) \quad mp = 2.046302$$

RESULTS FOR GIVEN PLASTIC COMPONENT DATA

PARAMETER VALUES FOR MEDIAN S/N CURVE

<table>
<thead>
<tr>
<th>$m$</th>
<th>$K$</th>
<th>$E(k)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.04630</td>
<td>0.44105E+01</td>
<td>1.4721</td>
</tr>
</tbody>
</table>

6 - 146
95% CONFIDENCE INTERVAL AND POINT ESTIMATE OF \( \mu_e \)
FOR GIVEN ELASTIC COMPONENTS

\[ \text{Joo} = (2.411092000, 11.447510000) \quad \mu_e = 6.929300 \]

RESULTS FOR GIVEN ELASTIC COMPONENT DATA

PARAMETER VALUES FOR MEDIAN S/N CURVE

\[
\begin{array}{ccc}
\text{m} & \text{K} & \text{E(k)} \\
6.92930 & 0.27148E+01 & 0.9925 \\
\end{array}
\]

ESTIMATED STRAIN DECOMPOSITION

SPECIFIC MATERIAL

DESCRIPTION: H2/HIGH PRESSURE/HIGH TEMPERATURE
NUMBER OF DATA POINTS: 8

<table>
<thead>
<tr>
<th>LIFE</th>
<th>TOTAL STRAIN</th>
<th>PLASTIC STRAIN</th>
<th>ELASTIC STRAIN</th>
</tr>
</thead>
<tbody>
<tr>
<td>105</td>
<td>1.8000</td>
<td>0.47500</td>
<td>1.32500</td>
</tr>
<tr>
<td>260</td>
<td>1.5000</td>
<td>0.27000</td>
<td>1.23000</td>
</tr>
<tr>
<td>600</td>
<td>1.3000</td>
<td>0.18000</td>
<td>1.12000</td>
</tr>
<tr>
<td>1950</td>
<td>1.0000</td>
<td>0.11500</td>
<td>0.88500</td>
</tr>
<tr>
<td>186</td>
<td>1.4900</td>
<td>0.31553</td>
<td>1.17447</td>
</tr>
<tr>
<td>190</td>
<td>1.4700</td>
<td>0.30950</td>
<td>1.16050</td>
</tr>
<tr>
<td>55</td>
<td>2.0200</td>
<td>0.58607</td>
<td>1.43393</td>
</tr>
<tr>
<td>1</td>
<td>6.7367</td>
<td>4.17000</td>
<td>2.56673</td>
</tr>
</tbody>
</table>

RELATED MATERIALS

NUMBER OF DATA SETS: 0

6 - 147
RESULTS OF INFORMATION AGGREGATION

95% CONFIDENCE INTERVAL AND POINT ESTIMATE OF \( m_p \) FOR ESTIMATED PLASTIC COMPONENTS

\[
J_{op} = (1.958583000, 2.176915000) \quad m_p = 2.067749
\]

POSTERIOR CREDIBILITY RANGE ON \( m_p \) FOR ESTIMATED PLASTIC COMPONENTS

\[
m_p = (1.9586, 2.1769)
\]

RESULTS FOR ESTIMATED PLASTIC COMPONENT DATA

PARAMETER VALUES FOR MEDIAN S/N CURVE

\[
\begin{array}{ccc}
  m & K & E(k) \\
  2.06775 & 0.41636E+01 & 1.4170 \\
\end{array}
\]

95% CONFIDENCE INTERVAL AND POINT ESTIMATE OF \( m_e \) FOR ESTIMATED ELASTIC COMPONENTS

\[
J_{oe} = (6.173140000, 8.136055000) \quad m_e = 7.154597
\]

POSTERIOR CREDIBILITY RANGE ON \( m_e \) FOR ESTIMATED ELASTIC COMPONENTS

\[
m_e = (6.1731, 8.1361)
\]

RESULTS FOR ESTIMATED ELASTIC COMPONENT DATA

PARAMETER VALUES FOR MEDIAN S/N CURVE

\[
\begin{array}{ccc}
  m & K & E(k) \\
  7.15460 & 0.25704E+01 & 0.9371 \\
\end{array}
\]
TOTAL STRAIN $E(\beta_o) = 25.5248$

SELECTED VALUES OF S/N CURVE PARAMETERS

NUMBER OF REGIONS: 1  $\beta_o = 21.1961$

<table>
<thead>
<tr>
<th>REGION</th>
<th>$m$</th>
<th>$K$</th>
<th>LIFE BOUND</th>
<th>STRESS BOUND</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.11391</td>
<td>0.39587E+01</td>
<td>0.100E+37</td>
<td>0.00000E+00</td>
</tr>
</tbody>
</table>

SELECTED VALUES OF S/N CURVE PARAMETERS

NUMBER OF REGIONS: 1  $\beta_o = 23.5854$

<table>
<thead>
<tr>
<th>REGION</th>
<th>$m$</th>
<th>$K$</th>
<th>LIFE BOUND</th>
<th>STRESS BOUND</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.55215</td>
<td>0.27405E+01</td>
<td>0.100E+37</td>
<td>0.00000E+00</td>
</tr>
</tbody>
</table>

PHI = 0.957870  $Z = 1.00000$

Output File - IOUTPR

| RANDOM NUMBER SEED: 675.000000000000 |
|---------------------------|-----------------|
| OUTPUT DUMP CONTROLLER: 0 | |
| NUMBER OF COMPONENTS: 2 | |
| TYPE OF S/N VARIATION DESIRED (0-NONE; 1-INTRINSIC; 2-UNIFORM; 3-NORMAL): 2 | |
| MEDIAN CURVE FOR NORMAL TYPE | |
| VARIATION DESIRED (0 - NO, 1 - YES): 0 | |
| MATERIALS PROCESS VARIATION DESIRED (0 - NO, 1 - YES): 0 | |
| VALUE OF TOTAL STRAIN: 1.50000 | |
| $K_p$: 3.95868 | $M_p$: 2.11391 | |
| $K_e$: 2.74054 | $M_e$: 6.55215 | |
| PHI = 0.957870 | $Z$: 1.00000 | |
| STRAIN: 1.50000 | LIFE: 187.393 | |

6 - 149
6.3.10 Error Messages and Possible Remedies

The following messages, when applicable, will appear in file IOUTPR. An error message stating that a limit has been exceeded will require that the user increase those limits, as directed, and reviewing or consulting Section 7.3.1.3 is desirable. The messages are listed in alphabetical order for the convenience of the user.

DERIVATIVE EQUAL TO ZERO

Fatal, Strain Formulation    During the iterative solution to calculate life, a value of life was obtained which resulted in a zero value for the derivative of the function, implying multiple solutions. Take note of all input parameters for this run and consult Sections 4.1.9 and 7.3 to aid in identification of the cause of this error.

ERROR CODE INCORRECTLY SPECIFIED

Fatal, Strain Formulation    This indicates a program error during the life calculation. Take note of all input parameters for this run and consult Sections 4.1.9 and 7.3 to aid in identification of the cause of this error.

ERROR: BAD VALUE FOR DELTA OR VALUE OF MO INCONSISTENT WITH DELTA IN REGION 'L'

Fatal, Stress Formulation    This error can occur during the use of the truncated Normal variation option of the materials characterization model for two reasons. First, the value of $\delta$ may be negative. Second, a value of $m_\alpha$ was specified, but the value for $m_\alpha$ is not positive. Check file SPECFD.

ERROR: BAD VALUE FOR DELTAE OR VALUE OF MOE INCONSISTENT WITH DELTAE

Fatal, Strain Formulation    This error can occur during the use of the truncated Normal variation option of the materials characterization model for two reasons. First, the value of $\delta_E$ may be negative. Second, a value of $m_{\alpha E}$ was specified, but the value for $m_{\alpha E}$ is not positive. Check file SPECFD.

ERROR: BAD VALUE FOR DELTAP OR VALUE OF MOP INCONSISTENT WITH DELTAP

Fatal, Strain Formulation    This error can occur during the use of the truncated Normal variation option of the materials characterization model for two reasons. First, the value of $\delta_P$ may be negative. Second, a value of $m_{\alpha P}$ was specified, but the value for $m_{\alpha P}$ is not positive. Check file SPECFD.

ERROR: $C_0$ TOO LOW

Fatal, Stress Formulation    The constraint, $C_0$, imposed on the coefficient of variation of fatigue strength is inconsistent with the observed S/N data.
ERROR: EXCEEDED LIMIT ON DEGREES OF FREEDOM IN CHI-SQUARE TABLE, IN REGION 'L'

*Fatal*  As implemented, the credibility interval calculations can handle no more than 150 degrees of freedom, and the amount of data in the region indicated requires more. The $\chi^2$ tables of routine INTRVL must be increased. See Sections 4.1.3.6 and 7.3.1.3 for more information.

ERROR: EXCEEDED LIMIT ON NUMBER OF REGIONS

*Fatal, Stress Formulation*  The materials characterization model can handle no more than 3 life regions. Check file SPECFD because the sum of the number of regions with data and the number of regions without data is greater than 3.

ERROR: EXCEEDED MAXIMUM NUMBER OF POINTS DUE TO ADDITION OF TENSILE DATA IN DATA SET 'J'

*Fatal, Strain Formulation*  The materials characterization model cannot accept more than 50 points in any S/N data set. The combination of strain/life data with tensile test data will be greater than 50 points for the data set indicated. '0' indicates the specific data set. Check files SPECFD and RELATD for the number of points in the data set. If more than 50 points are desired, the parameter **MAXDAT** must be increased. Refer to Section 7.3.1.3 for the routines involved.

ERROR: EXCEEDED MAXIMUM NUMBER OF POINTS IN RELATED DATA SET 'J'

*Fatal, Strain Formulation*  The materials characterization model cannot accept more than 50 S/N points in any related material data set. Check file RELATD for both the number of given decomposed strain points and the number of total strain points in the related data set indicated. One of these two numbers has been declared to be greater than 50. If more than 50 points are desired, the parameter **MAXDAT** must be increased. Refer to Section 7.3.1.3 for the routines involved.

ERROR: EXCEEDED MAXIMUM NUMBER OF POINTS IN SPECIFIC MATERIAL DATA SET

*Fatal, Strain Formulation*  The materials characterization model cannot accept more than 50 S/N points in the specific material data set. Check file SPECFD for both the number of given decomposed strain points and the number of total strain points in the specific data set. One of these two numbers has been declared to be greater than 50. If more than 50 points are desired, the parameter **MAXDAT** must be increased. Refer to Section 7.3.1.3 for the routines involved.
ERROR: EXCEEDED MAXIMUM NUMBER OF RELATED DATA SETS
  Fatal, Strain Formulation  The materials characterization model allows up to 5 related data sets. Check file RELATD to determine if more than 5 related data sets were specified. The parameter MAXSET must be increased. Refer to Section 7.3.1.3 for the routines involved.

ERROR: EXCEEDED MAXIMUM NUMBER OF TENSILE POINTS IN RELATED DATA SET 'J'
  Fatal, Strain Formulation  The materials characterization model cannot accept more than 5 tensile test points in any related material data set. Check file RELATD for the number of tensile test data points in the related data set indicated. If more than 5 points are desired, the parameter MAXTNS must be increased. Refer to Section 7.3.1.3 for the routines involved.

ERROR: EXCEEDED MAXIMUM NUMBER OF TENSILE POINTS IN SPECIFIC MATERIAL DATA SET
  Fatal, Strain Formulation  The materials characterization model cannot accept more than 5 tensile test points in the specific material data set. Check file SPECFD for the number of tensile test data points. If more than 5 points are desired, the parameter MAXTNS must be increased. Refer to Section 7.3.1.3 for the routines involved.

ERROR: INVALID RESPONSE TO NORMAL MEDIAN CURVE QUESTION
  Fatal  NMED can only have the integer value 0 or 1. Check file IOUTPR for the value used.

ERROR: INVALID TYPE OF MATERIALS PROCESS VARIATION DESIRED
  Fatal  MPROC can only have the integer value 0 or 1. Check file IOUTPR for the value used.

ERROR: INVALID TYPE OF S/N VARIATION DESIRED
  Fatal  VARY can only have the integer value 0, 1, 2, or 3. Check file IOUTPR for the value used.

ERROR: INVALID VALUE FOR RATIO: 'RATIO'
  Fatal, Stress Formulation  An invalid value for the stress ratio has been declared for the specific material data set. Only values between -1.0 and +1.0 inclusive, are possible. Check file SPECFD.
ERROR: INVALID VALUE OF RATIO: 'RATIO'
  Fatal, Stress Formulation  An invalid value for the stress ratio has been declared for a related material data set. Only values between −1.0 and +1.0 inclusive, are possible. Check file RELATD.

ERROR: NO INTERSECTION BETWEEN Jo AND Mc
ERROR: NO INTERSECTION BETWEEN Jo AND Mo
ERROR: NO INTERSECTION BETWEEN Jo, Mo, AND Mc
  Fatal  These errors indicate that the specified C constraint and/or prior credibility range on m do not agree with each other and/or the observed S/N data.

ERROR: NORMAL VARIATION REQUIRES A PRIOR RANGE ON M
  Fatal, Stress Formulation  The truncated Normal variation of the materials characterization model requires a prior range on m. The number of points for the prior range on m has been incorrectly specified. Check file SPECFD to verify that the number of points indicated for each range has an integer value of 1 or 2.

ERROR: NORMAL VARIATION REQUIRES PRIOR RANGES ON Mp AND Me
  Fatal, Strain Formulation  The truncated Normal variation of the materials characterization model requires prior ranges on mp and me. The number of points for the prior range on mp or me has been incorrectly specified. Check file SPECFD to verify that the number of points indicated for each range has an integer value of 1 or 2.

ERROR: NUMBER OF POINTS PER DIVISION INCORRECTLY SPECIFIED IN SET 'J'
  Fatal, Stress Formulation  The materials characterization model has been given conflicting information about the number of points in one of the related S/N data sets. Check file RELATD to compare for each related data set the total number of points declared with the sum of the numbers of points in each data division.

ERROR: NUMBER OF POINTS PER DIVISION INCORRECTLY SPECIFIED IN SPECIFIC DATA SET
  Fatal, Stress Formulation  The materials characterization model has been given conflicting information about the number of points in the specific S/N data set. Check file SPECFD, since the total number of points in the specific data set declared and the sum of the numbers of points in each data division do not agree.
ERROR: OVERALL PRIOR RANGE INCORRECTLY SPECIFIED IN REGION WITHOUT DATA

Fatal, Stress Formulation  The prior credibility range on \( m \) in one of the regions without data has been incorrectly specified. Check file SPECFD to verify that either more regions without data have been indicated than intended or that the number of points in the prior on \( m \) in a region without data has been incorrectly specified. Only the integer value 0, 1, or 2 is acceptable.

ERROR: OVER LIMIT ON NUMBER OF POINTS IN SET 'J'

Fatal, Stress Formulation  The materials characterization model cannot accept more than 50 S/N points in any related material data set. Check file RELATD for the total number of points in each related data set declared, or there may be more than 50 S/N points with an incorrect total declaration. It is suggested that the number of S/N data points in each related set be recounted. If more than 50 points are desired, the parameter MAXDAT must be increased. Refer to Section 7.3.1.3 for the routines involved.

ERROR: OVER LIMIT ON NUMBER OF RELATED DATA SETS

Fatal, Stress Formulation  The materials characterization model allows up to 5 related data sets. Check file RELATD to determine if more than 5 related data sets were specified. The parameter MAXSET must be increased. Refer to Section 7.3.1.3 for the routines involved.

ERROR: OVER NUMBER OF POINTS LIMIT IN SPECIFIC MATERIAL

Fatal, Stress Formulation  The materials characterization model cannot accept more than 50 S/N points in the specific material data set. Check file SPECFD for the total number of points in the specific data set declared, or there may be more than 50 S/N points with an incorrect total declaration. If more than 50 points are desired, the parameter MAXDAT must be increased. Refer to Section 7.3.1.3 for the routines involved.

ERROR: OVER REGION LIMIT IN RELATED MATERIAL 'J'

Fatal, Stress Formulation  No more than 3 life regions are allowed, and an attempt has been made to place some S/N data in a region number greater than 3. Check file RELATD for an invalid region number immediately following the stress ratio value in the data set indicated.

ERROR: OVER REGION LIMIT IN SPECIFIC DATA SET

Fatal, Stress Formulation  No more than 3 life regions are allowed, and an attempt has been made to place some S/N data in a region number greater
than 3. Check file SPECFD for an invalid region number immediately following the stress ratio value.

ERROR: POSTERIOR INTERVAL IN REGION 'L' IS INCONSISTENT WITH POINT POSTERIOR IN REGION 'L-1'

Fatal, Stress Formulation Check file DUMP to verify that the point posterior value of $m$ in region 'L-1' is greater than the upper bound of the posterior credibility range in region 'L'. This error indicates a violation of the concavity assumption.

ERROR: POSTERIOR INTERVAL IN REGION 'L' IS INCONSISTENT WITH THE POSTERIOR INTERVAL IN REGION 'L-1'

Fatal, Stress Formulation Check file DUMP to verify that the lower bound of the posterior credibility range of $m$ in region 'L-1' is greater than the upper bound of the posterior credibility range of $m$ in region 'L'. The data should be checked for consistency.

ERROR: PRIOR ON M INCORRECTLY SPECIFIED IN 'L'

Fatal The number of points for the specified prior range on $m$ in the indicated region has been incorrectly specified. Check file SPECFD to verify that the number of points indicated for each range has an integer value of 0, 1, or 2.

ERROR: SXY \geq 0 IN REGION 'L'

Fatal During the linear regression calculations for the region indicated, the resulting value of the sample covariance $S_{xy}$ was found to be non-negative. This suggests that the data is specified erroneously or is inadequate for the analysis, since life increasing with increasing stress contradicts the true fatigue behavior of materials.

ERROR: TOO FEW POINTS FOR REGRESSION IN REGION 'L'

Fatal The materials characterization model does not have the required minimum number of points in the region indicated to perform a linear regression. If there are no related data sets, then there must be at least 3 points in each region. If there are $N$ related data sets, then the total number of points in each region (specific and related combined) must be at least $N + 3$.

IMPOSSIBLE M RANGE IN REGION 'L'

Fatal, Stress Formulation Concavity constraints during the random $m$ selection have required an impossible range on $m$ for the region indicated. Take note of all input parameters for this run, and consult Sections 4.1.5.1, 4.1.5.2, and 7.3 to aid in identification of the cause of this error.
NCOMPS INCORRECTLY SPECIFIED

*Fatal*  **NCOMPS** can only have the integer values 1 or 2. Check file IOUTPR for the value used.

NO CONVERGENCE AFTER SPECIFIED NO. ITERATION STEPS

*Fatal, Strain Formulation*  This error occurred during the life calculation. The iterative solution did not converge after the maximum of 1000 iterations allowed. The variable IEND of routine GTLF2 must be increased.

NOTE: **E(m) IS NOT IN THE POSTERIOR RANGE ON m IN REGION 'L'**

*Warning*  This means that the estimate of **m** based on the S/N data only, in the region indicated, is outside the range indicated by the specified constraints on **m** and **C**.

PROGRAM EXECUTION TERMINATED

*Fatal*  This message is produced by routine TRMNAT and follows all other fatal messages.

### 6.3.11 Summary of Input/Output Files

**Input Files**

**SPECFD**
This file is opened in MATCHR. It contains all parameters for the run options and the specific and exogenous materials input, including yield and ultimate strengths (psi), stress ratio, S/N data points, life (cycles) boundaries, region information, coefficient of variation constraint, **C**, and prior ranges on the materials shape parameter **m** for each region or strain component.

**RELATD**
This file is opened in subroutine INFAGG or DECOMP. It contains the related material data input, including yield and ultimate strengths (psi), stress ratio, S/N data points, and region information.

**Output Files**

**SPECFO**
This file is opened in MATCHR. It contains the echo of the information contained in SPECFD.
RELATO
This file is opened in subroutine INFAGG or DECOMP. It contains the echo of the information contained in RELATD.

DUMP
This file is opened in MATCHR. It contains the results of the information aggregation portion of the materials model calculations, such as $I_0$ and $J_0$; the point estimates of $m$ and $C$; posterior credibility ranges for $m$; estimated strain decomposition; and a list of the estimated values for all S/N curve parameters. See Section 4.1.

IOUTPR
This file is opened in MATCHR. It contains information on the particular run that is not echoed to SPECFO and the data dump provided when the variable IOUT is equal to 10.
Section 6.4
Prior Distribution Parameter Estimation User's Guide

6.4.1 BFIT Program

The user's guide for running the prior failure distribution parameter \( \beta \) estimation code BFIT is given here. The pertinent methodology is discussed in Section 2.1.1. The program description and flowcharts are presented in Section 4.2.2, and the code structure and listing are provided in Section 7.4.1.

The program BFIT was used to estimate the parameter \( \beta \) of the prior failure distribution produced by appropriate Probabilistic Failure Modeling (PFM) of this report.

6.4.2 How To Use Program BFIT

The program BFIT is intended to run in batch (i.e., background) mode. BFIT requires two input files: BFITD and LOWLIF. File BFITD contains the indices which define the data base used to estimate \( \beta \). The file LOWLIF contains the failure times generated by the PFMs. A complete description of the input data for the BFITD and LOWLIF data files is given in Section 6.4.3.

The results from the BFIT program are written to two output files: BFITO and IOUTPR. BFITO contains the estimate \( b \) for the parameter \( \beta \). File IOUTPR contains, if requested, a dump of intermediate calculations.

6.4.3 Description of the Input Data Files

Annotated examples of the complete data file format structure for BFITD and LOWLIF are presented in Figures 6-13 and 6-14, respectively. The data lines of the input files are given in boxes with a description of each data line located adjacent to each box. The specific input parameters of Figures 6-13 and 6-14 are individually defined in Sections 6.4.3.1 and 6.4.3.2. Input parameter values given in Figures 6-13 and 6-14 are not necessarily those used in the application case studies of Section 3.

The input data is read by free format statements from files BFITD and LOWLIF. Thus, the numbers may be provided sequentially on a line up to 80 characters in length, with each number separated by a blank character or comma. Each number may also be on a separate line in the file. It is recommended that this input format be followed whenever possible.
Output dump controller
Indices for first and last life for linear regression and number of lives in LOWLIF

Figure 6-13 Format for File BFITD

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\[2\) \(F(N_2), N_2\) 
\[3\) \(F(N_3), N_3\) 
\[4\) \(F(N_4), N_4\) 
\[5\) \(F(N_5), N_5\)

196, 9.8E-3, 56611082.90833
197, 9.85E-3, 56827320.11307
198, 9.9E-3, 57986738.95375
199, 9.95E-3, 59037352.04528
200, 1.E-2, 59300005.83862

\[196 \) \(F(N_{196}), N_{196}\) 
\[197 \) \(F(N_{197}), N_{197}\) 
\[198 \) \(F(N_{198}), N_{198}\) 
\[199 \) \(F(N_{199}), N_{199}\) 
\[200 \) \(F(N_{200}), N_{200}\)

Figure 6-14 Format for File LOWLIF

6.4.3.1 Input File BFITD
The input parameters are described below by using the following convention: the input variable names are indicated by **BOLD UPPERCASE** letters; the variable types are specified as integer [INT], and double precision real [DRE]; the function of the variable is **underlined** and followed by a description and a list of options, when appropriate; the program and file names are indicated by **UPPERCASE** letters.

IOUT
[INT]

Output dump controller
BFIT has the ability to write intermediate calculations to file IOUTPR. The following integer values control the "dump" of BFIT's calculations.
Analysis Indices
This line contains indices necessary to perform the regression. **START** is the index of the first element of \texttt{LIFE(I)} to be used in the linear regression to estimate $\beta$. **END** is the index of the last element of \texttt{LIFE(I)} to be used in the linear regression to estimate $\beta$. \texttt{M} is the total number of lives provided in file \texttt{LOWLIF}. $1 \leq \text{START} < \text{END} \leq \text{M}$

### 6.4.3.2 Input File \texttt{LOWLIF}

The data format for the failure times file is given below.

\[
\begin{array}{ccc}
I & \text{FOFN} & \text{LIFE(I)} \\
\text{[INT]} & \text{[DRE]} & \text{[DRE]}
\end{array}
\]

**Failure time data**
The failure times generated by a PFM. The data is entered as \texttt{FOFN}, \texttt{LIFE(I)} pairs, one pair per line for $I = 1, \ldots, M$, where \texttt{FOFN} and \texttt{LIFE} are $F(N_i)$ and $N_i$ of Equation 2-9, respectively.

### 6.4.4 Options and Capabilities

BFIT is a parameter estimation program which utilizes a linear least squares algorithm to estimate the parameter $\beta$ of the prior failure distribution. The program requires a list of failure times and their associated failure probabilities. The results consist of the estimate $b$ of the prior failure distribution parameter $\beta$. A printout of intermediate calculations in various parts of the program may be obtained via the \texttt{IOUT} option. This output will be printed to the \texttt{IOUTPR} file. It is recommended that such output not be requested when the \texttt{IOUT = 10} option is used since the information will include all intermediate calculations for the regression.

### 6.4.5 Code Execution Example

The following example run of the prior failure distribution parameter estimation code BFIT was carried out with two hundred failure times, $M = 200$, provided in file \texttt{LOWLIF}. The linear regression to obtain $\beta$ was performed by using failure times 20 through 200, \texttt{START} = 20 and \texttt{END} = 200. The dump parameter \texttt{IOUT} is zero, hence only important regression information is in file \texttt{IOUTPR}. If further explanation of files BFITD
or LOWLIF is required, refer to Sections 6.4.3.1 and 6.4.3.2, and Figures 6-13 and 6-14, respectively. The results of the parameter estimation were written to file BFITO with $\beta = 1.85889$.

**Input File - BFITD**

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**Input File - LOWLIF**

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Output File - BFITO

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Sponsorship under NASA Contract NAS7-918 is acknowledged.

The solution is
Beta: .1858893E+01

Output File - IOUTPR

\[
\begin{align*}
\text{MEANX} &= 12.1168219315321 \\
\text{MEANY} &= -5.34883972165613 \\
\text{SX2} &= 0.102189088449329 \\
\text{SXY} &= 0.189958590797969 \\
B &= 1.8588930957318 \\
\text{LNC} &= -27.8727163526519
\end{align*}
\]

6.4.6 Summary of Input/Output Files

Input Files

BFITD
This file is opened in BFIT. It contains the indices which define the data base for the
least squares algorithm.

LOWLIF
This file is opened in BFIT. It contains the failure times produced by a PFM.
Output Files

BFITO
This file is opened in BFIT. It provides the results of the parameter estimation.

IOUTPR
This file is opened in BFIT. It contains the data dump provided when the variable IOUT is equal to 10.

6.4.7 ABTFIT Program
The user's guide for running the prior failure distribution parameter estimation code ABTFIT is given here. The pertinent methodology is discussed in Section 2.1.1. The program description and flowcharts are presented in Section 4.2.3, and the code structure and listing are provided in Section 7.4.2.

The program ABTFIT was used to estimate the parameters $\alpha$ and $\theta$, given $\beta$ of the prior failure distribution produced by the Probabilistic Failure Modeling (PFM) of this publication.

6.4.8 How to Use Program ABTFIT
The program ABTFIT is intended to run in batch (i.e., background) mode. ABTFIT requires two input files: PARAMS and LOWLIF. File PARAMS contains the analysis indices, the initial parameter values and scale factors required for the parameter estimation. The file LOWLIF contains the failure times generated by the PFMs. A complete description of the input data for the PARAMS and LOWLIF data files is given in Section 6.4.9.

The results from the ABTFIT program are written to three output files: ABTOUT, BAYESD and IOUTPR. ABTOUT contains the estimated parameters and the number of iterations involved. BAYESD contains the estimated parameters in the format required by programs LZERO and BAYES. File IOUTPR contains, if requested, a dump of intermediate calculations.

6.4.9 Description of the Input Data Files
Annotated examples of the complete data file format structure for PARAMS and LOWLIF are presented in Figures 6-15 and 6-14, respectively. The data lines of the input files are given in boxes with a description of each data line located adjacent to the box. The specific input parameters of Figures 6-15 and 6-14 are individually defined in Sections 6.4.9.1 and 6.4.9.2. Input parameter values given in Figures 6-14 and 6-15 are not necessarily those used in the application case studies of Section 3.
The input data is read by free format statements from files PARAMS and LOWLIF. Thus, the numbers may be provided sequentially on a line up to 80 characters in length, with each number separated by a blank character or comma. Each number may also be on a separate line in the file. It is recommended that this input format be followed whenever possible.

6.4.9.1 Input File PARAMS

The input parameters are described below by using the following convention: the input variable names are indicated by **BOLD UPPERCASE** letters; the variable types are specified as integer [INT], and double precision real [DRE]; the function of the variable is underlined and followed by a description and a list of options when appropriate; the program and file names are indicated by **UPPERCASE** letters.

**IOUT**

[INT]

Output dump controller
ABTFIT has the ability to write intermediate calculations to file IOUTPR. The following integer values control the “dump” of ABTFIT’s calculations.

- **IOUT = 0**  no intermediate calculation output
- **IOUT = 10** parameter estimation calculations
- **IOUT = 20** nonlinear regression iteration trace

**START**  **END**  **MTOT**

[INT]  [INT]  [INT]

Analysis Indices
This line contains indices necessary to perform the regression. **START** is the index of the first element of **LIFE(I)** to be used in the regression to estimate \( \alpha \) and \( \theta \). **END** is the index of the last element of **LIFE(I)** to be used in the regression to estimate \( \alpha \) and \( \theta \). **MTOT** is the total number of lives provided in file LOWLIF. \( 1 \leq \text{START} < \text{END} \leq \text{MTOT} \)
XGUESS(1) XGUESS(2) B
[DRE] [DRE] [DRE]

Initial guesses and $\beta$

Initial guesses of the parameters $\theta$ and $\alpha$, and the estimate of $\beta$ provided by the user. See Section 2.1.1 for a discussion on obtaining initial guesses for $\theta$ and $\alpha$.

XSCALE(1) XSCALE(2) LSCALE
[DRE] [DRE] [DRE]

Scaling factors

Scaling factors for the parameters $\theta$ and $\alpha$ required by DUNLSJ, and the life scaling factor. The answer is insensitive to the required parameter scaling factors. In the absence of other information, provide a value of 1.0 for the parameter scaling factors, and one over the B1-life\footnote{A B-life is the value of the failure parameter (e.g., time) at a failure probability specified as a percent: e.g., B.1 is the failure time at a probability of 0.001 or 0.1%.} for the life scaling factor.

6.4.9.2 Input File LOWLIF

The data format for the failure times file is given below.

I FOFN LIFE(I)
[INT] [DRE] [DRE]

Failure time data

The failure times generated by a PFM. The data is entered as FOFN, LIFE(I) pairs, one pair per line for $I = 1, ..., \text{MTOT}$, where FOFN and LIFE are $F(N_i)$ and $N_i$ of Equation 2-10, respectively.

6.4.10 Options and Capabilities

ABTFIT is a parameter estimation program which utilizes a nonlinear least squares algorithm to estimate the parameters $\alpha$ and $\theta$ of the prior failure distribution, given $\beta$. The program requires a list of failure times and their associated failure probabilities. The results consist of the prior failure distribution parameters and the number of iterations required for the nonlinear least squares algorithm. The estimated parameters are also written to file BAYESD in the appropriate format for the assurance calculation program LZERO and the Bayesian program BAYES. A printout of inter-
mediate calculations in various parts of the program may be obtained via the IOUT option. This output will be printed to the IOUTPR file. It is recommended that such output not be requested when the IOUT = 10 option is used since the information will include all intermediate calculations for each iteration. However, the IOUT = 20 option provides information on the convergence of the nonlinear least squares portion of ABTFIT.

6.4.11 Code Execution Example

The following example run of the prior failure distribution parameter estimation code ABTFIT was carried out with two hundred failure times, MTOT = 200, provided in file LOWLIF. The nonlinear regression to obtain \( \alpha \) and \( \theta \) was performed using failure times 20 through 200, START = 20 and END = 200. The iteration trace was requested, IOUT = 20 and written to file IOUTPR. The value of B provided by the user was 1.85889309575318.\(^{59}\) No parameter scaling was used, XSCALE(1) = XSCALE(2) = 1. The B1-life is on the order of \( 10^4 \) so a life scaling factor of LSCALE = \( 10^{-4} \) was used. Section 2.1.1 describes how to choose initial values for \( \theta \) and \( \alpha \):

\[
\theta_0 = N_{0.01}^b = (16450.6)^{1.8589} = 6.8780 \times 10^7
\]

\[
XGUESS(1) = (N_{0.01} \times LSCALE)^b = (16450.6 \times 10^{-4})^{1.8589} = 2.522669
\]

\[
XGUESS(2) = \alpha_0 = - \ln 0.999 / \ln 2 = 0.0014434
\]

If further explanation of files PARAMS or LOWLIF is required, refer to Sections 6.4.9.1 and 6.4.9.2, and Figures 6-15 and 6-14, respectively.

The results of the parameter estimation were written to file ABTOUT with \( \alpha = 0.014826, \beta = 1.85889, \) and \( \theta = 1.14996 \times 10^9 \). The number of iterations required to estimate \( \alpha \) and \( \theta \) was 13 with 14 function evaluations and 14 Jacobian evaluations.

Input File - PARAMS

```
20
20 200 200
2.522669 0.0014434 1.85889309575318
1.0 1.0 1.0e-4
```

\(^{59}\) See Section 6.4.5 for the estimate of \( b \) of \( \beta \) provided by program BFIT.
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199, 9.95E-3, 73300.5780415
200, 1.E-2, 73318.12226789

Output File - ABTOUT

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The solution is
 Alpha: .148260E-01
 Beta: .185889E+01
 Theta: .114996E+10

The number of iterations is 13
The number of function evaluations is 14
The number of Jacobian evaluations is 14

Output File - BAYESD

1.85889309575318 1149961573.79229 0.148259825241493D-001

Output File - IOUTPR

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<thead>
<tr>
<th>THETA</th>
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<tbody>
<tr>
<td>F 0.252267E+01</td>
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<tr>
<td>J 0.252267E+01</td>
<td>0.144340E-02</td>
</tr>
<tr>
<td>F 0.603934E+00</td>
<td>0.215062E-02</td>
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<td>J 0.603934E+00</td>
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<td>0.218638E-02</td>
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<td>0.359085E-02</td>
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6.4.12 Summary of Input/Output Files

Input Files

PARAMS
This file is opened in ABTFIT. It contains the indices and parameters for the least squares algorithms.

LOWLIF
This file is opened in ABTFIT. It contains the failure times produced by a PFM.

Output Files

ABTOUT
This file is opened in ABTFIT. It provides the results of the parameter estimation.

BAYESD
This file is opened in ABTFIT. It contains the parameters of the prior failure distribution for use by programs LZERO and BAYES.

IOUTPR
This file is opened in ABTFIT. It contains the data dump provided when the variable IOUT is equal to 10 or 20.

6.4.13 LZERO Program

The user’s guide for running LZERO is given here. The program LZERO computes the value of \( \lambda_0 \) for a specified assurance level. The resulting value of \( \lambda_0 \) determines the reliability function corresponding to that specified assurance level. The pertinent methodology is discussed in Section 2.1.1. The program description and flowcharts are presented in Section 4.2.4, and the code structure and listing are provided in Section 7.4.3. The program LZERO was used to obtain the 95% assurance level failure curves presented in Section 3.
Parameters of the failure distribution $\beta, \theta, \alpha$

\begin{array}{ccc}
5.70 & 0.44E+12 & 0.75E-01 \\
\end{array}

Figure 6-16 Format for File BAYESD

| 0 | Output dump controller |
| 0.95 | Desired assurance level, $A$ |
| 1.454742E-11 | $\lambda_o$ lower bound, $\lambda_{lb}$ |
| 2.0E-11 | $\lambda_o$ upper bound, $\lambda_{ub}$ |

Figure 6-17 Format for File LDAT

6.4.14 How to Use Program LZERO

The program LZERO is intended to run in batch (i.e., background) mode. LZERO requires two input files: BAYESD and LDAT. File BAYESD contains the parameters of the prior or posterior failure distribution. The file LDAT contains the desired assurance level, and upper and lower bounds on $\lambda_o$. A complete description of the input data for the BAYESD and LDAT data files is given below in Section 6.4.15.

The results from the LZERO program are written to two output files: LOUT and IOUTPR. LOUT contains the $\lambda_o$ corresponding to the desired assurance level. File IOUTPR contains, if requested, a dump of intermediate calculations.

6.4.15 Description of the Input Data Files

Annotated examples of the complete data file format structure for BAYESD and LDAT are presented in Figures 6-16 and 6-17, respectively. The data lines of the input files are given in boxes with a description of each data line located adjacent to each box. The specific input parameters of Figures 6-16 and 6-17 are individually defined in Sections 6.4.15.1 and 6.4.15.2. Input parameter values given in Figures 6-16 and 6-17 are not necessarily those used in the application case studies of Section 3.

The input data is read by free format statements from files BAYESD and LDAT. Thus, the numbers may be provided sequentially on a line up to 80 characters in length, with each number separated by a blank character or comma. Each number may also be on a separate line in the file. It is recommended that this input format be followed whenever possible.
6.4.15.1 Input File BAYESD

The input parameters are described below by using the following convention: the input variable names are indicated by **BOLD UPPERCASE** letters; the variable types are specified as integer [INT], and double precision real [DRE]; the function of the variable is _underlined_; the program and file names are indicated by **UPPERCASE** letters.

<table>
<thead>
<tr>
<th>BETA</th>
<th>THETA</th>
<th>ALPHA</th>
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</thead>
<tbody>
<tr>
<td>[DRE]</td>
<td>[DRE]</td>
<td>[DRE]</td>
</tr>
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</table>

Failure distribution parameters β, θ, and α of Equation 2-1. They are the parameters of the prior or posterior failure distribution.

6.4.15.2 Input File LDAT

The data format for the LDAT data file is given below.

<table>
<thead>
<tr>
<th>IOUT</th>
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</thead>
<tbody>
<tr>
<td>[INT]</td>
</tr>
</tbody>
</table>

Output dump controller LZERO has the ability to write intermediate calculations to file IOUTPR. The integer value of 10 controls the "dump" of LZERO's calculations.

<table>
<thead>
<tr>
<th>A</th>
</tr>
</thead>
<tbody>
<tr>
<td>[DRE]</td>
</tr>
</tbody>
</table>

Desired assurance level The user requested assurance level specified as the decimal equivalent percentage.

<table>
<thead>
<tr>
<th>LAML</th>
</tr>
</thead>
<tbody>
<tr>
<td>[DRE]</td>
</tr>
</tbody>
</table>

Lower bound on \( \lambda_o \)
Lower bound \( \lambda_{lb} \) on the value of \( \lambda_o \) provided by the user.

<table>
<thead>
<tr>
<th>LAMU</th>
</tr>
</thead>
<tbody>
<tr>
<td>[DRE]</td>
</tr>
</tbody>
</table>

Upper bound on \( \lambda_o \)
Upper bound \( \lambda_{ub} \) on the value of \( \lambda_o \) provided by the user.
6.4.16 Options and Capabilities

LZERO is used to calculate $\lambda_o$ corresponding to the specified level of assurance. A printout of intermediate calculations in various parts of the program may be obtained via the IOUT option. This output will be printed to the IOUTPR file. It is recommended that such output not be requested when the IOUT = 10 option is used since the information will include all intermediate calculations for each iteration.

6.4.17 Code Execution Example

The following example run of the assurance calculation code LZERO was carried out by using the parameters of the Gamma distribution calculated in Sections 6.4.5 and 6.4.11. The dump parameter IOUT is zero, hence nothing is written to file IOUTPR. We are interested in calculating $\lambda_o$ for a 95% assurance level ($A = 0.95$). As described in Section 4.2.4, the $\lambda_o$ that corresponds to the 95% assurance level is obtained by using Mueller's iteration method. This method requires bounding values for $\lambda_o$. The bounding values for $\lambda_o$ may be obtained by using

$$\lambda = \frac{-\ln (1 - F)}{N^\beta}$$

which is Equation 2-1 solved for $\lambda$. For the probability level $F = .001$, the B.1 life $N = 1.64506 \times 10^4$ and $\beta = 1.8588931$, the above equation gives a value for $\lambda$ of $1.454742 \times 10^{-11}$. Use this value for the lower bound $\lambda_{lb}$, and try $2.0 \times 10^{-11}$ for $\lambda_{ub}$. If further explanation of files BAYESD and LDAT is required, refer to Section 6.4.15.1 and 6.4.15.2, and Figures 6-16 and 6-17, respectively.

The results of the assurance calculation were written to file LOUT with $\lambda_o = 1.581782 \times 10^{-11}$, the assurance at $\lambda_{lb} = 0.9488418$, and the assurance at $\lambda_{ub} = 0.9532446$. If $\lambda_o$ is not bounded by $\lambda_{lb}$ and $\lambda_{ub}$, LZERO will stop before Mueller's iteration method begins and provide only the assurances at the upper and lower bounds in file LOUT. The assurance results for the bounds can then be used to make subsequent estimates of bounding values for $\lambda_o$.

Input File - BAYESD

1.85889309575318 1149961573.79229 0.148259825241493D-001

Input File - LDAT

0
0.95
1.454742E-11
2.0E-11
Output File - LOUT

Copyright (C) 1990, California Institute of Technology. U.S. Government Sponsorship under NASA Contract NAS7-918 is acknowledged.

The Gamma distribution parameters are

\[ \begin{align*}
\text{Alpha} & \quad 0.1482598 \times 10^{-1} \\
\text{Theta} & \quad 1.149962 \times 10^{10}
\end{align*} \]

\[ \begin{align*}
\text{Lambda lower bound} & \quad 0.1454742 \times 10^{-10} \\
\text{Lambda upper bound} & \quad 0.2000000 \times 10^{-10}
\end{align*} \]

\[ \begin{align*}
\text{Assurance} & \quad 0.9488418 \\
\text{Assurance} & \quad 0.9532446
\end{align*} \]

At an assurance level of 0.9500000
The value of lambda is 0.1581782 \times 10^{-10}

6.4.18 Summary of Input/Output Files

Input Files

**BAYESD**
This file is opened in LZERO. It contains the parameters of the prior or posterior failure distribution provided by program ABTFIT or BAYES.

**LDAT**
This file is opened in LZERO. It contains the desired assurance level and bounding values for \( \lambda_0 \).

Output Files

**LOUT**
This file is opened in LZERO and contains the results of the assurance calculations.

**IOUTPR**
This file is opened in LZERO only when \( \text{IOUT} = 10 \), and contains the data dump.
Section 6.5
Bayesian Statistical Procedure User’s Guide

6.5.1 BAYES Program

The user’s guide for running the Bayesian statistical procedure code BAYES is given here. The Bayesian statistical procedure is discussed in Section 2.1.1, the program description and flowcharts are presented in Section 4.3, and the code structure and listing are provided in Section 7.5.

The BAYES program was used to perform the Bayesian analysis to combine operating experience with the prior failure distribution obtained from probabilistic failure modeling. The output of BAYES consists of the parameters of the posterior failure distribution as given by Equation 2-2.

6.5.2 How To Use Program BAYES

The program BAYES is intended to be run in batch (i.e., background) mode. BAYES requires one input data file: BAYESD. The file BAYESD contains the parameters of the prior failure distribution and the operating experience. A complete description of the input data for the BAYESD data file is given in Section 6.5.3.

The results from the BAYES program are written to two output files: BAYESO and UBAYES. BAYESO contains the echo of the information in BAYESD and the results of the Bayesian analysis. UBAYES contains the parameters of the posterior failure distribution.

6.5.3 Description of the Input Data File

An annotated example of the complete data file format structure for BAYESD is presented in Figure 6-18. The data lines of the input file are given in boxes with a description of each data line located adjacent to each box. The specific input parameters of Figure 6-18 are individually defined in Section 6.5.3.1. Input parameter values given in Figure 6-18 are not necessarily those used in the application case studies of Section 3.

The input data is read by free format statements from file BAYESD. Thus, the numbers may be provided sequentially on a line up to 80 characters in length, with each number separated by a blank character or comma. Each number may also be on a separate line in the file. It is recommended that this input format be followed whenever possible.
Parameters of the prior failure distribution $\beta, \theta, \alpha$

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<td>$0.75E-01$</td>
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Number of failure and suspension times

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<td>Suspension 1, $t_3$</td>
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<td>10</td>
<td>Suspension 3, $t_5$</td>
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Figure 6-18 Format for File BAYESD

6.5.3.1 Input File BAYESD

The required data for the BAYESD file is divided into the two blocks shown in Figure 6-19: prior failure distribution parameters and operating experience. The prior failure distribution parameters block contains the distribution parameters $\beta, \theta, \alpha$. The operating experience block contains the number of failure and suspension data points and the operating times.

Figure 6-19 Data Blocks for Input File
The input parameters are described below by using the following convention: the input variable names are indicated by **BOLD UPPERCASE** letters; the variable types are specified as integer [INT] and real [RE]; the function of the variable is **underlined** and followed by a description and a list of options when appropriate; the program and file names are indicated by **UPPERCASE** letters. The user is reminded about the difference between the number “0” and the letter “O” when preparing the input files.

**Prior Failure Distribution Parameters Block**

<table>
<thead>
<tr>
<th>BETA</th>
<th>THETA</th>
<th>ALPHA</th>
</tr>
</thead>
<tbody>
<tr>
<td>[RE]</td>
<td>[RE]</td>
<td>[RE]</td>
</tr>
</tbody>
</table>

Prior distribution parameters
β, θ, and α of Equation 2-1. They are the parameters of the prior failure distribution.

**Operating Experience Block**

<table>
<thead>
<tr>
<th>FAIL</th>
<th>SUSP</th>
</tr>
</thead>
<tbody>
<tr>
<td>[INT]</td>
<td>[INT]</td>
</tr>
</tbody>
</table>

Number of failure and suspension data points
s and n-s of Equation 2-2. They are the number of failure and suspension times.

**TYME(I)**

| [RE] |

Operating experience times
A block of (FAIL + SUSP) lines must be provided. First, the failure times are provided, one per line for I = 1, ..., FAIL lines. Then, the suspension times are provided one per line for I = (FAIL + 1), ..., (FAIL + SUSP) lines. BAYES can accept up to 50 operating times.

**6.5.4 Options and Capabilities**

BAYES is a Bayesian analysis program which combines the operating experience of a component with the failure distribution obtained from the probabilistic failure model analysis. The program will accept the operating experience as failure and/or suspension times. The results consist of the posterior failure distribution and some B-lives\(^60\) for both the prior and posterior distributions. The parameters of the posterior

---

\(^60\) A B-life is the value of the failure parameter (e.g., time) at a failure probability specified as a percent: e.g., B.1 is the failure time at a probability of 0.001 or 0.1%.
failure distribution are written to file UBAYES in the format required for further updating as new operating experience becomes available.

6.5.5 Code Execution Example

The following example run of BAYES utilizes only suspension data. The parameters of the prior failure distribution are BETA is 5.7, THETA is $4.4 \times 10^{13}$, and ALPHA is 0.075. The data set consists of no failure times and three suspension times (FAIL = 0, and SUSB = 3). The posterior failure distribution parameters are contained in file UBAYES and have the values BETA is 5.7, THETUP is $4.42052 \times 10^{13}$, and ALPHUP is 0.075.

Input File - BAYESD

```
5.70 0.44E+12 0.75E-01
0 3
30
42
10
```

Output File - BAYESO

Copyright (C) 1990, California Institute of Technology. U.S. Government Sponsorship under NASA Contract NAS7-918 is acknowledged.

BAYESIAN UPDATING SUMMARY

<table>
<thead>
<tr>
<th>PRIOR DISTRIBUTION</th>
<th>POSTERIOR DISTRIBUTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>PARAMETERS:</td>
<td></td>
</tr>
<tr>
<td>BETA</td>
<td>5.700000</td>
</tr>
<tr>
<td></td>
<td>5.700000</td>
</tr>
<tr>
<td>ALPHA</td>
<td>0.750000E-01</td>
</tr>
<tr>
<td></td>
<td>0.750000E-01</td>
</tr>
</tbody>
</table>

61 The condition for using failure data requires that it corresponds to the design under analysis. Typically, a failure is not relevant to evaluation of reliability because it will lead to a redesign or a change in operating conditions.
<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th>BAYESD</th>
<th>BAYESD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theta</td>
<td>0.440000E+12</td>
<td>0.442052E+12</td>
</tr>
<tr>
<td>Lambda</td>
<td>0.170455E-12</td>
<td>0.169663E-12</td>
</tr>
<tr>
<td>Eta</td>
<td>0.173808E+03</td>
<td>0.173949E+03</td>
</tr>
<tr>
<td>BLIVES</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B.01</td>
<td>0.345447E+02</td>
<td>0.345729E+02</td>
</tr>
<tr>
<td>B.1</td>
<td>0.517963E+02</td>
<td>0.518386E+02</td>
</tr>
<tr>
<td>B1</td>
<td>0.784758E+02</td>
<td>0.785399E+02</td>
</tr>
</tbody>
</table>

**OPERATING EXPERIENCE**

**NUMBER OF SUSPENSIONS:** 3

**SUSPENSION TIMES:**

- 0.300000E+02
- 0.420000E+02
- 0.100000E+02

**Output File - UBAYES**

5.70000  0.442052E+12  0.750000E-01

### 6.5.6 Summary of Input/Output Files

**Input Files**

**BAYESD**

This file is opened in BAYES. It contains the parameters of the prior failure distribution and the operating experience.
Output Files

BAYESO
This file is opened in BAYES. It contains the echo of the information contained in BAYESD and the results of the Bayesian analysis.

UBAYES
This file is opened in BAYES. It contains the parameters of the posterior failure distribution.
Section 6.6
Reference Time History Generation User’s Guide

6.6.1 NBSIN Program

The user’s guide for running the time history generation code NBSIN is given here. The narrow-band time history generation is accomplished by means of the AR(1) process (autoregressive process of order one) discussed in Section 2.1.4. The program description and flowchart are presented in Section 4.5, and the code structure and listing are provided in Section 7.7.

The program NBSIN was used to generate the reference narrow-band and accompanying sinusoidal reference time histories required in order to construct the stress-time histories used in the High Cycle Fatigue (HCF) analyses of this report.

6.6.2 How To Use Program NBSIN

The program NBSIN is intended to be run in batch (i.e., background) mode. NBSIN requires one input data file: NBSIN. File NBSIN contains all parameters required for time history generation including storage filenames, frequencies, load sets, amplitudes, and phase angles. A complete description of the input data for the NBSIN data file is given in Section 6.6.3.

The results from the NBSIN program are written to file IOUTPR and to as many as twenty-nine user-specified output files. These time history storage files contain the time histories generated by NBSIN. File IOUTPR, if requested, contains a dump of the intermediate calculations.

6.6.3 Description of the Input Data File

An annotated example of the complete data file format structure for NBSIN is presented in Figure 6-20. The data lines of the input file are given in boxes, with a description of each data line located adjacent to each box. The specific input parameters of Figure 6-20 are individually defined in Section 6.6.3.1. Input parameter values given in Figure 6-20 are not necessarily those used in the application case studies of Section 3.

The input data is read by free format statements from file NBSIN. Thus, the numbers may be provided sequentially on a line up to 80 characters in length, with each number separated by a blank character or comma. Each number may also be on a separate line in the file. It is recommended that this input format be followed whenever possible.
Generation parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Random number seed</td>
<td>1275</td>
</tr>
<tr>
<td>Value of output dump controller</td>
<td>0</td>
</tr>
<tr>
<td>Damping coefficient, $f$</td>
<td>0.05</td>
</tr>
<tr>
<td>$N$</td>
<td>10</td>
</tr>
<tr>
<td>$T$</td>
<td>1.0</td>
</tr>
<tr>
<td>Clipping level (no clipping desired)</td>
<td>1.0E+36</td>
</tr>
<tr>
<td>Phase angle shift, $\psi$</td>
<td>0.0</td>
</tr>
<tr>
<td>Number of narrow-band and sinusoidal processes</td>
<td>6 6 6 1 6</td>
</tr>
</tbody>
</table>

Narrow-band process information

<table>
<thead>
<tr>
<th>Process ID</th>
<th>Amplitude</th>
<th>File Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>'XP'</td>
<td>1.0</td>
<td>File 1, $\sigma_{N1}$, $f_{o1}$</td>
</tr>
<tr>
<td>'XT'</td>
<td>1.0</td>
<td>File 2, $\sigma_{N2}$, $f_{o2}$</td>
</tr>
<tr>
<td>'XM2'</td>
<td>1.0</td>
<td>File 3, $\sigma_{N3}$, $f_{o3}$</td>
</tr>
<tr>
<td>'XM3'</td>
<td>1.0</td>
<td>File 4, $\sigma_{N4}$, $f_{o4}$</td>
</tr>
<tr>
<td>'XV2'</td>
<td>1.0</td>
<td>File 5, $\sigma_{N5}$, $f_{o5}$</td>
</tr>
<tr>
<td>'XV3'</td>
<td>1.0</td>
<td>File 6, $\sigma_{N6}$, $f_{o6}$</td>
</tr>
<tr>
<td>'YP'</td>
<td>1.0</td>
<td>File 7, $\sigma_{N7}$, $f_{o7}$</td>
</tr>
<tr>
<td>'YT'</td>
<td>1.0</td>
<td>File 8, $\sigma_{N8}$, $f_{o8}$</td>
</tr>
<tr>
<td>'YM2'</td>
<td>1.0</td>
<td>File 9, $\sigma_{N9}$, $f_{o9}$</td>
</tr>
<tr>
<td>'YM3'</td>
<td>1.0</td>
<td>File 10, $\sigma_{N10}$, $f_{o10}$</td>
</tr>
<tr>
<td>'YV2'</td>
<td>1.0</td>
<td>File 11, $\sigma_{N11}$, $f_{o11}$</td>
</tr>
<tr>
<td>'YV3'</td>
<td>1.0</td>
<td>File 12, $\sigma_{N12}$, $f_{o12}$</td>
</tr>
<tr>
<td>'ZP'</td>
<td>1.0</td>
<td>File 13, $\sigma_{N13}$, $f_{o13}$</td>
</tr>
<tr>
<td>'ZT'</td>
<td>1.0</td>
<td>File 14, $\sigma_{N14}$, $f_{o14}$</td>
</tr>
<tr>
<td>'ZM2'</td>
<td>1.0</td>
<td>File 15, $\sigma_{N15}$, $f_{o15}$</td>
</tr>
<tr>
<td>'ZM3'</td>
<td>1.0</td>
<td>File 16, $\sigma_{N16}$, $f_{o16}$</td>
</tr>
<tr>
<td>'ZV2'</td>
<td>1.0</td>
<td>File 17, $\sigma_{N17}$, $f_{o17}$</td>
</tr>
<tr>
<td>'ZV3'</td>
<td>1.0</td>
<td>File 18, $\sigma_{N18}$, $f_{o18}$</td>
</tr>
<tr>
<td>'AERO'</td>
<td>1.0</td>
<td>File 19, $\sigma_{N19}$, $f_{o19}$</td>
</tr>
</tbody>
</table>

Sinusoidal process information

<table>
<thead>
<tr>
<th>Process ID</th>
<th>Amplitude</th>
<th>Frequency</th>
<th>File Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>'SIN1'</td>
<td>1.0</td>
<td>500.</td>
<td>7.4703, File 1, $A_1$, $f_{c1}$, $\varphi_1$</td>
</tr>
<tr>
<td>'SIN2'</td>
<td>1.0</td>
<td>600.</td>
<td>90.3813, File 2, $A_2$, $f_{c2}$, $\varphi_2$</td>
</tr>
<tr>
<td>'SIN3'</td>
<td>1.0</td>
<td>1000.</td>
<td>134.2636, File 3, $A_3$, $f_{c3}$, $\varphi_3$</td>
</tr>
<tr>
<td>'SIN4'</td>
<td>1.0</td>
<td>1500.</td>
<td>176.7569, File 4, $A_4$, $f_{c4}$, $\varphi_4$</td>
</tr>
<tr>
<td>'SIN5'</td>
<td>1.0</td>
<td>1800.</td>
<td>-69.0515, File 5, $A_5$, $f_{c5}$, $\varphi_5$</td>
</tr>
<tr>
<td>'SIN6'</td>
<td>1.0</td>
<td>2000.</td>
<td>82.2972, File 6, $A_6$, $f_{c6}$, $\varphi_6$</td>
</tr>
</tbody>
</table>

Figure 6-20 Format for File NBSIN
6.6.3.1 Input File NBSIN

The required data for the NBSIN file is divided into the three blocks shown in Figure 6-21: generation parameters, narrow-band process information, and sinusoidal process information. The generation parameters block contains the common parameters and the keys to select the program options. The time history file name, magnitude, and frequency for each narrow-band process are contained in the narrow-band process information block. The sinusoidal process information block contains the time history file name, amplitude, frequency, and phase angle for each sinusoidal process.

The input parameters are described below by using the following convention: the input variable names are indicated by BOLD UPPERCASE letters; the variable types are specified as character [CHR], integer [INT], real [RE], and double precision real [DRE]; the function of the variable is underlined and followed by a description and a list of options when appropriate; the program and file names are indicated by UPPERCASE letters. A consistent set of units is given in parentheses for specifying input parameters. All character strings must be enclosed by 'single quotes'. The user is reminded about the difference between the number "0" and the letter "O" when preparing the input files.

Generation Parameters Block

**RAND**

[DRE]

Random number seed

Needed by NBSIN's built-in random number generator.
IOUT
[INT]

Output dump controller
NBSIN has the ability to write intermediate calculations to file IOUTPR. The integer value of 10 controls the “dump” for NBSIN’s calculations.

F
[DRE]

Frequency controlling time increment
\( f \) of Equation 2-58. It is the frequency used to calculate the time increment and it is usually the maximum of all the narrow-band and sinusoidal frequencies.

XC
[DRE]

Damping Coefficient
\( \xi \) of Equation 2-58, the damping coefficient.

N
[INT]

Number of points per cycle of frequency \( F \)
This is used to calculate the time increment. The program requires a positive value.\(^{62}\)

LASTT
[DRE]

Length of generated time history
The length of time \( T \) in seconds to be simulated by NBSIN.\(^{63}\)

CLIP
[DRE]

Peak clipping level
The user may specify a peak clipping level for the narrow-band time histories. All peaks having absolute values larger than CLIP will be set equal to CLIP. If no clipping

\(^{62}\) \( N \) is discussed on Page 2-30.

\(^{63}\) \( T \) is discussed on Page 2-30.
is desired, then set CLIP equal to a number larger than any peaks that are likely to be generated. CLIP must be positive.

SHIFT

SHIFT

Sinusoidal phase angle shift, \( \psi \)

The user may specify a phase angle for shifting all sinusoidal processes. The sinusoid arguments will all be shifted this amount (degrees). If no shifting is desired, then set \( \text{SHIFT} \) equal to zero.

\[
\begin{align*}
\text{NRAND}(1) & \quad \text{NRAND}(2) \quad \text{NRAND}(3) \quad \text{NRAND}(4) \quad \text{NSIN} \\
\text{[INT]} \quad \text{[INT]} \quad \text{[INT]} \quad \text{[INT]} \quad \text{[INT]}
\end{align*}
\]

Number of narrow-band and sinusoidal time histories

NBSIN can generate up to a total of nineteen narrow-band processes with up to four loads sets. NBSIN can generate up to ten sinusoidal processes. Non-negative values are required.

\[
\begin{align*}
\text{NRAND}(1) & \quad \text{the number of narrow-band time histories in load set 1} \\
\text{NRAND}(2) & \quad \text{the number of narrow-band time histories in load set 2} \\
\text{NRAND}(3) & \quad \text{the number of narrow-band time histories in load set 3} \\
\text{NRAND}(4) & \quad \text{the number of narrow-band time histories in load set 4} \\
\text{NSIN} & \quad \text{the number of sinusoidal time histories}
\end{align*}
\]

Narrow-band Process Information Block

\[
\begin{align*}
\text{HISNAM}(K) & \quad \text{SIGMAN}(K) \quad \text{FO}(K) \\
\text{[CHR]} \quad \text{[DRE]} \quad \text{[DRE]}
\end{align*}
\]

Narrow-band process generation information

A block of \( \text{NRAND}(0) \) lines must be provided. \( K \) goes from 1 to \( \text{NRAND}(0) \).\(^6^4\) The line contains the time history storage file name, \( \sigma_N \), and \( f_0 \). The file name is a character string up to six characters long enclosed by single quotes. \( \sigma_N \) of Equation 2-58, is the magnitude of the narrow-band process, and must be positive. It must be set equal to 1.0 when a reference time history is being generated. \( f_0 \) (Hz) of Equation 2-58 is the frequency of the narrow-band process.

\(^6^4\) The total number of narrow-band time histories, \( \text{NRAND}(0) = \text{NRAND}(1) + \text{NRAND}(2) + \text{NRAND}(3) + \text{NRAND}(4) \).
Sinusoidal Process Block

HISNAM(J)  A(J)  FC(J)  PHASE(J)
[CHR]  [DRE]  [DRE]  [DRE]

Sinusoidal process generation information
A block of NSIN lines must be provided. J goes from 1 to NSIN. The line contains
the time history storage file name, A, f_c, and \( \phi \). The file name is a character string up
to six characters long enclosed by single quotes. A is the amplitude of the sinusoidal
process, and must be positive. It must be set equal to 1.0 when a reference time
history is being generated. \( f_c \) (Hz) is the frequency for the sinusoidal process, and
\( \phi \) (rad) is the phase angle.

6.6.4 Options and Capabilities

NBSIN is a simulation program which can be used to generate reference time
histories for use with the HCF analysis programs DCTHCF and HEXHCF. The
simulation uses AR(1) processes to generate an approximation to a narrow-band
process. The approximation ensures that the spectral density function of the AR(1)
process closely follows the spectral density function of the narrow-band process in
the neighborhood of their peaks. The program also generates sinusoidal processes
at the same time increments for use in composite load HCF cases. For applications
to date, as many as 4 load sets for a total of 19 narrow-band random and 10 sinusoidal
processes have been generated simultaneously with each reference time history
composed of up to 25,000 points.

The reference time history components have scale factors \( A = 1 \) and \( \sigma_N = 1 \). Formation of the composite stress-time history by specifying \( A \) and \( \sigma_N \) values takes
place in the Probabilistic Failure Model (PFM). Currently, NBSIN can generate up to
\( NRAND(0) = 19 \) narrow-band, in four load sets, and \( NSIN = 10 \) sinusoidal processes
of up to 25,000 points simultaneously.

A printout of intermediate calculations may be obtained via the IOUT option. The
information will be printed in the IOUTPR file. It is recommended that such output not
be requested when the simulation size is large since the information will be dumped
at every time increment.

6.6.5 Code Execution Example

The following example run of NBSIN is a substantially reduced version of the HPOTP
main discharge duct HCF analysis reference time history generation. This will
generate two narrow-band processes and one sinusoidal process (\( NRAND(1) =
NRAND(2) = 1 \), \( NRAND(3) = NRAND(4) = 0 \) and \( NSIN = 1 \)). The largest of the
three frequencies is 2000 Hz, so this is used for F. The damping coefficient, \( \beta \) is 0.03333 or 1/30. Ten points per cycle of frequency F are specified (N = 10) together with a history length T of 5\( \times \)10^{-4} seconds. No clipping or phase angle shifting is desired (CLIP = 10^{36} and SHIFT = 0).

The three processes simulated for this problem are:

<table>
<thead>
<tr>
<th>TYPE</th>
<th>NAME</th>
<th>FREQUENCY</th>
<th>PHASE ANGLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Narrow-band</td>
<td>Axial</td>
<td>1306</td>
<td>NA</td>
</tr>
<tr>
<td>2. Narrow-band</td>
<td>Moment</td>
<td>498</td>
<td>NA</td>
</tr>
</tbody>
</table>

Since the three component processes are reference time histories, corresponding \( \sigma_x \) and A are set equal to one (SIGMAN(1) = SIGMAN(2) = A(1) = 1.0). The rationale for the specification of the processes is given in Section 3.

The generated reference time histories are in the user-specified output files AXIAL, MOMENT, and SIN. The dump parameter IOUET is zero; therefore, no output is in file IOUETPR.

Input File - NBSIN

```
1275
0
2000
0.033333
10
0.0005
1.0E+36
0.0
1 1 0 0 1
'AXIAL' 1.0 1306.
'MOMENT' 1.0 498.
'SIN' 1.0 2000. -13.1221
```

Output File - IOUETPR

```
0
```

Output File - AXIAL

```
-1.02049947079946
-0.981144655736187
-0.684737677520974
-0.366017655522998
 0.158197622376050
```

6 - 193
0.364337198737643
0.430778879959374
0.603244733602086
0.680397341762041
0.500667800781674

Output File - MOMENT

-1.88608227754315
-2.01955579985522
-2.15463039452833
-2.21239214023729
-2.16788029353809
-1.92173426909737
-1.69366840411679
-1.74476896203846
-1.59120552672873
-1.29450122918237

Output File - SIN

0.973888469945478
0.921335424736327
0.516863543379789
-0.850326546259054D-001
-0.654449266970346
-0.973888489792803
-0.921335390749091
-0.516863468539960
0.850327417320549D-001
0.654449333071226

6.6.6 Summary of Input/Output Files

Input Files

NBSIN
This file is opened in NBSIN. It contains all parameters required for the time history generation including storage file names, frequencies, load sets, amplitudes, and phase angles.

Output Files

IOUTPR
This file is opened in NBSIN. It contains the data dump provided when the variable IOUT is equal to 10.
These are the time history storage files and are opened in NBSIN. They contain the time histories generated by NBSIN.