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

Volume II: Software Documentation

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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,[1] 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[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.

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[2] Currently of Structural Integrity Engineering, Chatsworth, CA.

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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.

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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. Doebler, 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.

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4.0 Statistical Analysis Software

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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:

NAME	TYPE	CONTENTS
SPECFD	Input	Simulation parameters and specific material data
SPECFO	Output	Input data echo
DUMP	Output	Results of simulation
IOUTPR	Output	Run information and intermediate calculations

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.

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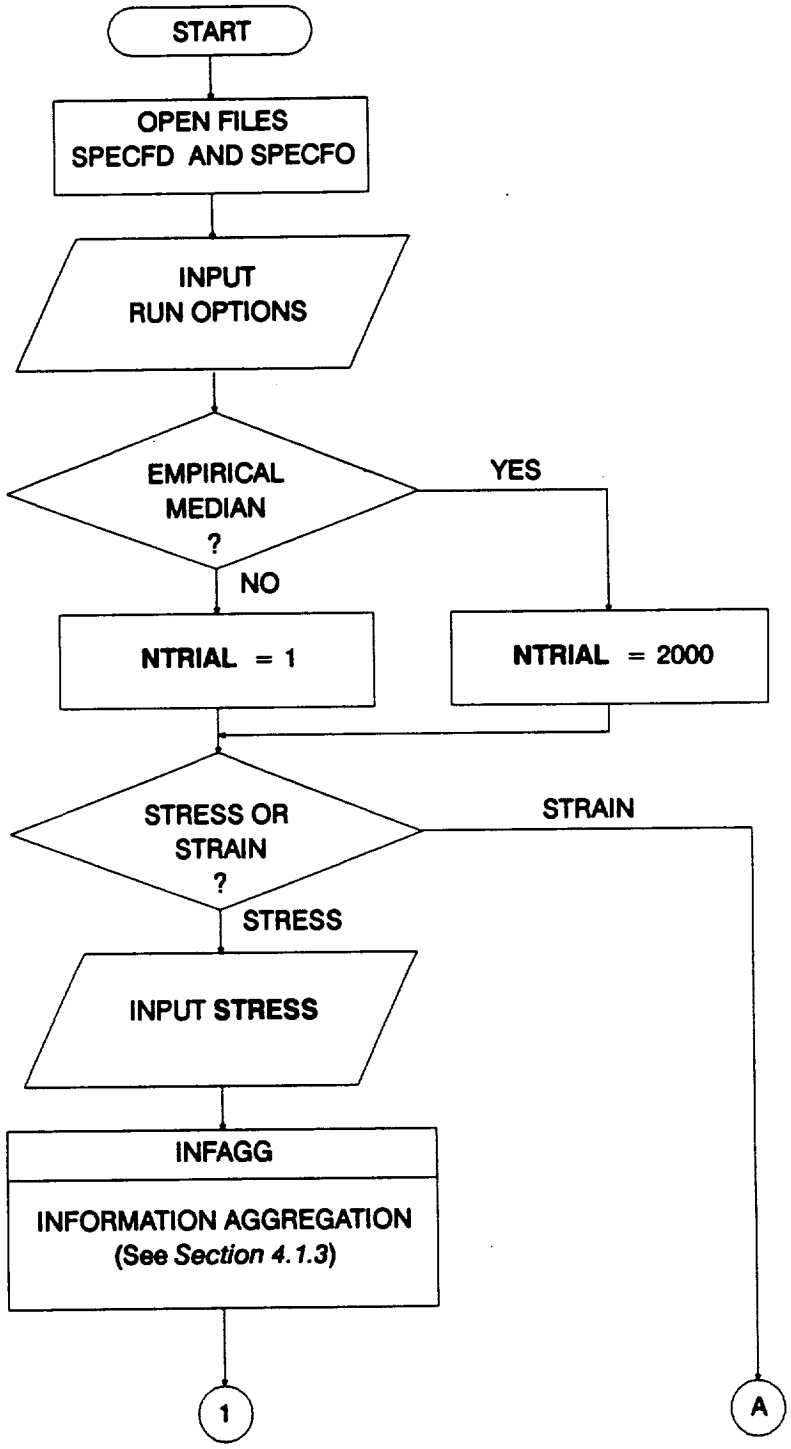

Figure 4-1 Main Flowchart for the Materials Characterization Model Program MATCHR

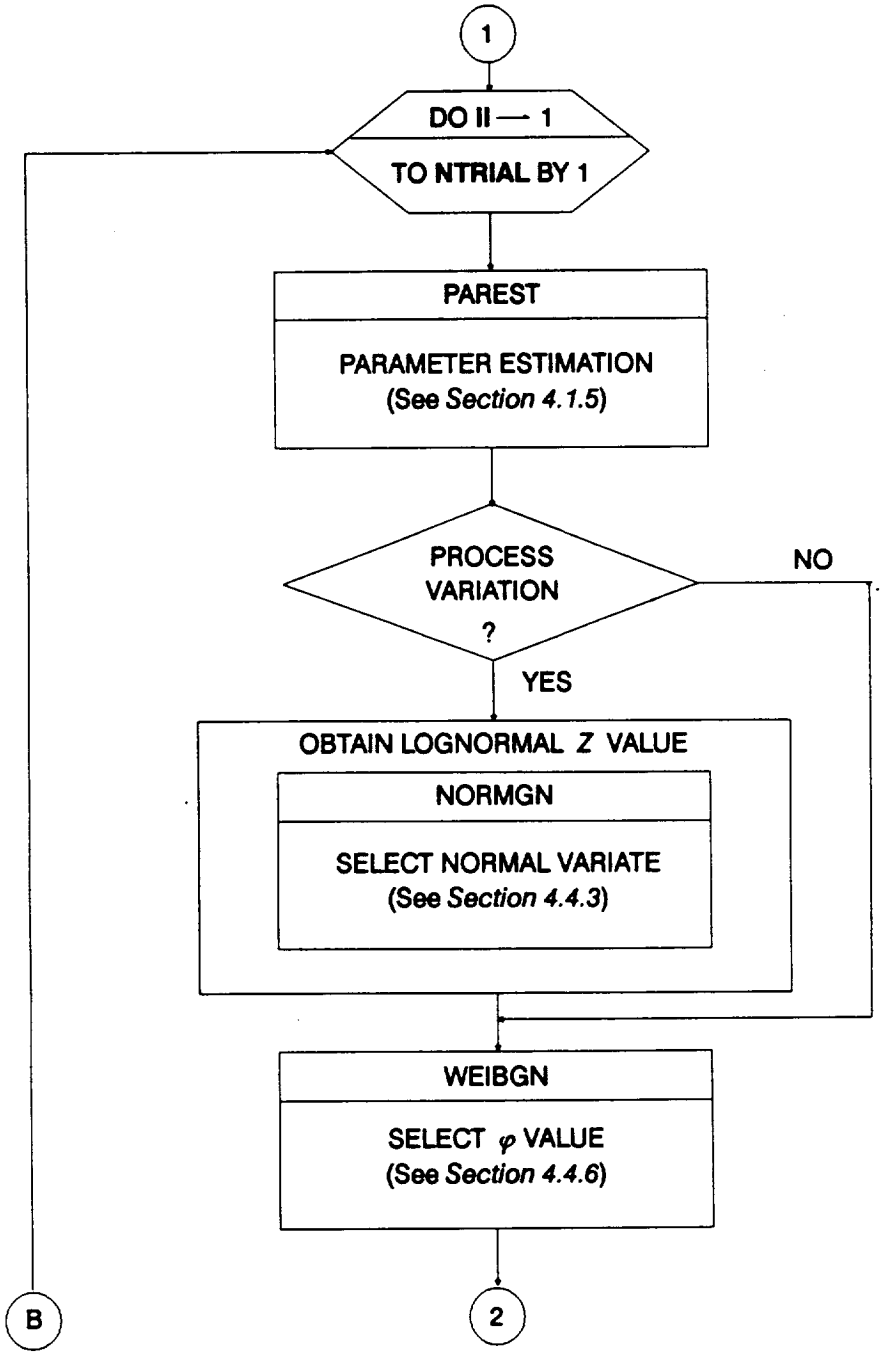

Figure 4-1 Main Flowchart for the Materials Characterization Model Program MATCHR (Cont'd)

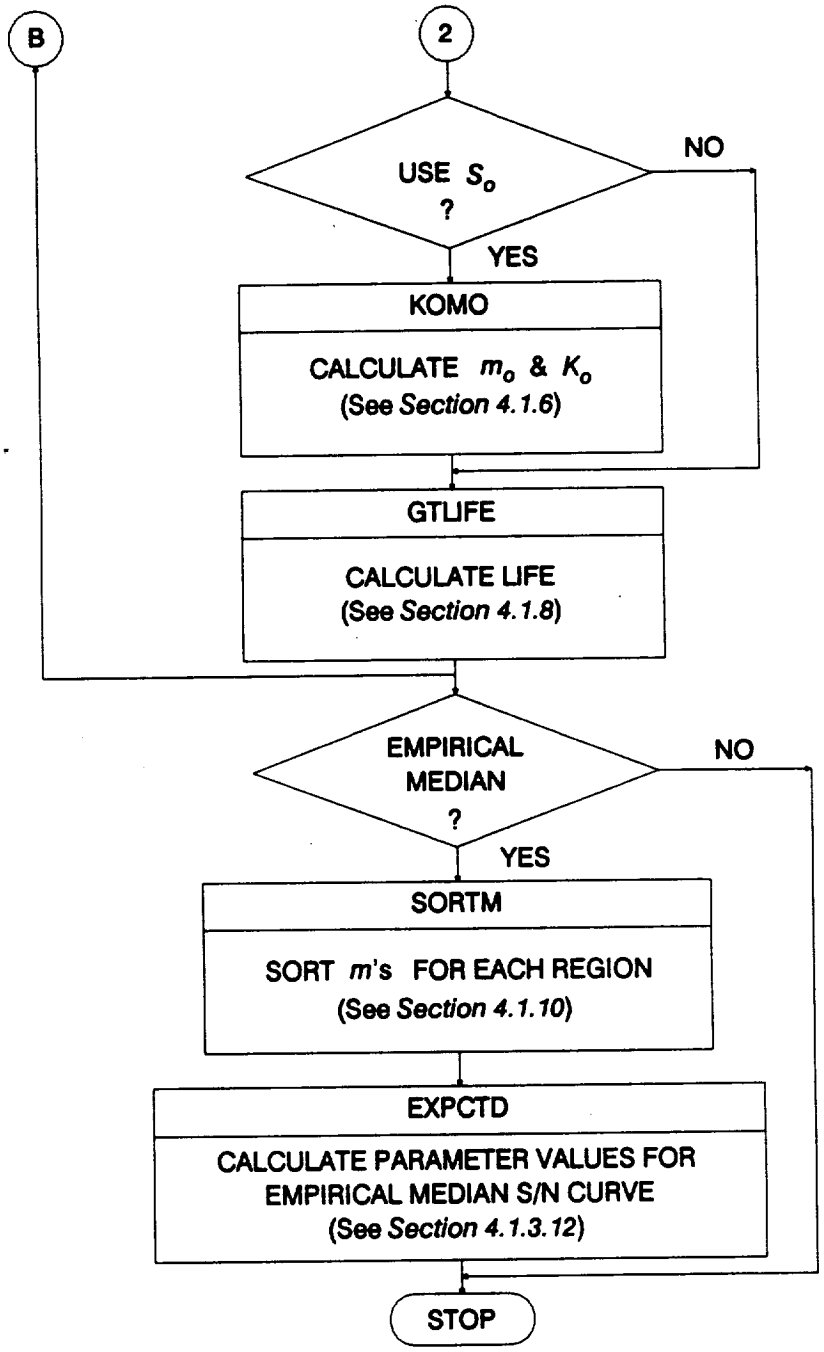

Figure 4-1 Main Flowchart for the Materials Characterization Model Program MATCHR (Cont'd)

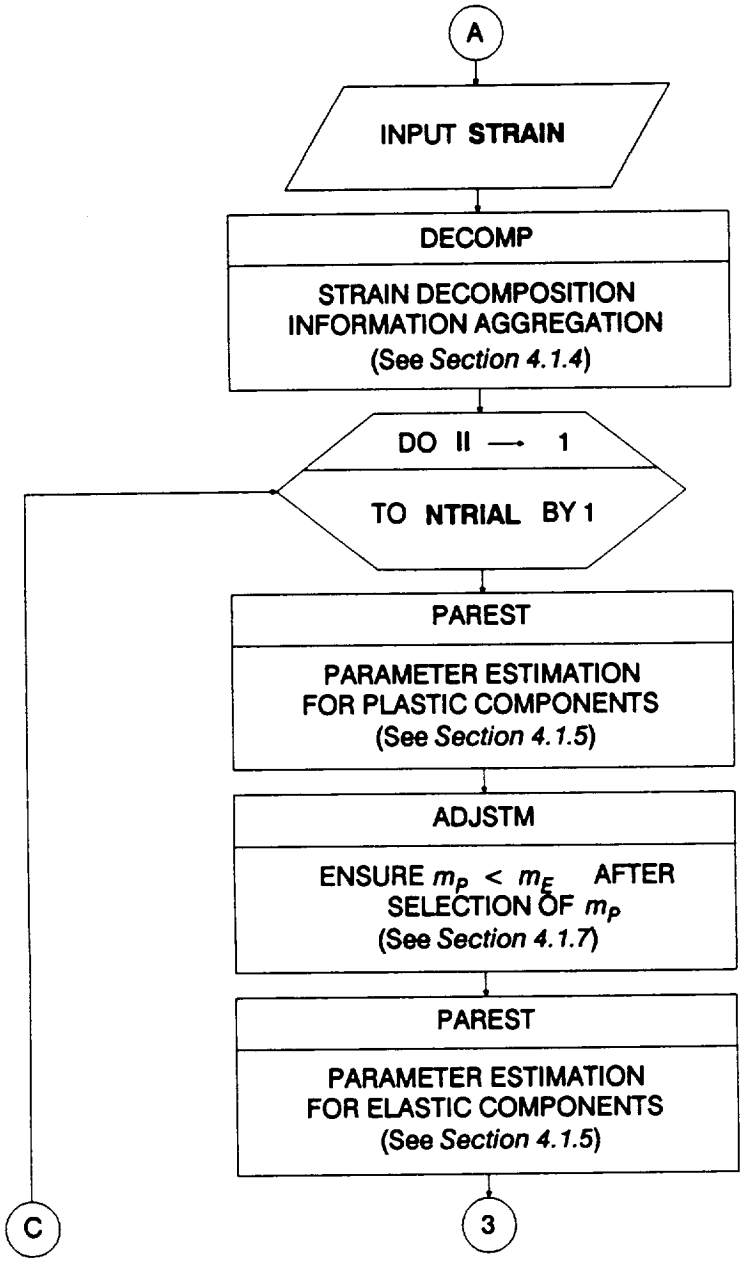

Figure 4-1 Main Flowchart for the Materials Characterization Model Program MATCHR (Cont'd)

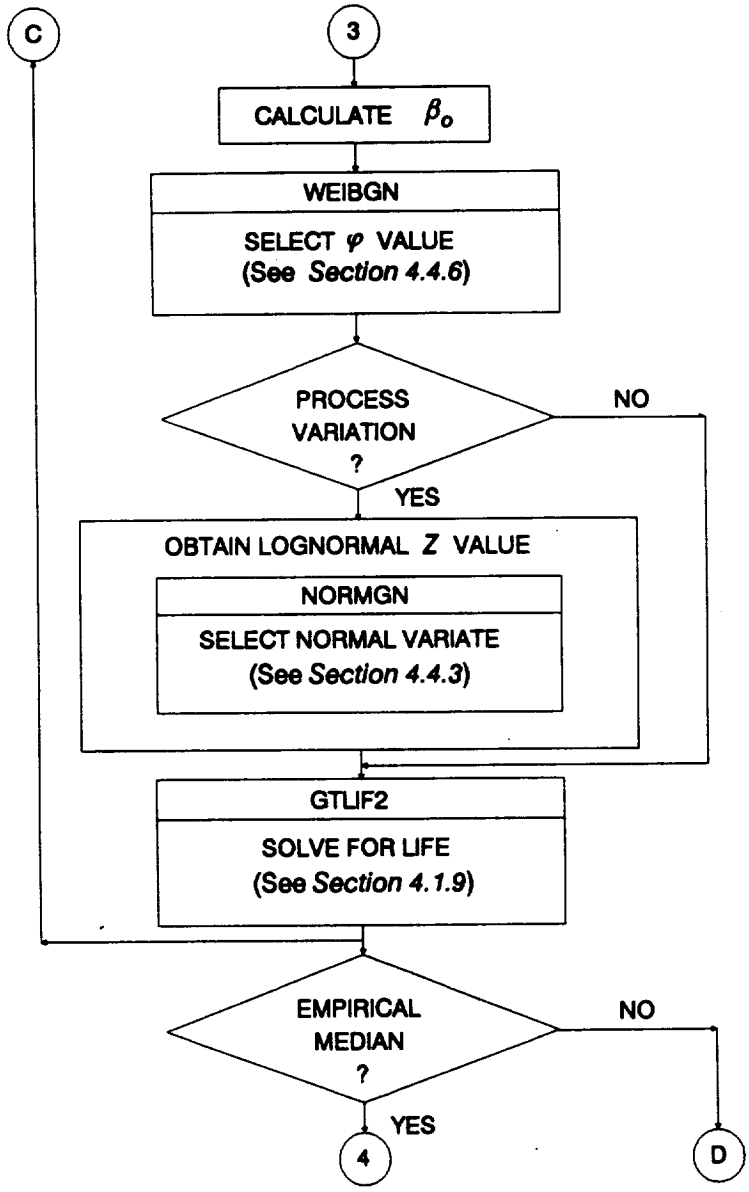

Figure 4-1 Main Flowchart for the Materials Characterization Model Program MATCHR (Cont'd)

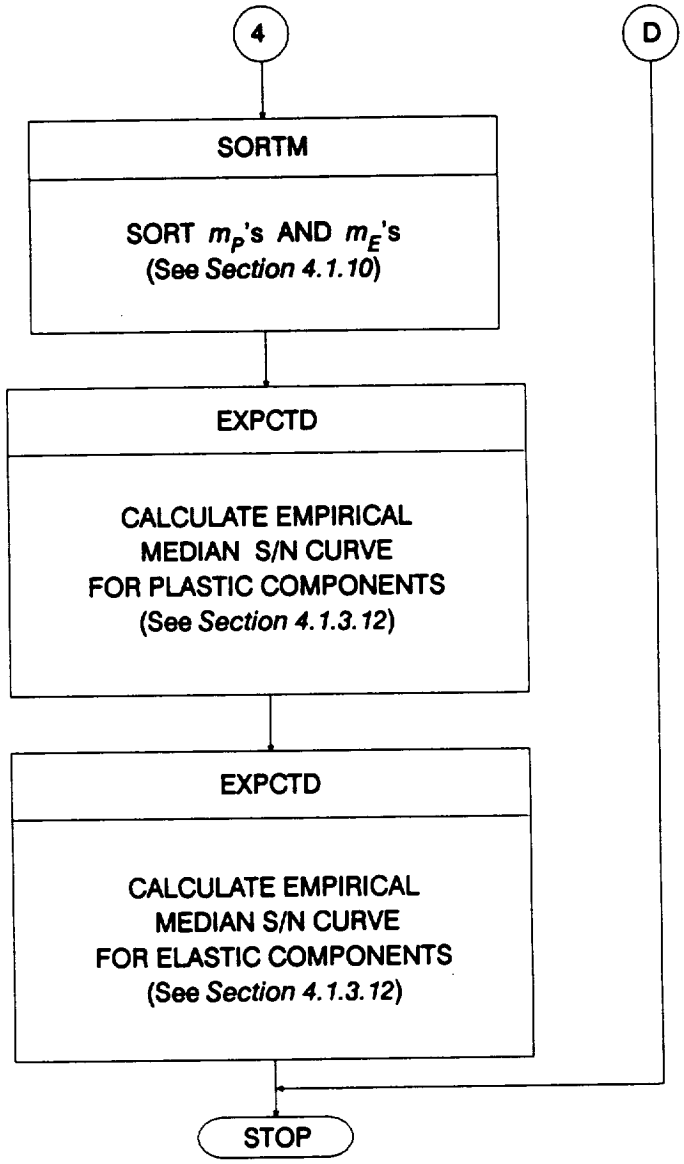

Figure 4-1 Main Flowchart for the Materials Characterization Model Program MATCHR (Cont'd)

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*.[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*.[4] 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 φ. 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_o by routine KOMO.[5] 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.[6] 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*.[3] 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.[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 φ based on β_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.[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:

NAME	TYPE	CONTENTS
RELATD	Input	Related material data input
RELATO	Output	Related material data echo

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

[7] The parameter estimation calculations are discussed on *Pages 2-15* through *2-18*.

[8] The median S/N curve for the truncated Normal case is discussed on *Page 2-15*.

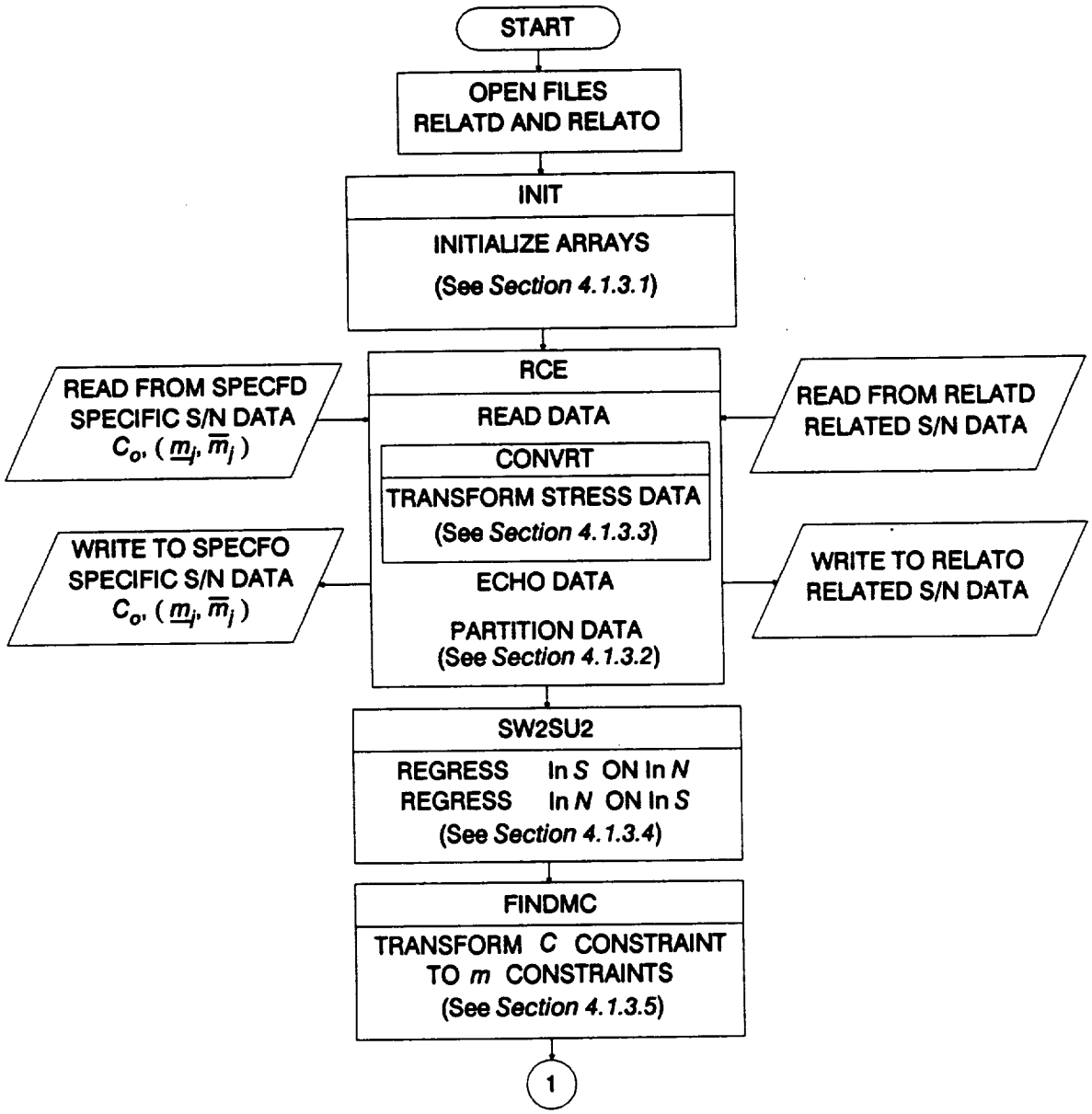

Figure 4-2 Flowchart for Subprogram INFAGG, Stress Formulation

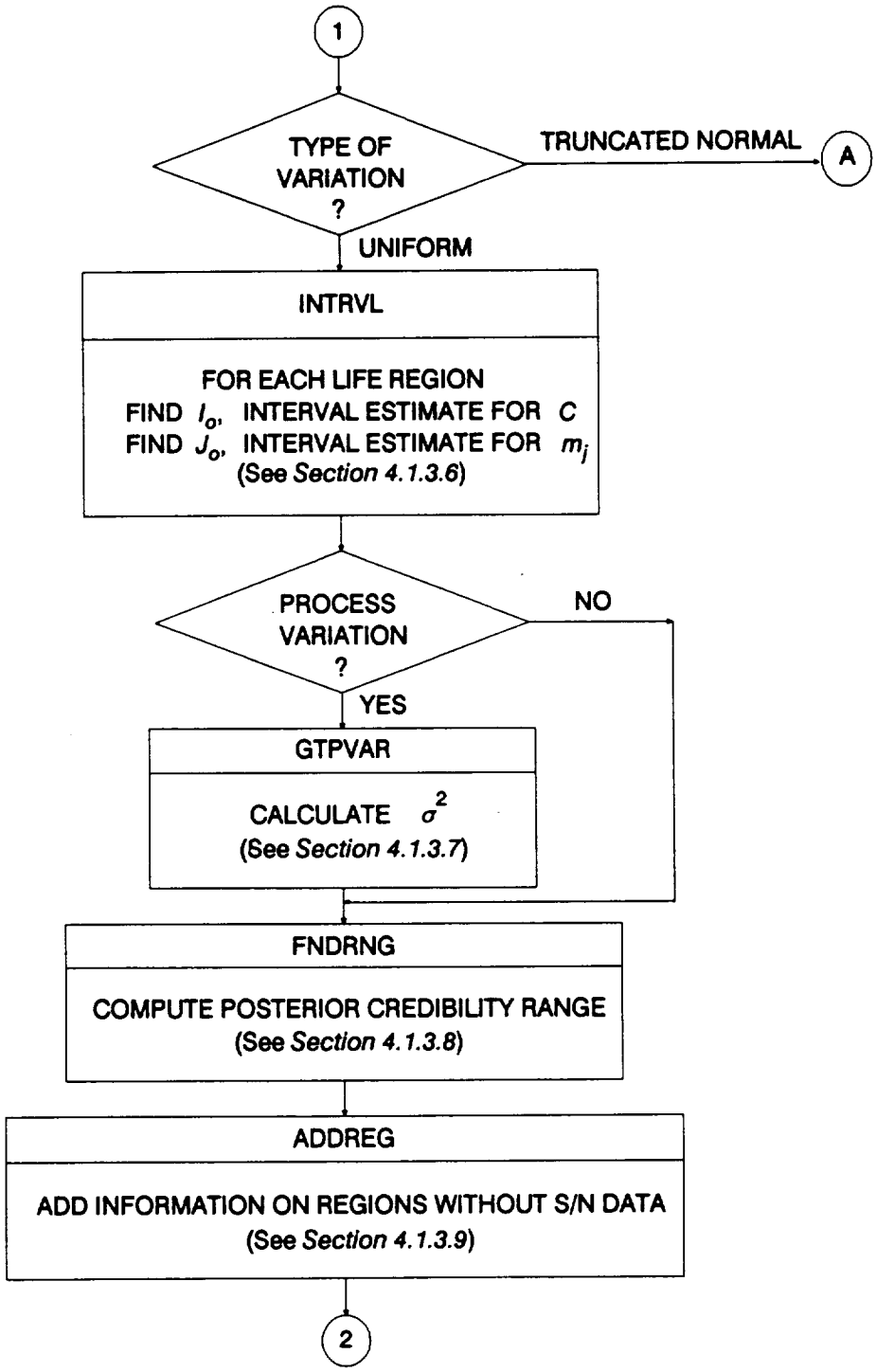

Figure 4-2 Flowchart for Subprogram INFAGG, Stress Formulation (Cont'd)

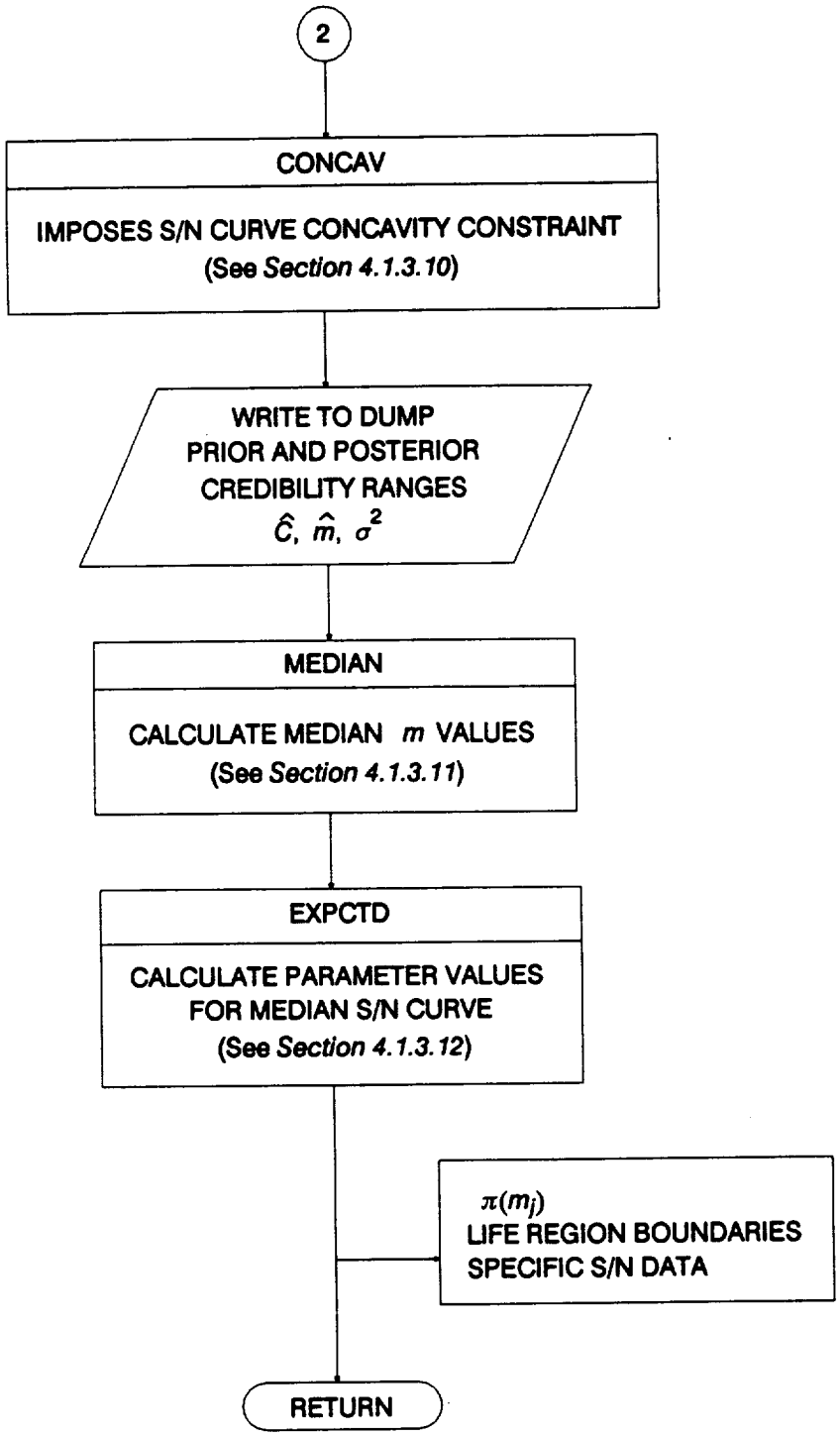

Figure 4-2 Flowchart for Subprogram INFAGG, Stress Formulation (Cont'd)

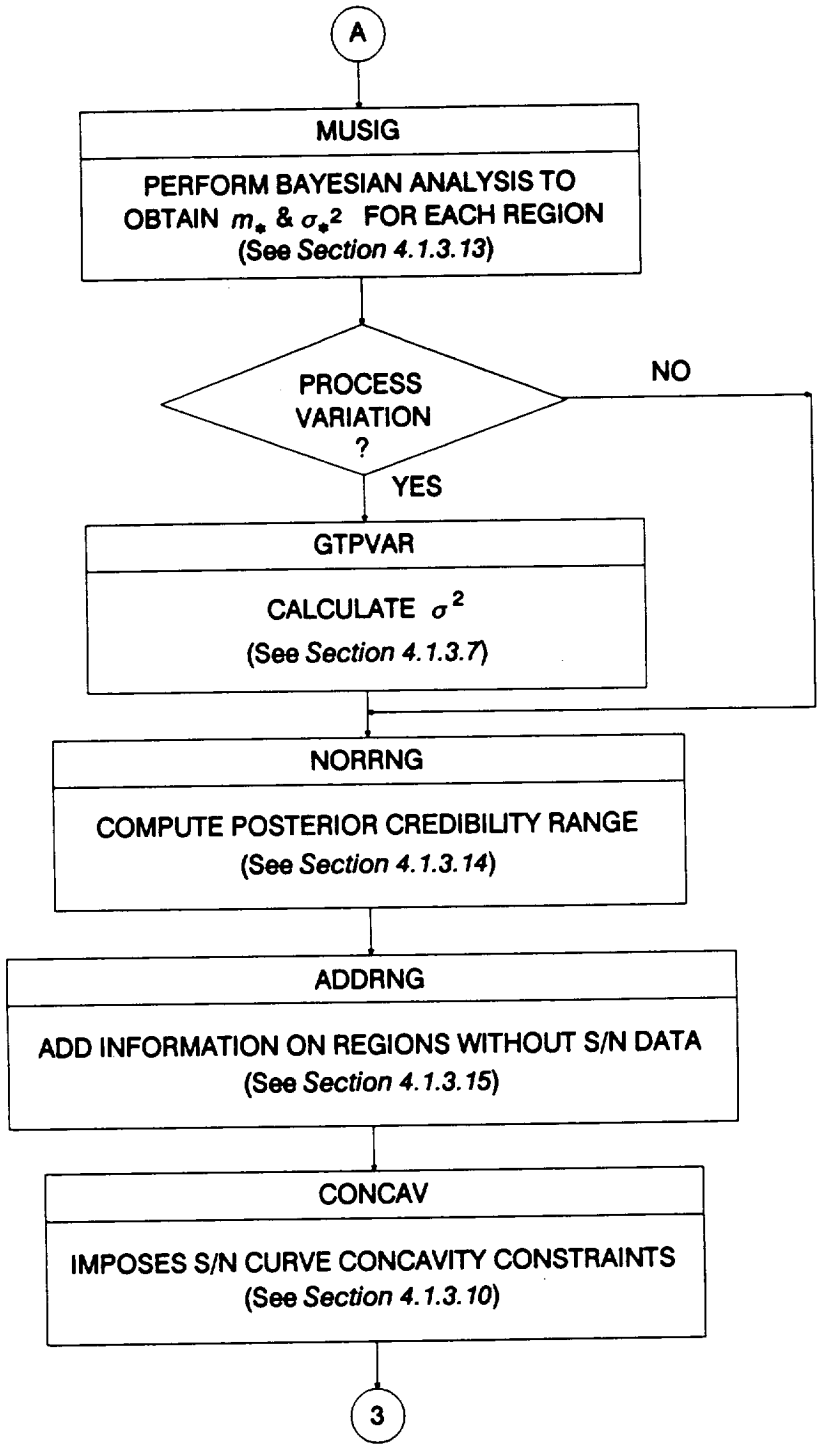

Figure 4-2 Flowchart for Subprogram INFAGG, Stress Formulation (Cont'd)

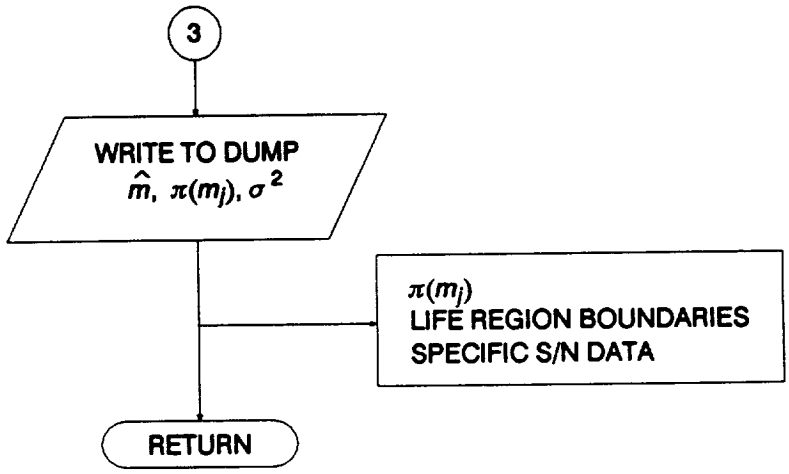

Figure 4-2 Flowchart for Subprogram INFAGG, Stress Formulation (Cont'd)

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 σ^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 $\pi(m_j)$.[9] 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.[10] 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 σ^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 $\pi(m_j)$.[9] 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 σ_*^2 by routine ADDRGN.[10] 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.[11] 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.[12] 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.[13]

When the truncated Normal variation of the shape parameters is specified, RCE reads and echoes the Bayesian prior information for each life region.[14] 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*.

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[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*.

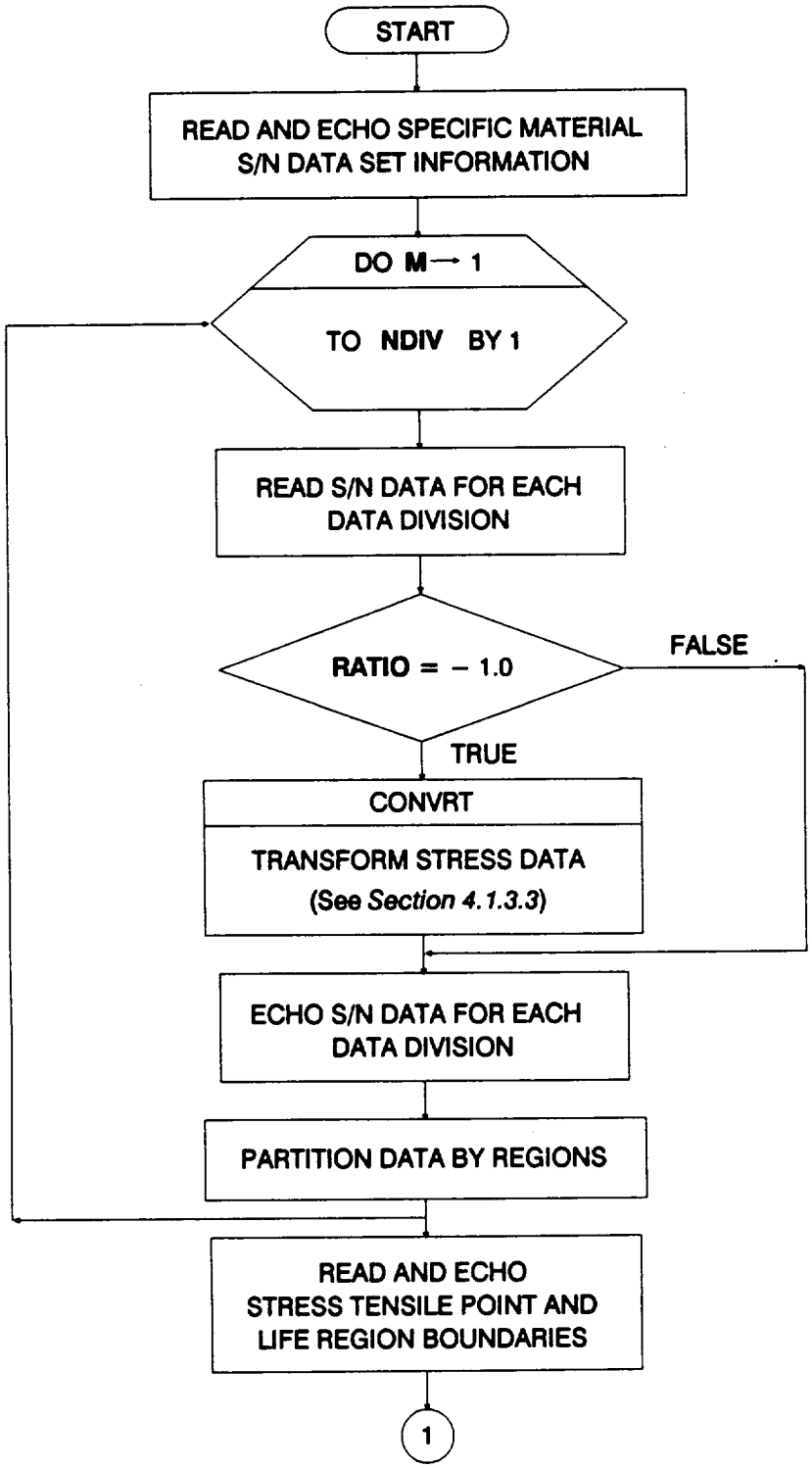

Figure 4-3 Flowchart for Subprogram RCE, Stress Formulation

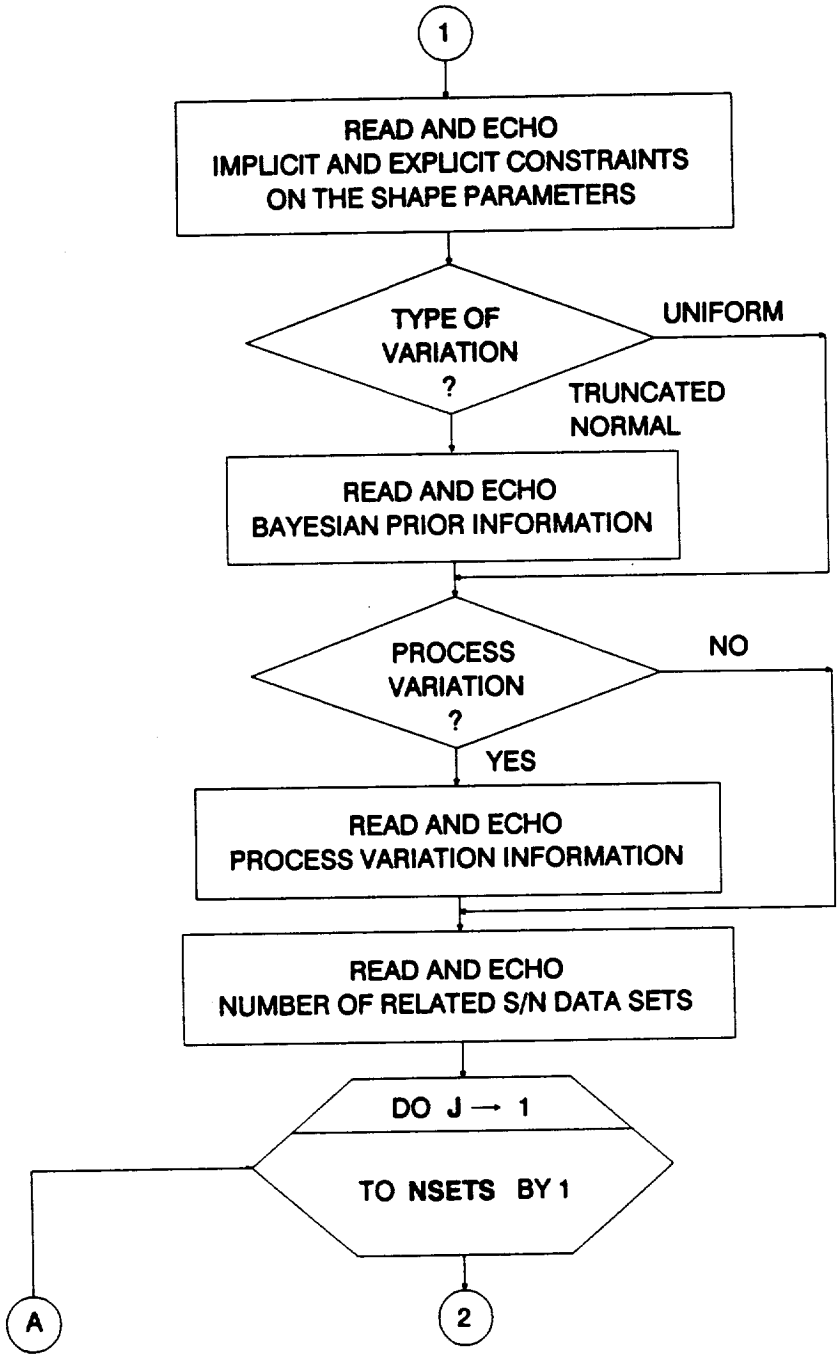

Figure 4-3 Flowchart for Subprogram RCE, Stress Formulation (Cont'd)

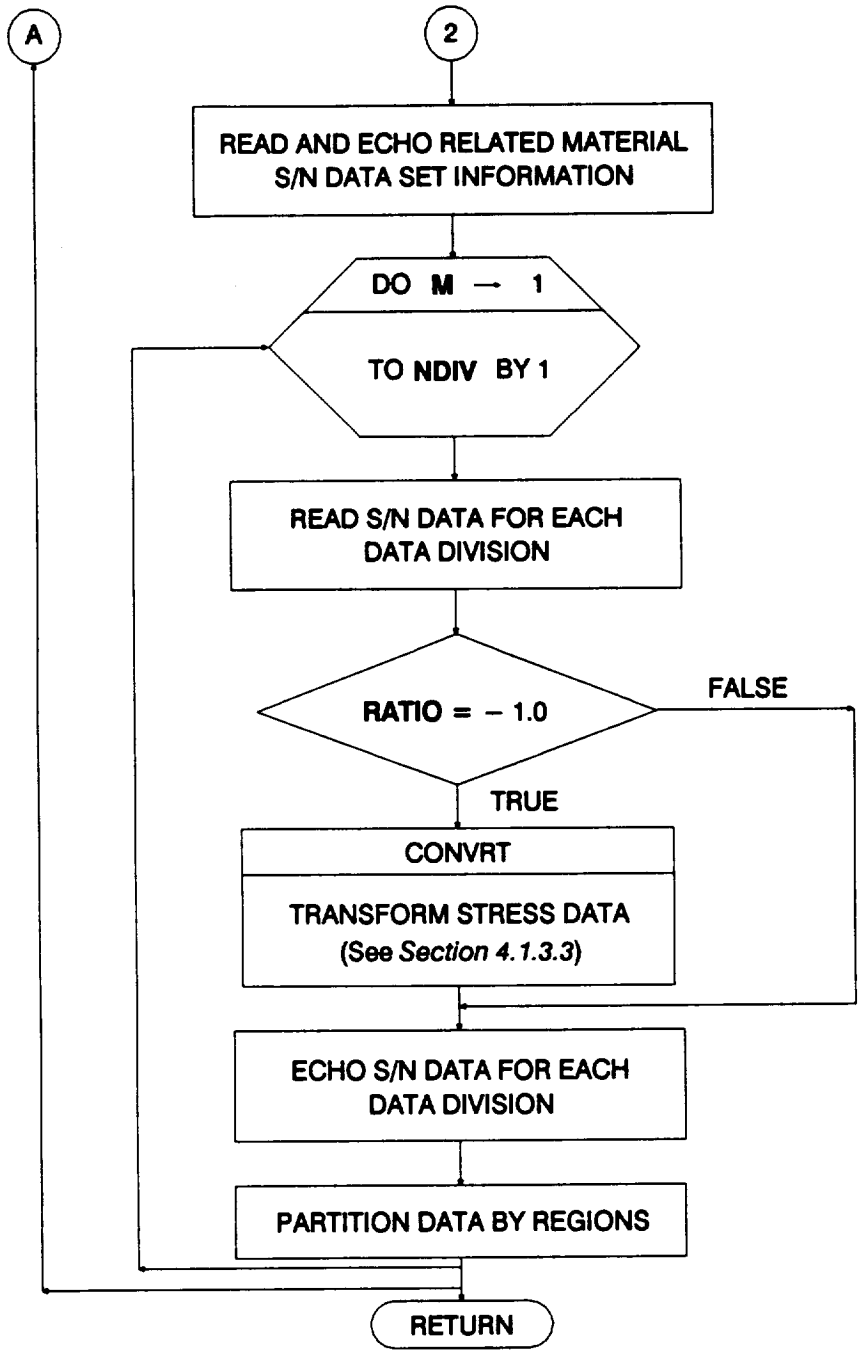

Figure 4-3 Flowchart for Subprogram RCE, Stress Formulation (Cont'd)

Next, RCE reads the data from file RELATD which contains the related S/N data[15] 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 σ_{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 σ_{alt} is calculated from the maximum stress σ_{max} and the stress ratio R. This stress is checked against the yield stress σ_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

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

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

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

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 $S_{\hat{w}}^2$ and $S_{\hat{u}}^2$ for each life region. For the calculations, x is

[15] Related S/N data is discussed on *Page 2-7*.

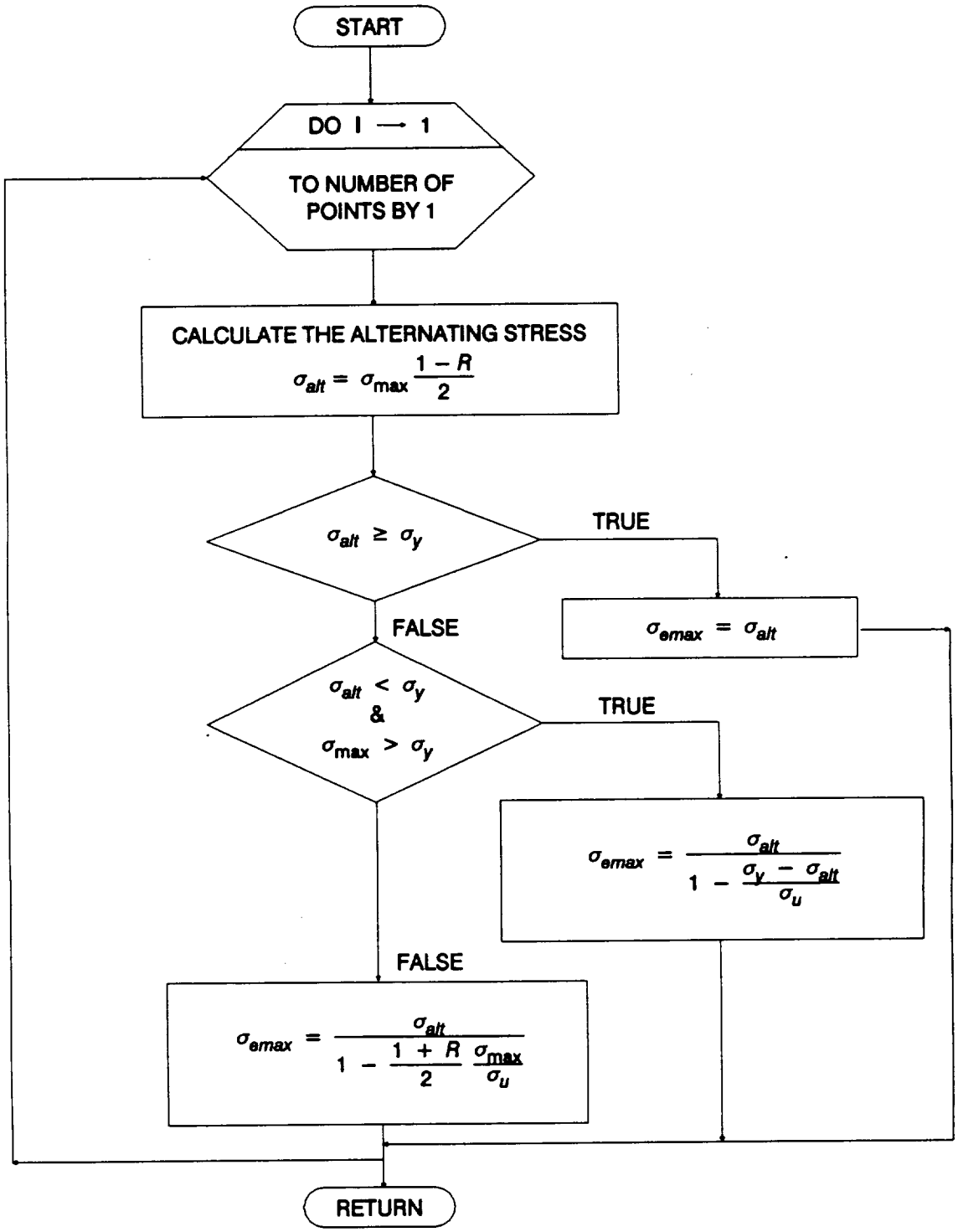

Figure 4-4 Flowchart for Subprogram CONVRT, Stress Formulation

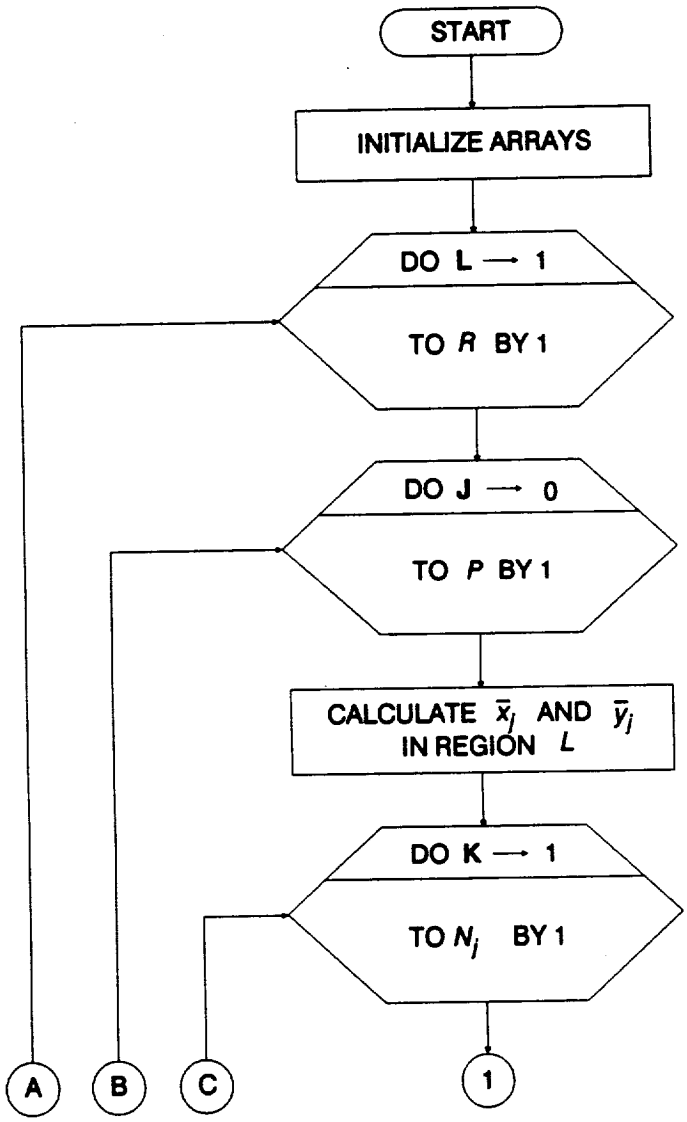

Figure 4-5 Flowchart for Subprogram SW2SU2

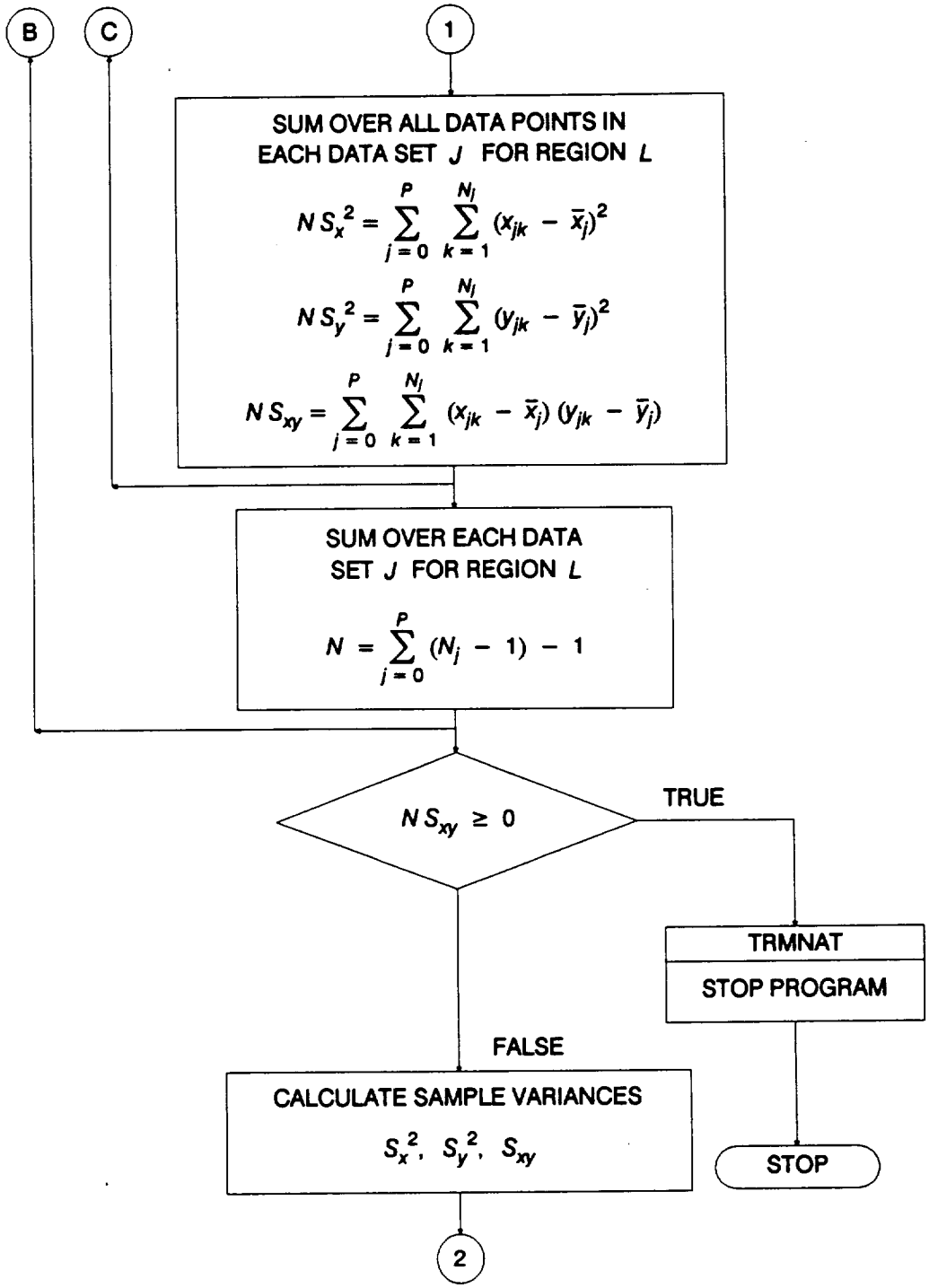

Figure 4-5 Flowchart for Subprogram SW2SU2 (Cont'd)

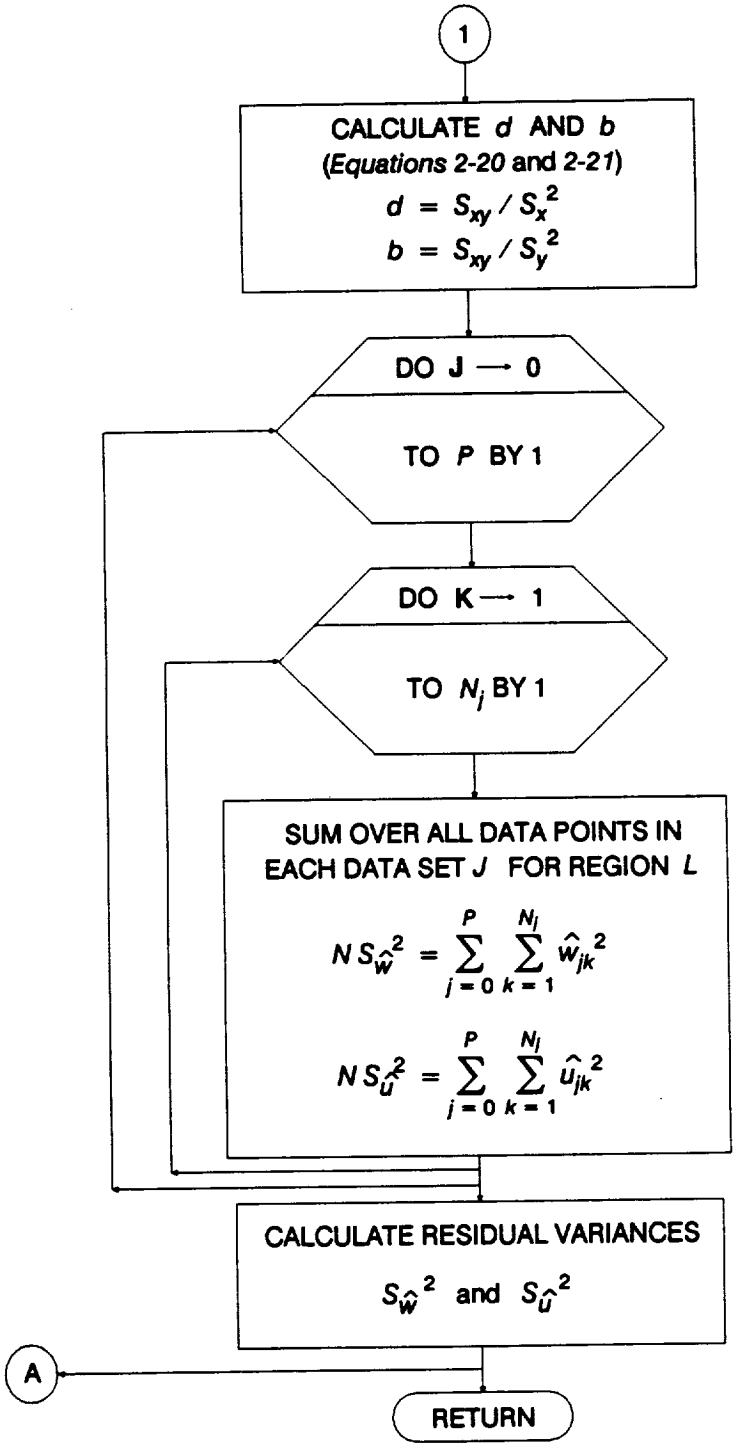

Figure 4-5 Flowchart for Subprogram SW2SU2 (Cont'd)

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 $L = 1, ..., R$, 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, $j = 0, ..., P$, and the inner DO loop is for each data point in each data set, $k = 1, ..., N_j$. 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:

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

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

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

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

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*,

$$d = S_{xy} / S_x^2 \text{ and } b = S_{xy} / S_y^2.$$

The second set of DO loops calculates the residual variances $S_{\hat{w}}^2$ and $S_{\hat{u}}^2$ for each life region given by

[16] R is equal to one for the strain formulation.

$$N S_{\hat{w}}^2 = \sum_{j=0}^{P} \sum_{k=1}^{N_j} \hat{w}_{jk}^2$$

$$N S_{\hat{u}}^2 = \sum_{j=0}^{P} \sum_{k=1}^{N_j} \hat{u}_{jk}^2$$

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 ($\underline{m}_c$, $\overline{m}_c$) 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*

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

If $S_x^2 > C_o^2$, then the solution is an interval constraint given by *Equation 2-32*

$$\frac{-S_{xy} - \left[S_{xy}^2 - S_y^2\,(S_x^2 - C_o^2)\right]^{1/2}}{S_X^2 - C_O^2} < m_c < \frac{-S_{xy} + \left[S_{xy}^2 - S_y^2\,(S_x^2 - C_o^2)\right]^{1/2}}{S_X^2 - C_O^2}.$$

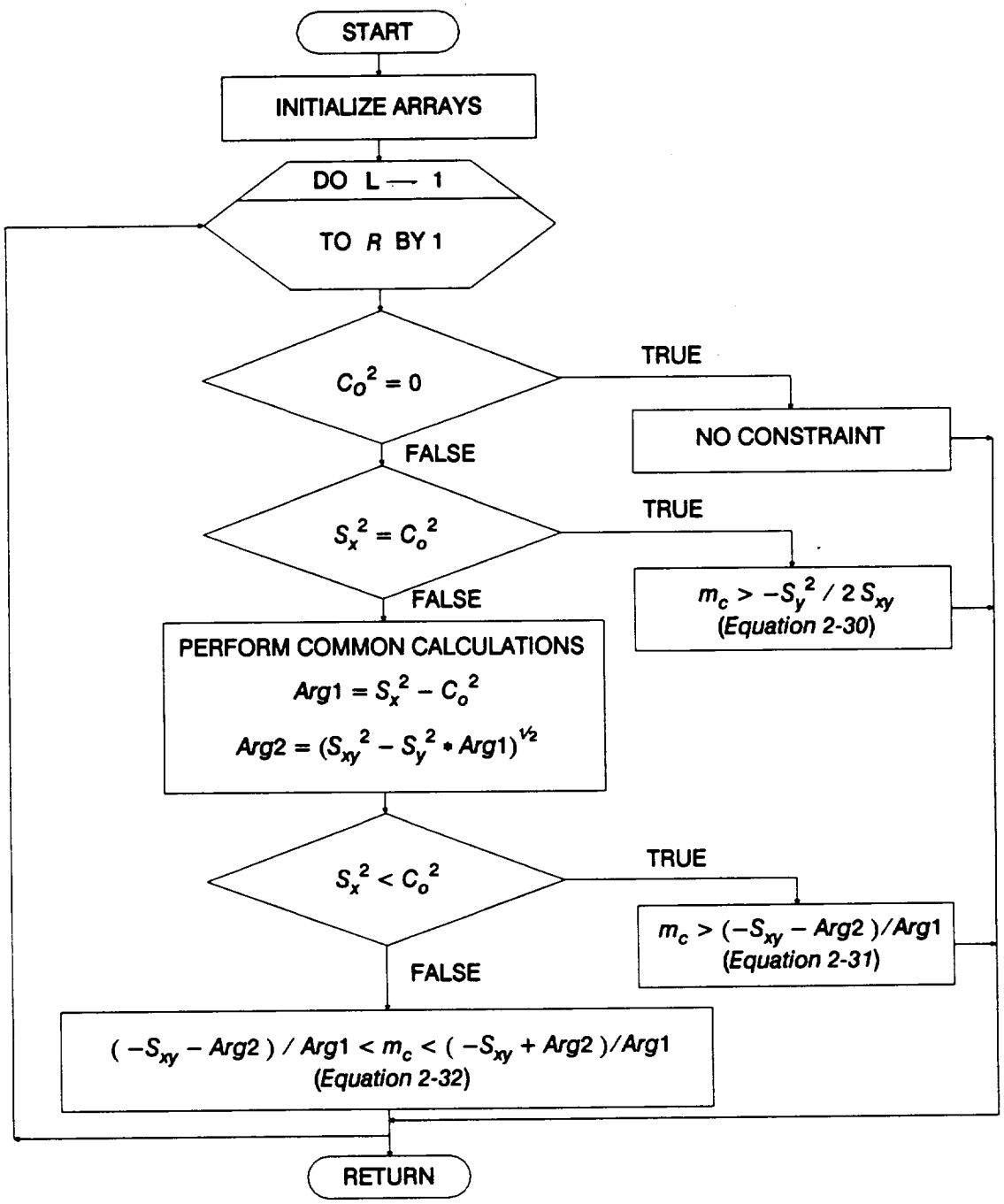

Figure 4-6 Flowchart for Subprogram FINDMC, Stress Formulation

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*

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

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

$$I_o \equiv \left[\hat{C}\left(N / \chi_{.975}^2(N)\right)^{1/2}, \hat{C}\left(N / \chi_{.025}^2(N)\right)^{1/2}\right].$$

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

$$J_o \equiv \left[\left(\hat{m} - t_{.025}(N)\frac{S_{\hat{w}}}{(N S_x^2)^{1/2}}\right), \left(\hat{m} + t_{.025}(N)\frac{S_{\hat{w}}}{(N S_x^2)^{1/2}}\right)\right].$$

4.1.3.7 Routine GTPVAR

The flowchart for GTPVAR is given in *Figure 4-8*. Routine GTPVAR calculates σ^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 σ^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*:

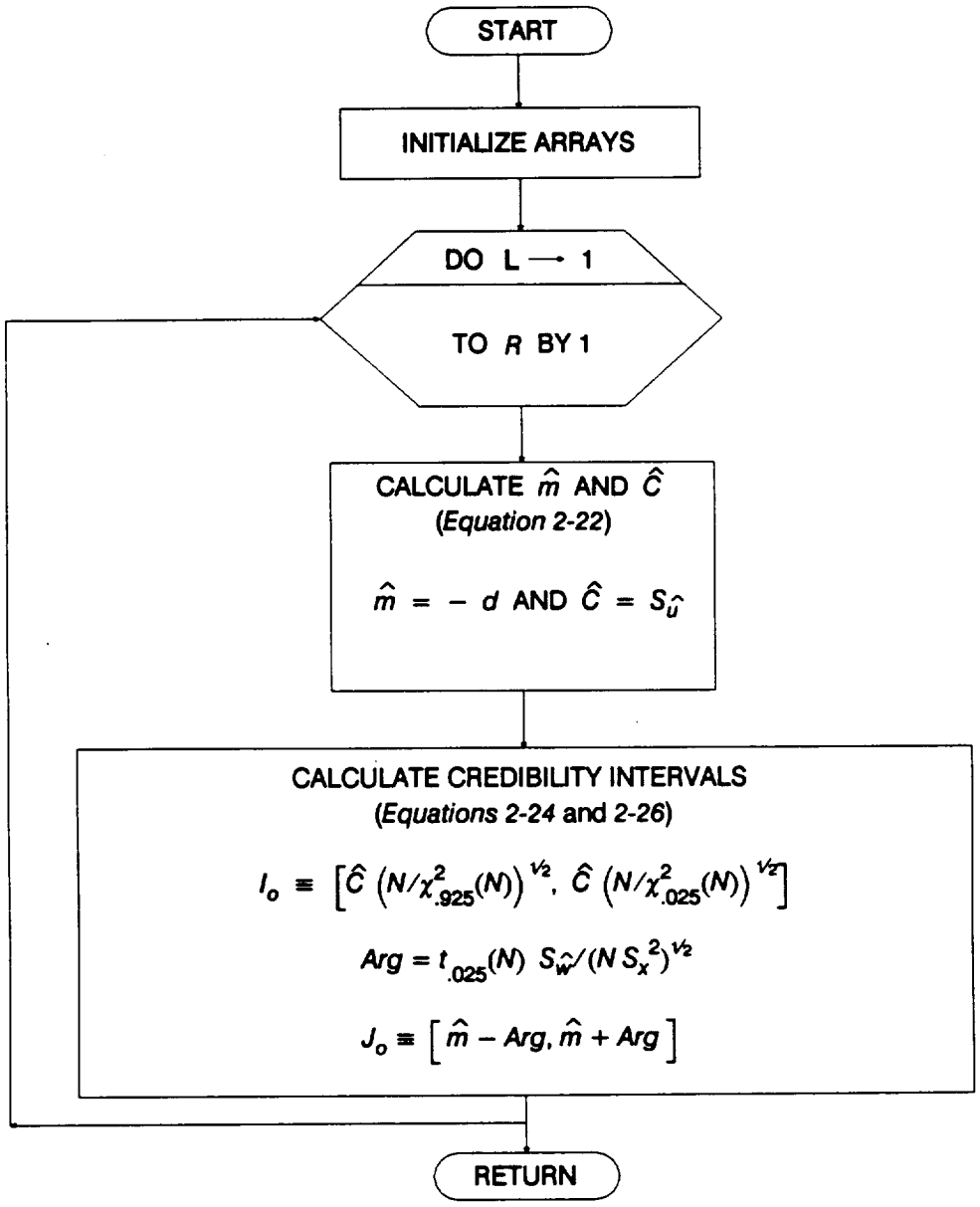

Figure 4-7 Flowchart for Subprogram INTRVL, Uniform Distribution

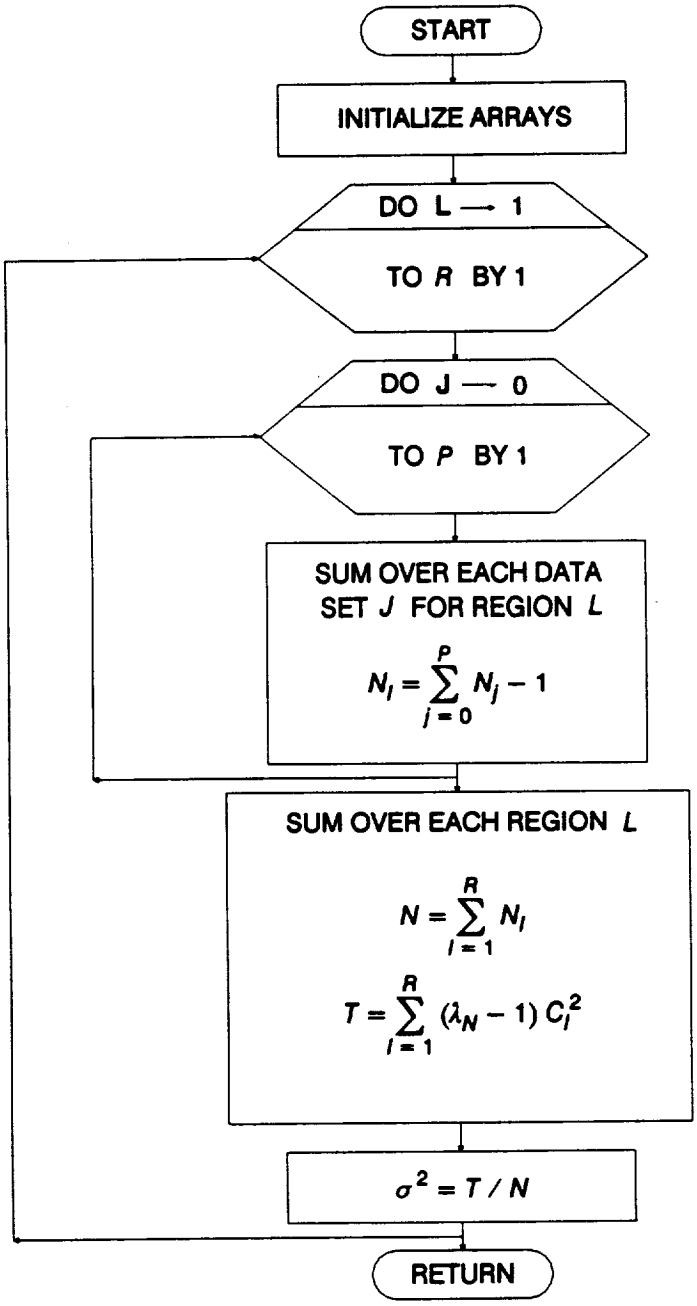

Figure 4-8 Flowchart for Subprogram GTPVAR

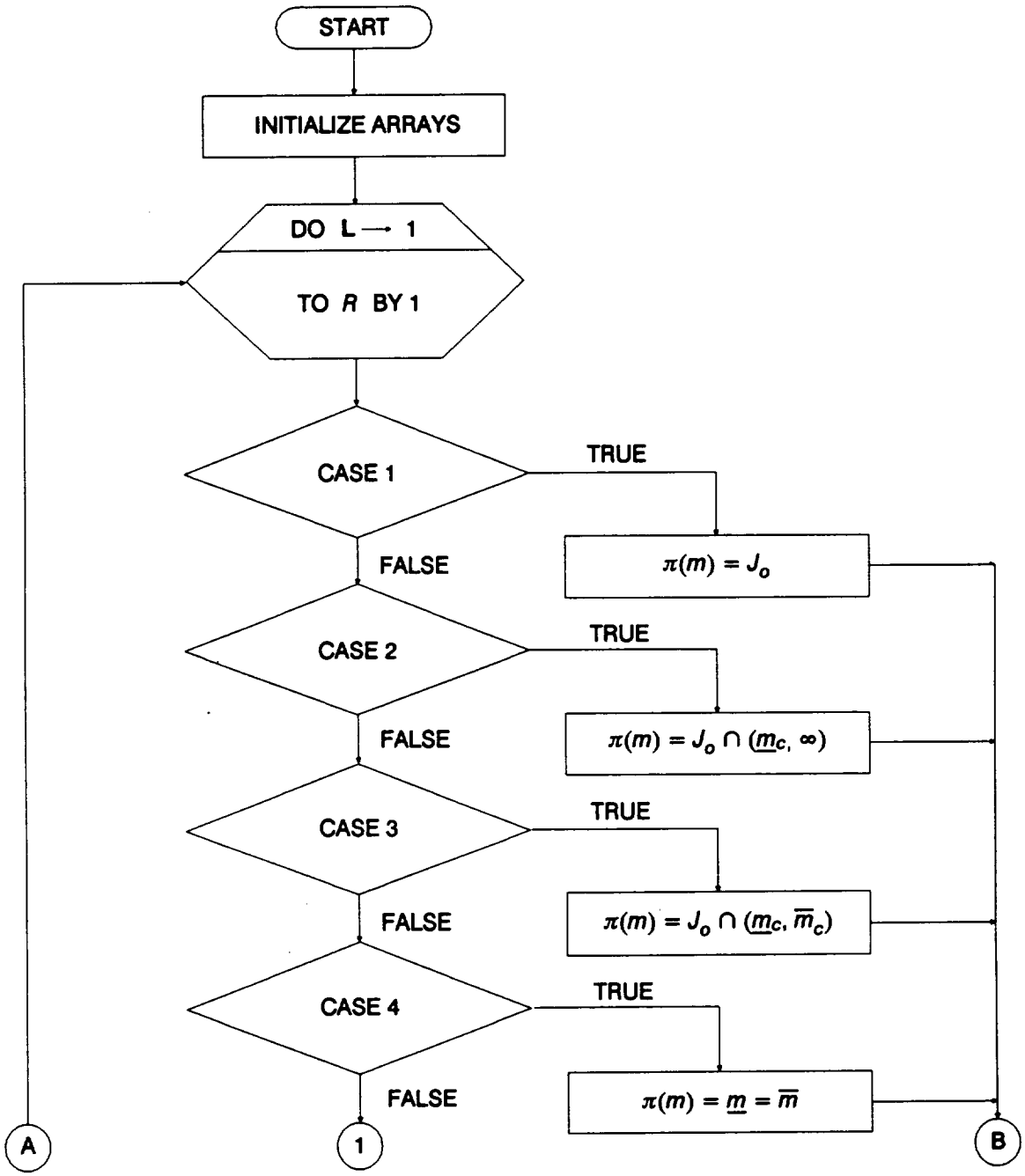

Figure 4-9 Flowchart for Subprogram FNDRNG, Uniform Distribution

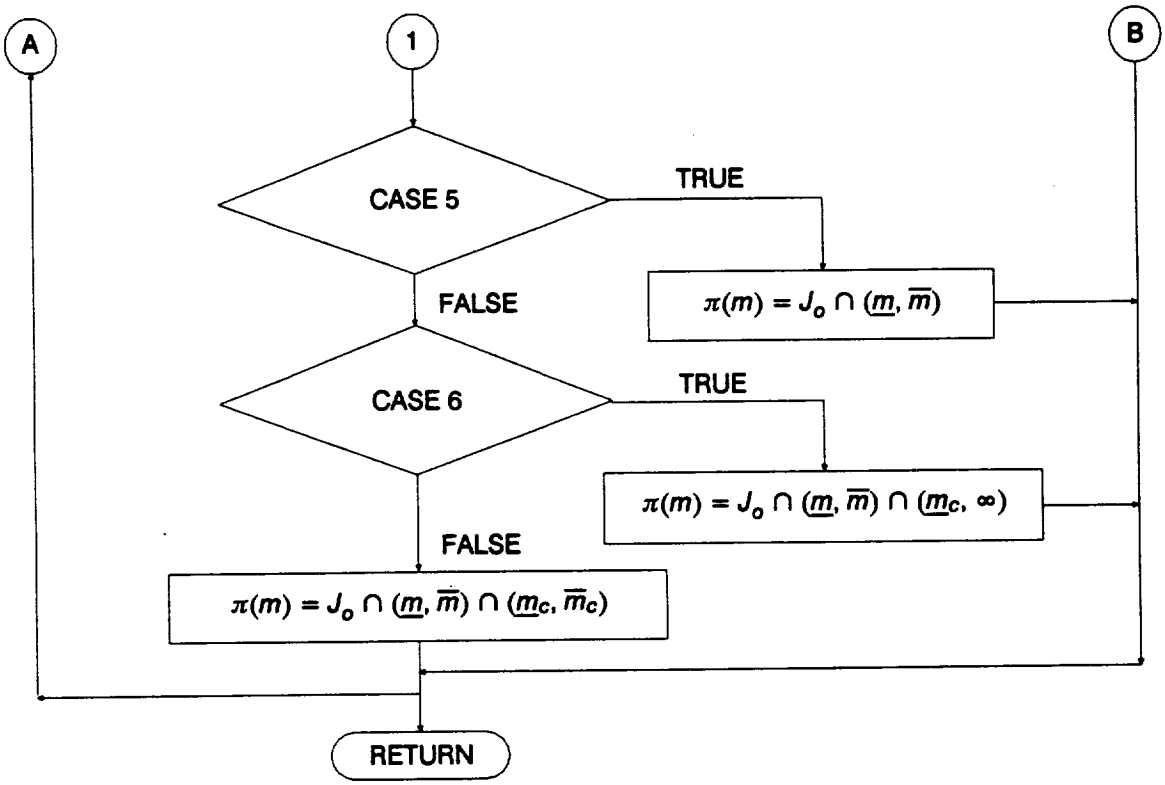

Figure 4-9 Flowchart for Subprogram FNDRNG, Uniform Distribution (Cont'd)

Table 4-1 The Seven Cases Considered by Subprogram FNDRNG

Case	$(\underline{m}, \overline{m})$	$(\underline{m}_C, \overline{m}_C)$
1	NA	NA
2		$\underline{m}_C < m$
3		$\underline{m}_C < m < \overline{m}_C$
4	$\underline{m} = m = \overline{m}$	NA
		$\underline{m}_C < m$
		$\underline{m}_C < m < \overline{m}_C$
5	$\underline{m} < m < \overline{m}$	NA
6		$\underline{m}_C < m$
7		$\underline{m}_C < m < \overline{m}_C$

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 $\underline{m}_C$, 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 $\underline{m}_C$, and the upper bound of $\pi(m)$ is the minimum of the upper bound of J_o and $\overline{m}_C$.

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 $\underline{m}$, and the upper bound of $\pi(m)$ is the minimum of the upper bound of J_o and $\overline{m}$.

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, $\underline{m}$, and $\underline{m}_c$, 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, $\underline{m}$, and $\underline{m}_c$, and the upper bound is the minimum of the upper bound of J_o, $\overline{m}$, and $\overline{m}_c$.

4.1.3.9 Routine ADDREG

Routine ADDREG adds the user-provided $\pi(m_j)$ ranges for the life regions to the right without data for the Uniform distribution case of the stress formulation.[17] 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,[18] 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 ith 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.

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[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*.

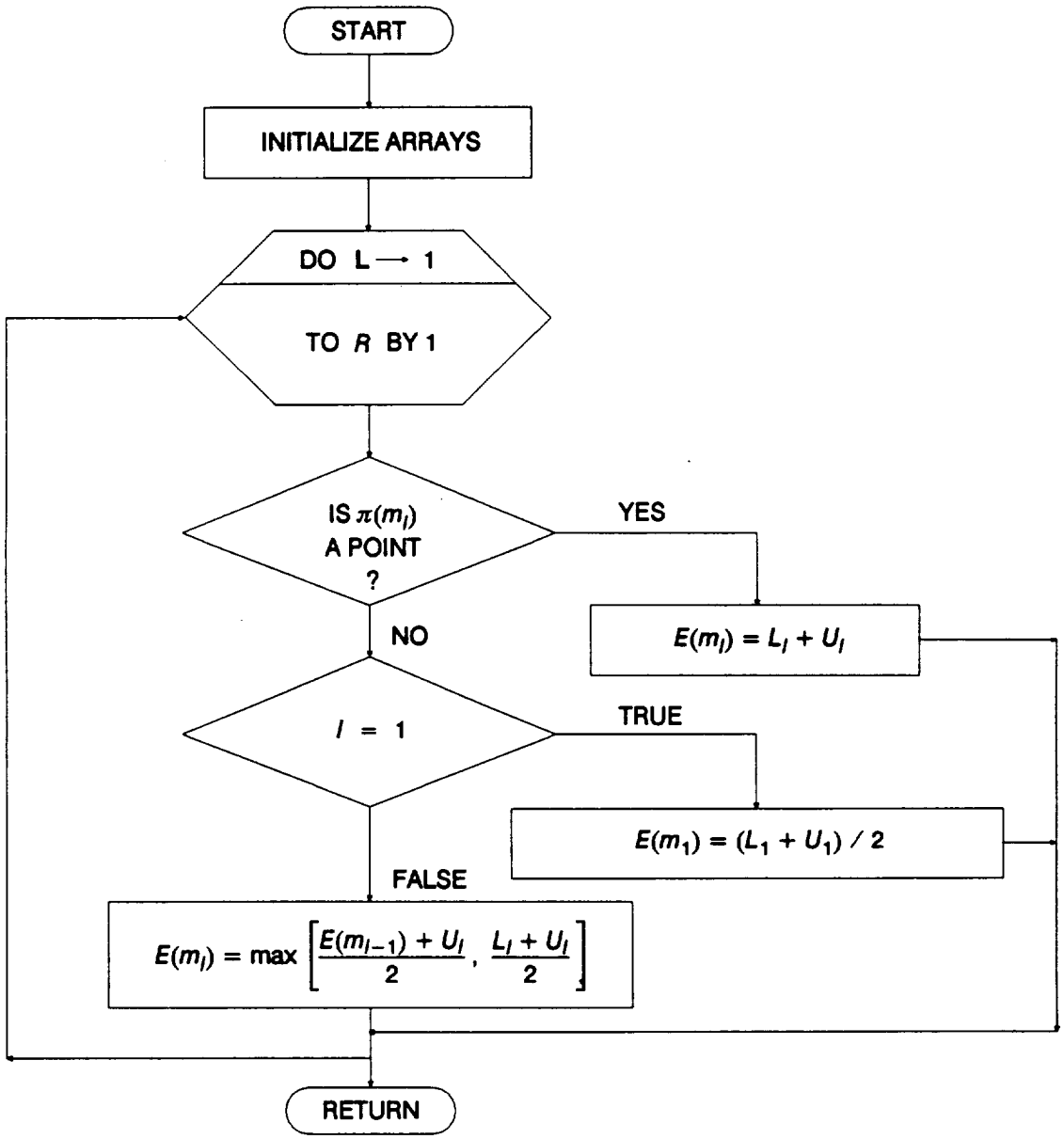

Figure 4-10 Flowchart for Subprogram MEDIAN, Stress Formulation, Uniform Distribution

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 $l = 2, ..., R$ is

$$E(m_l) = \max \left[\frac{E(m_{l-1}) + U_l}{2}, \frac{L_l + U_l}{2} \right]$$

where L_l and U_l are the lower and upper bounds, respectively, of the posterior credibility range in region l.

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 β_o 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.[19] The transformation produces the $\{Z_i\}$ as a function of the S/N data, the $\{m_j\}$, 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 β_o. 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.[20] 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.[21] The routine begins by initializing the arrays that are to contain the point estimates of m and C and the parameters m_* and σ_*^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*.

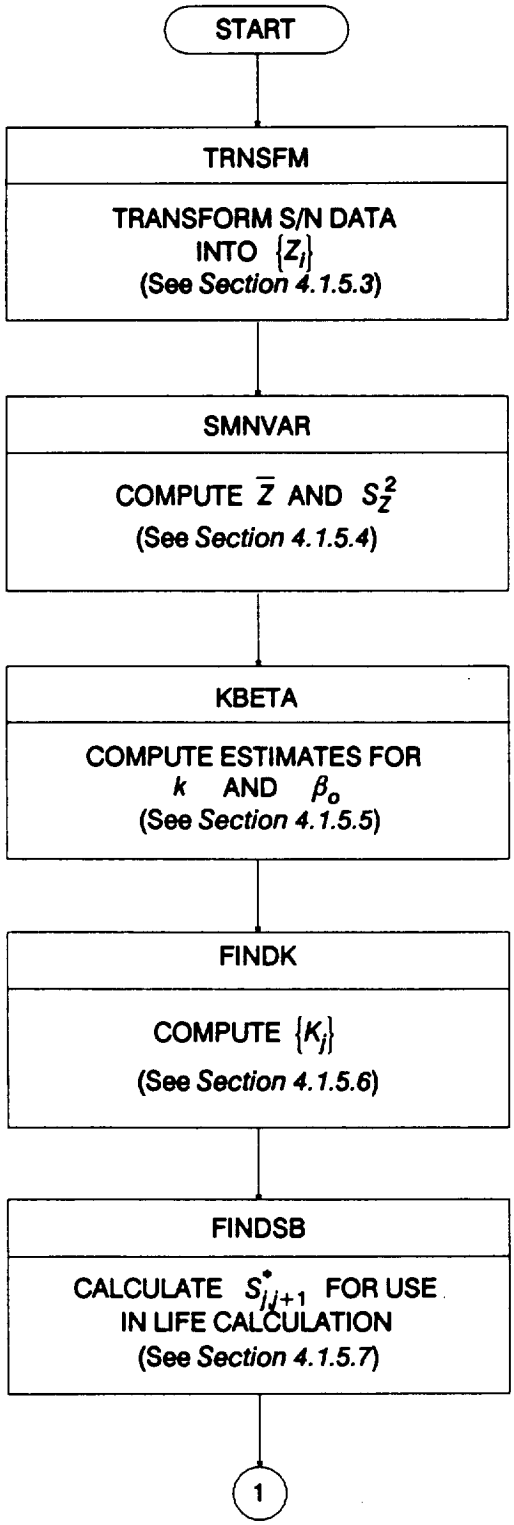

Figure 4-11 Flowchart for Subprogram EXPCTD

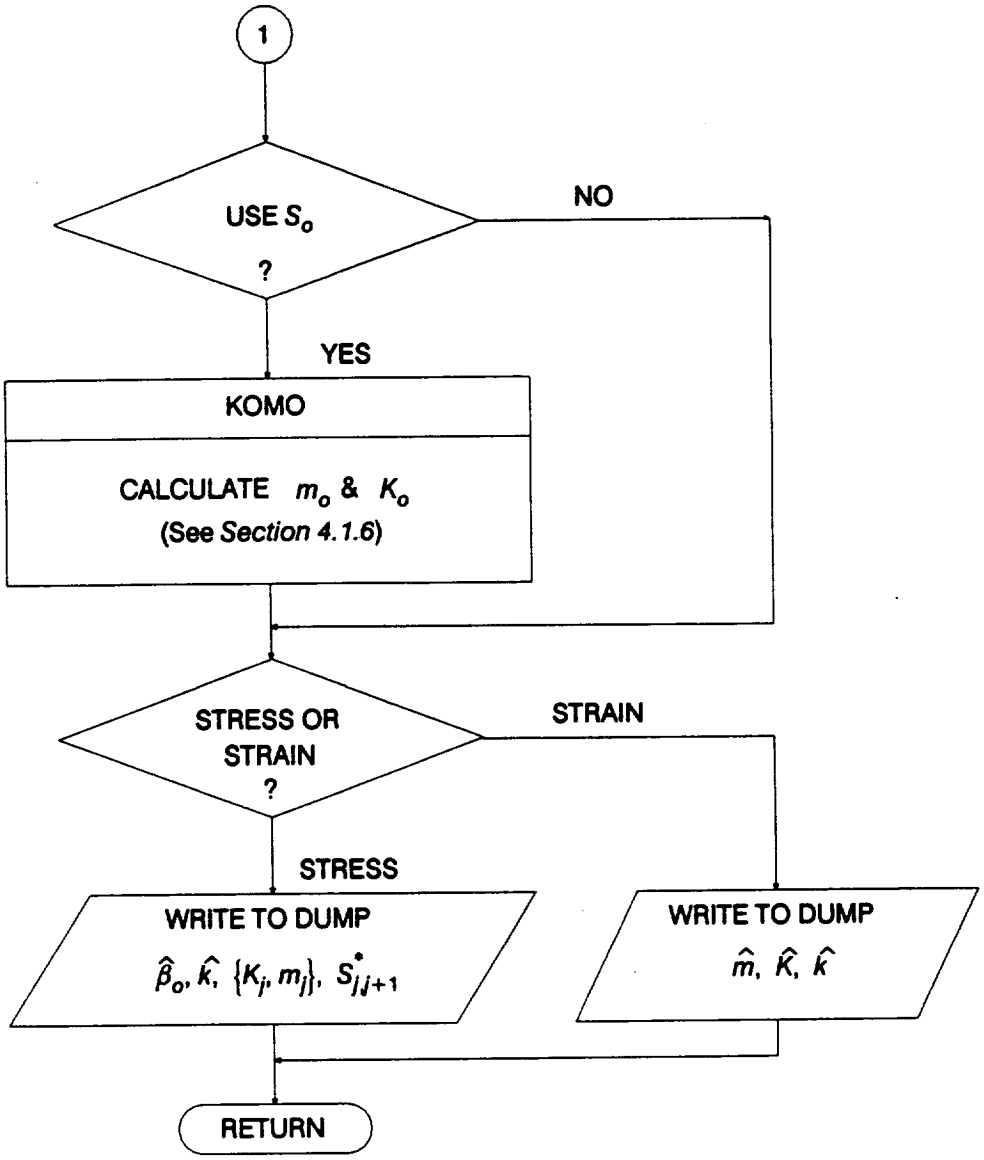

Figure 4-11 Flowchart for Subprogram EXPCTD (Cont'd)

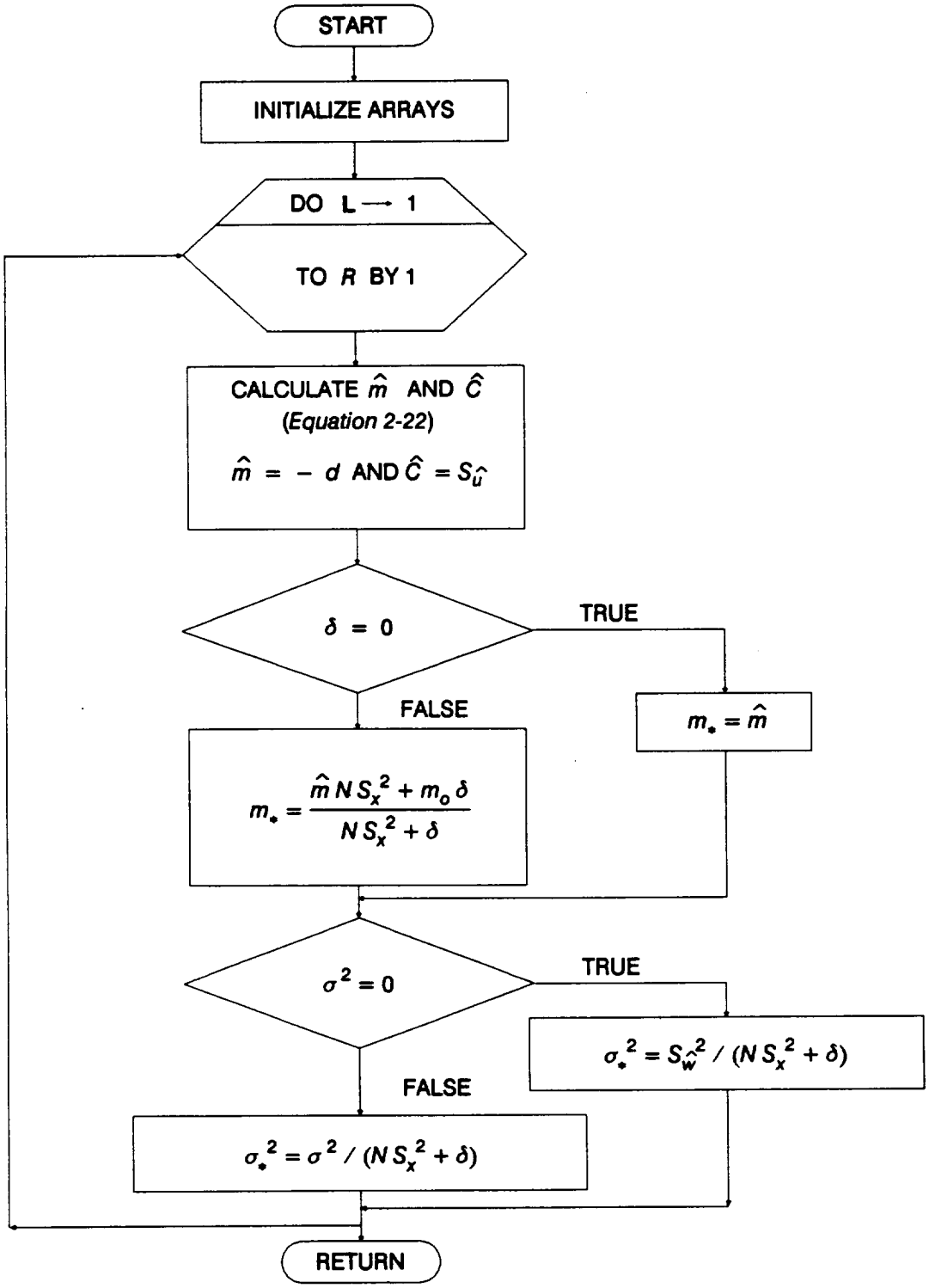

Figure 4-12 Flowchart for Subprogram MUSIG, Truncated Normal Distribution

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 δ, indicated by $\delta = 0$, then m_* is given by the point estimate $\hat{m}$. When a value for δ has been provided, then m_* is given by

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

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

$$\sigma_*^2 = S_{\hat{w}}^2 \,/\, (N\, S_x^2 + \delta)$$

otherwise σ_*^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 4-2 The Four Cases Considered by Subprogram NORRNG

Case	$(\underline{m}, \overline{m})$	$(\underline{m}_c, \overline{m}_c)$
1	$\underline{m} = m = \overline{m}$	NA
		$\underline{m}_c < m$
		$\underline{m}_c < m < \overline{m}_c$
2	$\underline{m} < m < \overline{m}$	NA
3		$\underline{m}_c < m$
4		$\underline{m}_c < m < \overline{m}_c$

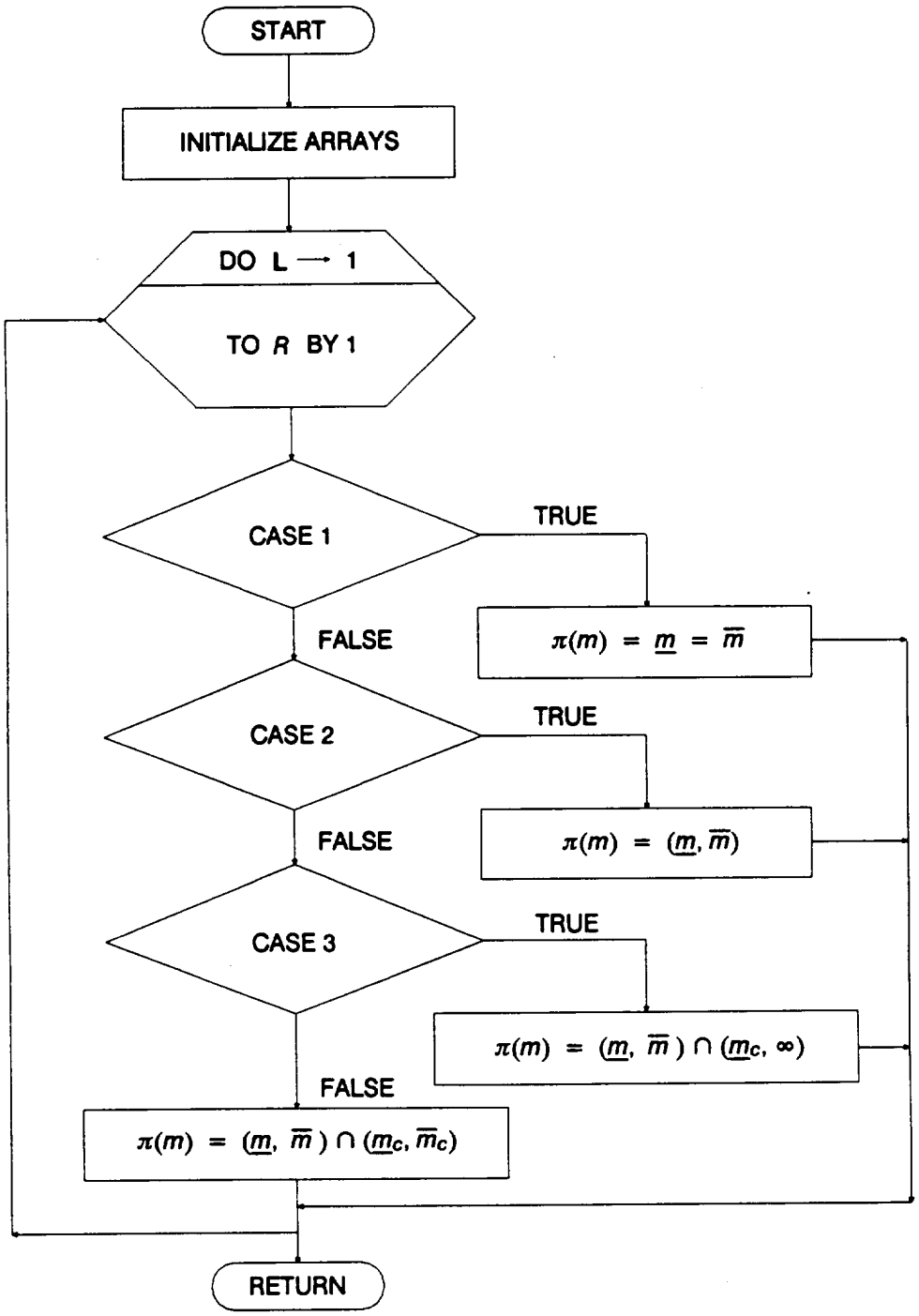

Figure 4-13 Flowchart for Subprogram NORRNG, Truncated Normal Distribution

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 $(\underline{m}, \overline{m})$.

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 $\underline{m}_C$, 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 $\underline{m}_C$, 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 $\pi(m_j)$ ranges for the life regions to the right without data for the truncated Normal distribution case of the strain formulation.[22] 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:

NAME	TYPE	CONTENTS
RELATD	Input	Related material data input
RELATO	Output	Related material data echo

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*.

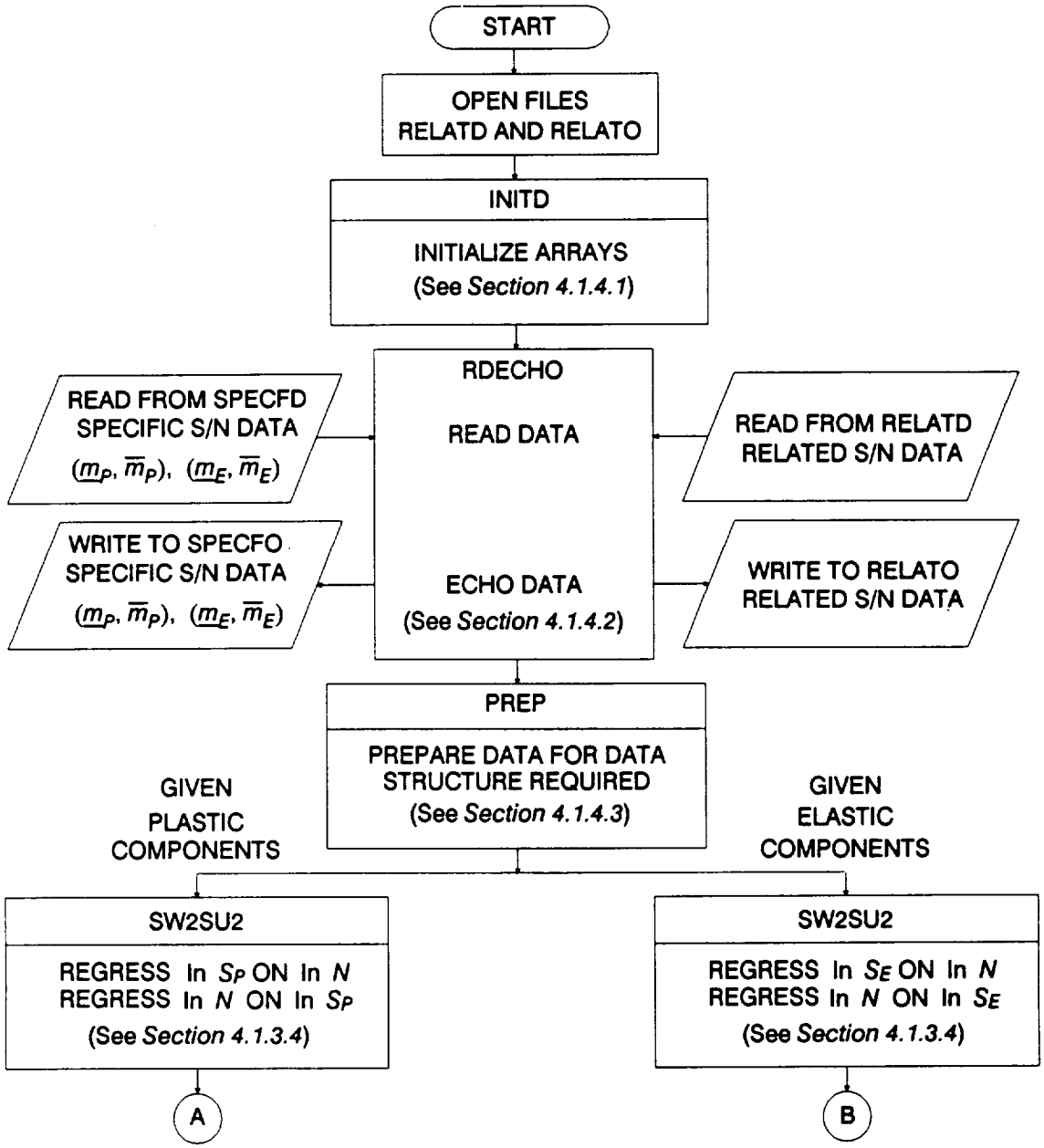

Figure 4-14 Flowchart for Subprogram DECOMP, Strain Formulation

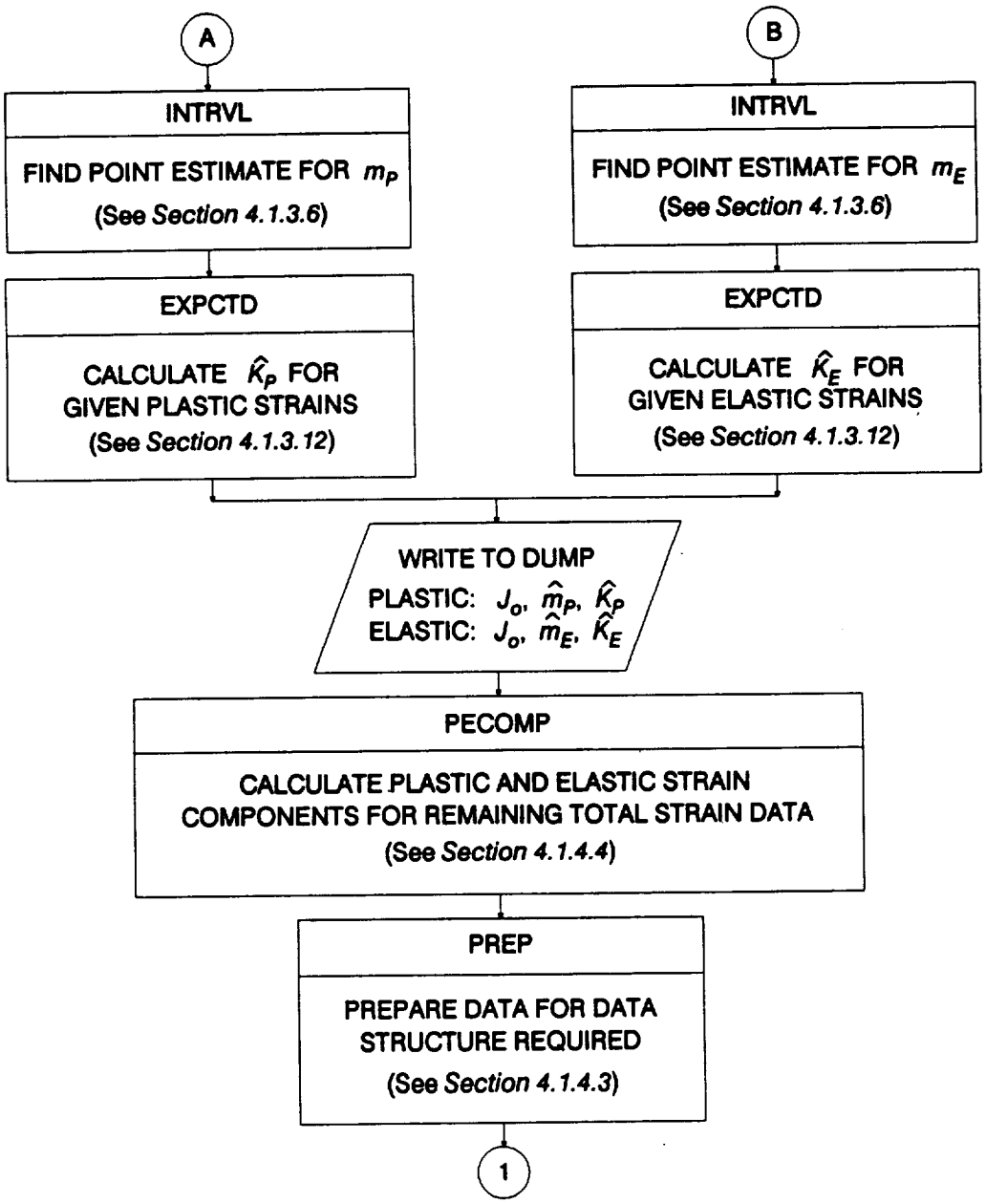

Figure 4-14 Flowchart for Subprogram DECOMP, Strain Formulation (Cont'd)

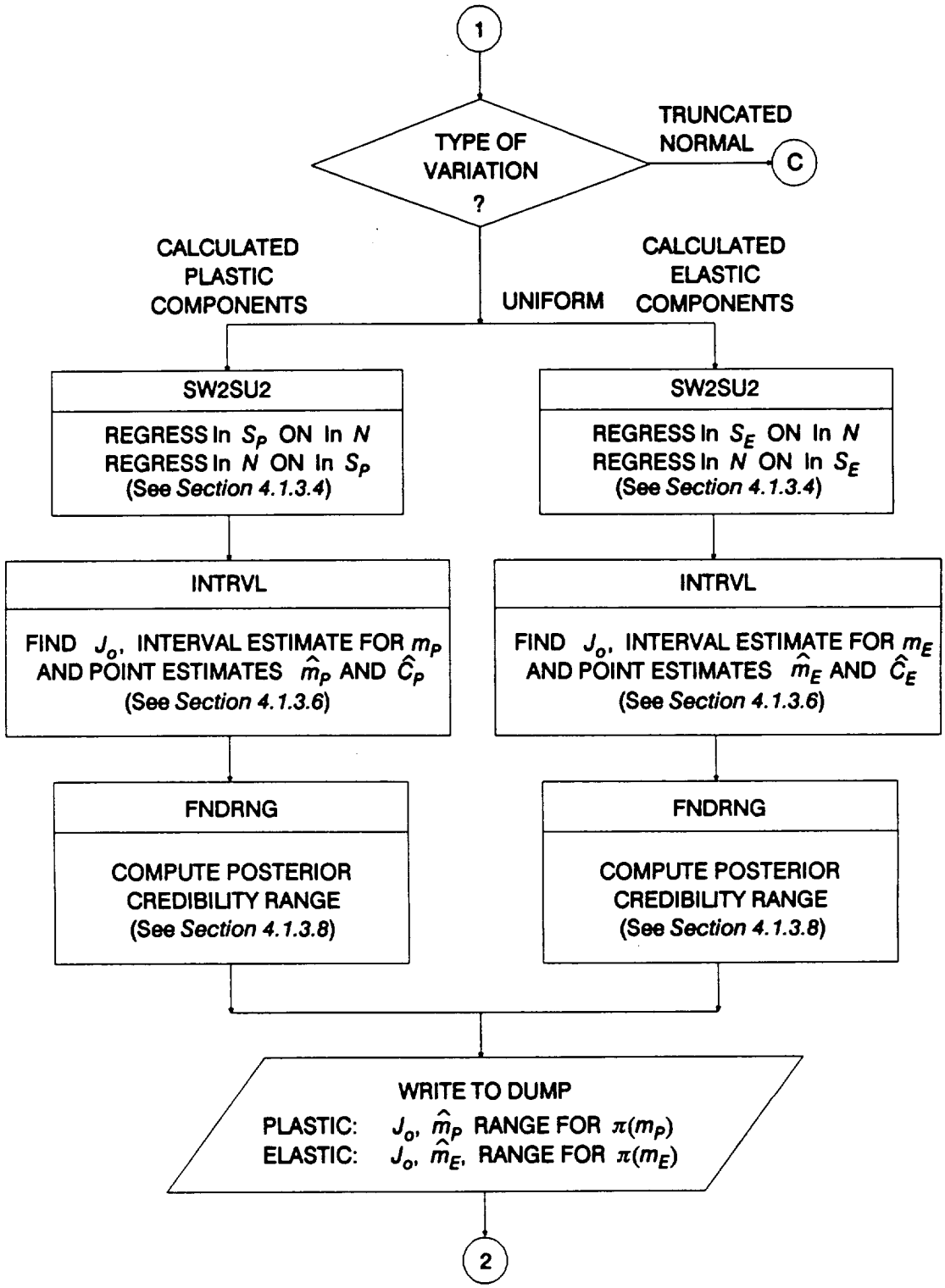

Figure 4-14 Flowchart for Subprogram DECOMP, Strain Formulation (Cont'd)

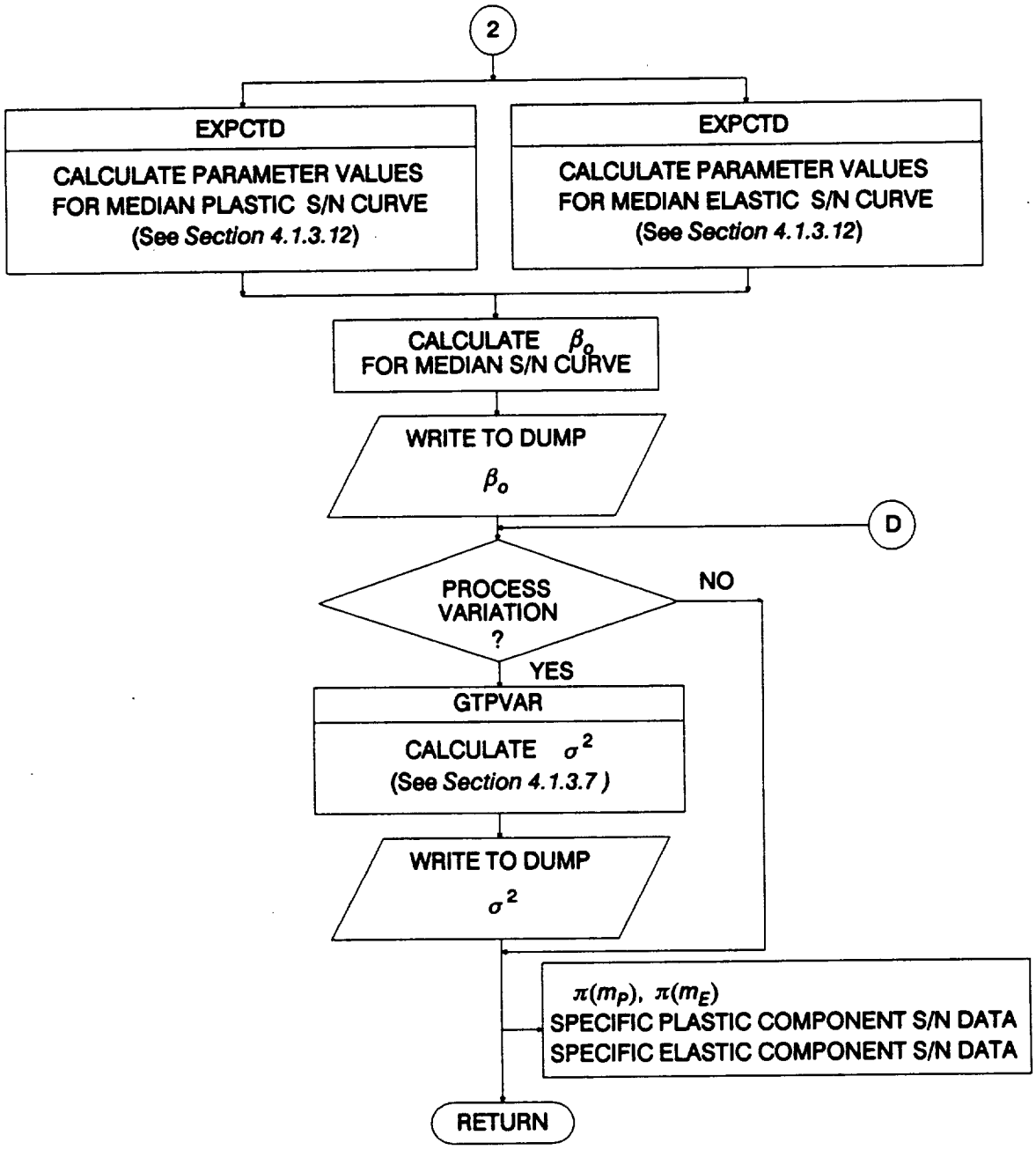

Figure 4-14 Flowchart for Subprogram DECOMP, Strain Formulation (Cont'd)

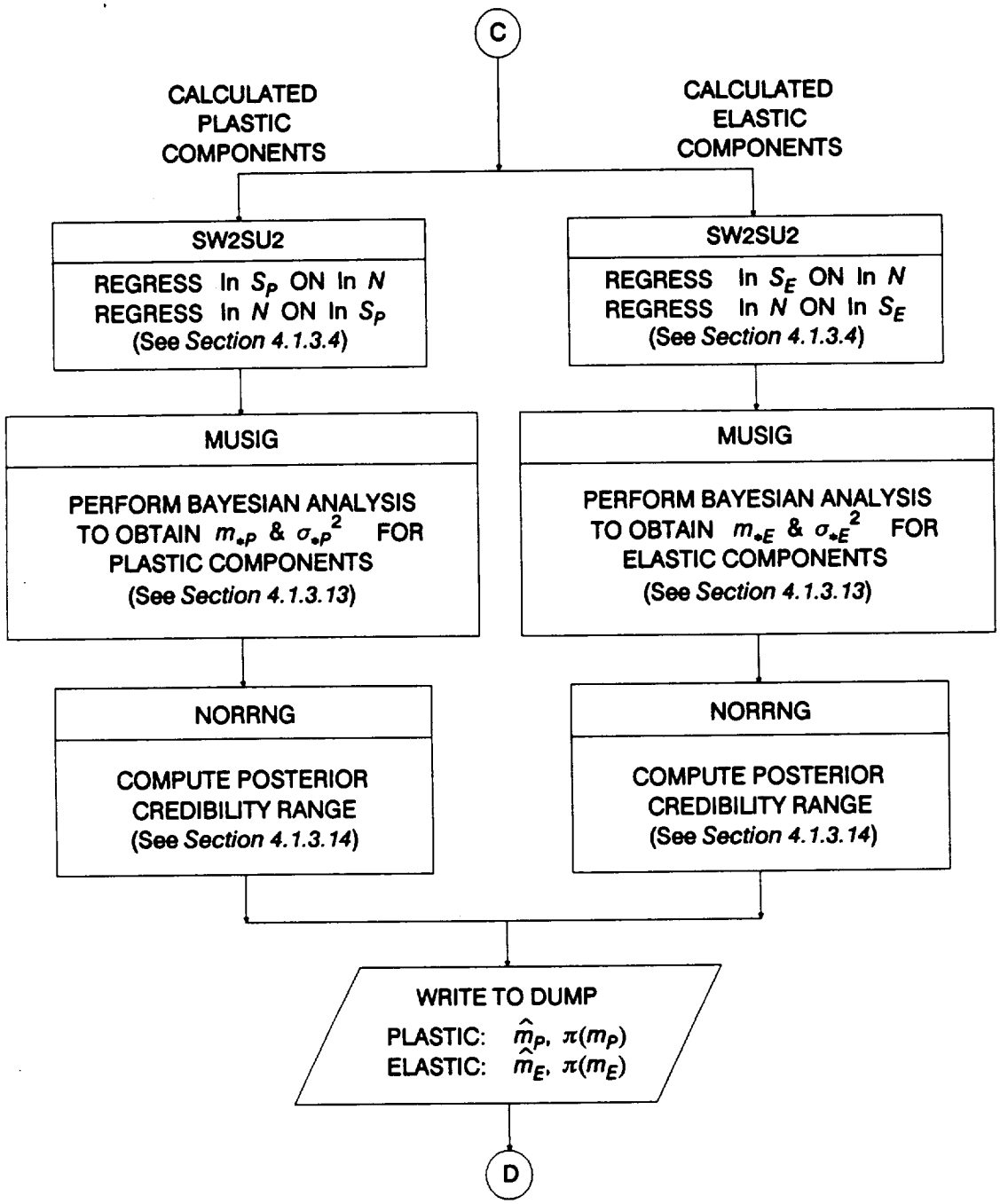

Figure 4-14 Flowchart for Subprogram DECOMP, Strain Formulation (Cont'd)

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 FNDRNG to obtain the posterior credibility range on the shape parameter $\pi(m_P)$.[23] The results of these calculations are written to file DUMP. The median S/N curve is then calculated by routine EXPCTD and written to file DUMP. The calls to SW2SU2, INTRVL, FNDRNG, and EXPCTD are repeated for the elastic strain components. β_o, defined as the average of the β_o's resulting from the two calls to EXPCTD, is calculated. Routines SW2SU2, INTRVL, FNDRNG, 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 NORRNG into a posterior credibility range on the shape parameter m_P. The results of these calculations are written to file DUMP. The calls to SW2SU2, MUSIG, and NORRNG are repeated for the elastic strain components. Routines SW2SU2, MUSIG, and NORRNG are described in *Sections 4.1.3.4, 4.1.3.13*, and *4.1.3.14*, respectively.

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[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 σ^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.[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.[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*.

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[24] The explicit constraint on the materials shape parameter provided by prior information on the materials shape parameter is discussed on *Page 2-12*.

[25] Specifications of the Bayesian prior distribution for the truncated Normal case is discussed on *Page 2-14*.

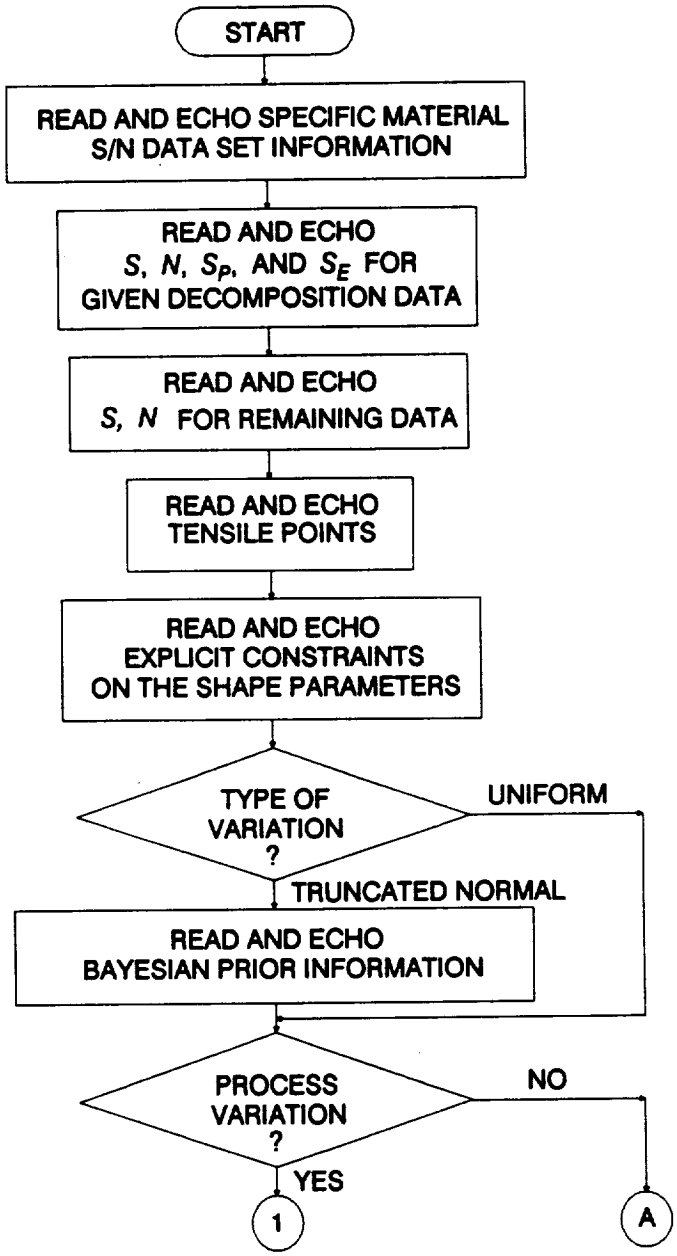

Figure 4-15 Flowchart for Subprogram RDECHO, Strain Formulation

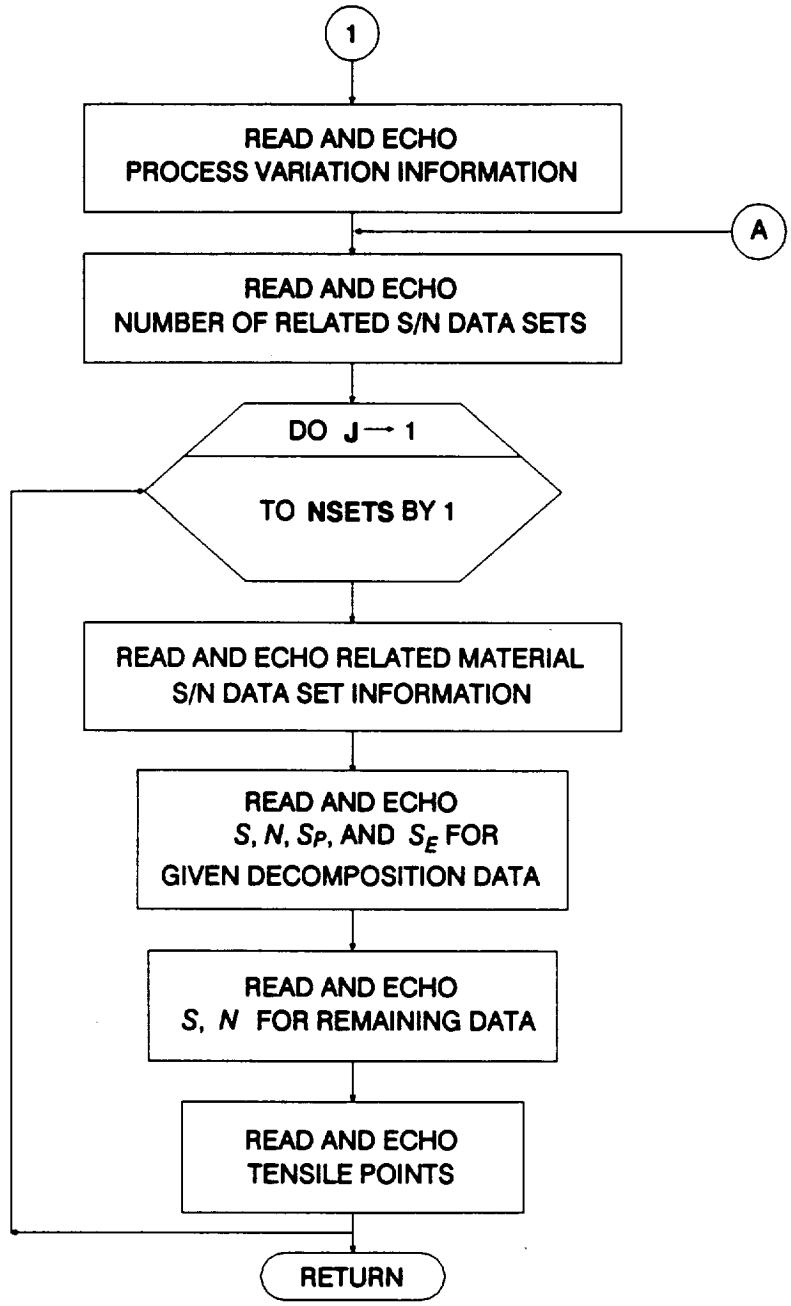

Figure 4-15 Flowchart for Subprogram RDECHO, Strain Formulation (Cont'd)

Next, RDECHO reads the data from file RELATD which contains the related S/N data[26] 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 $\hat{K}_P$, $\hat{m}_P$, $\hat{K}_E$, 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*.

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[26] Related S/N data is discussed on *Page 2-7*.

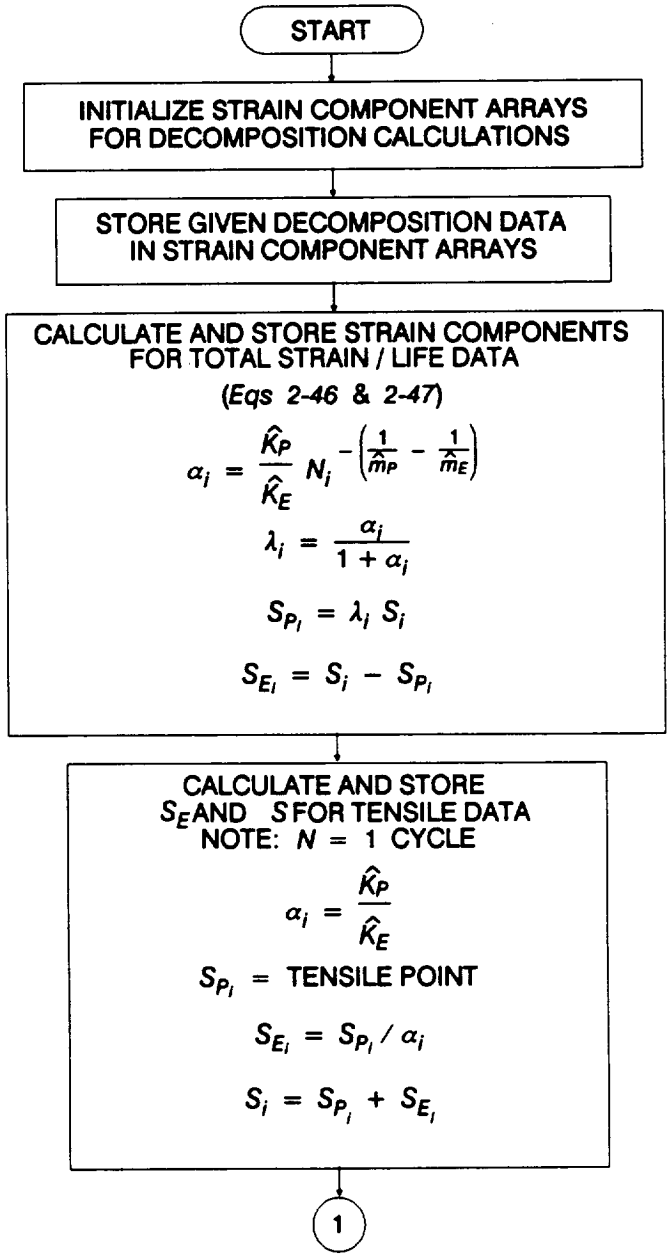

Figure 4-16 Flowchart for Subprogram PECOMP, Strain Formulation

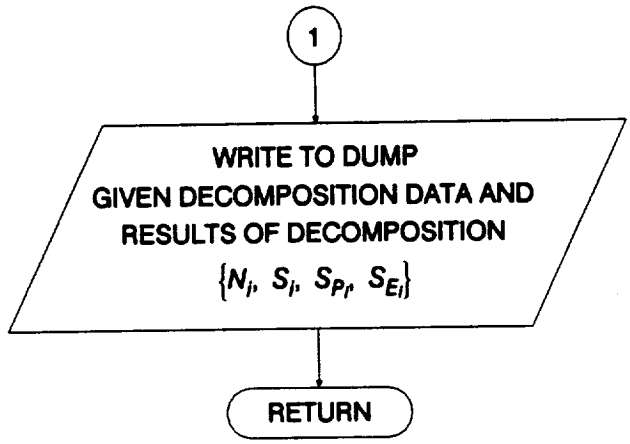

Figure 4-16 Flowchart for Subprogram PECOMP, Strain Formulation (Cont'd)

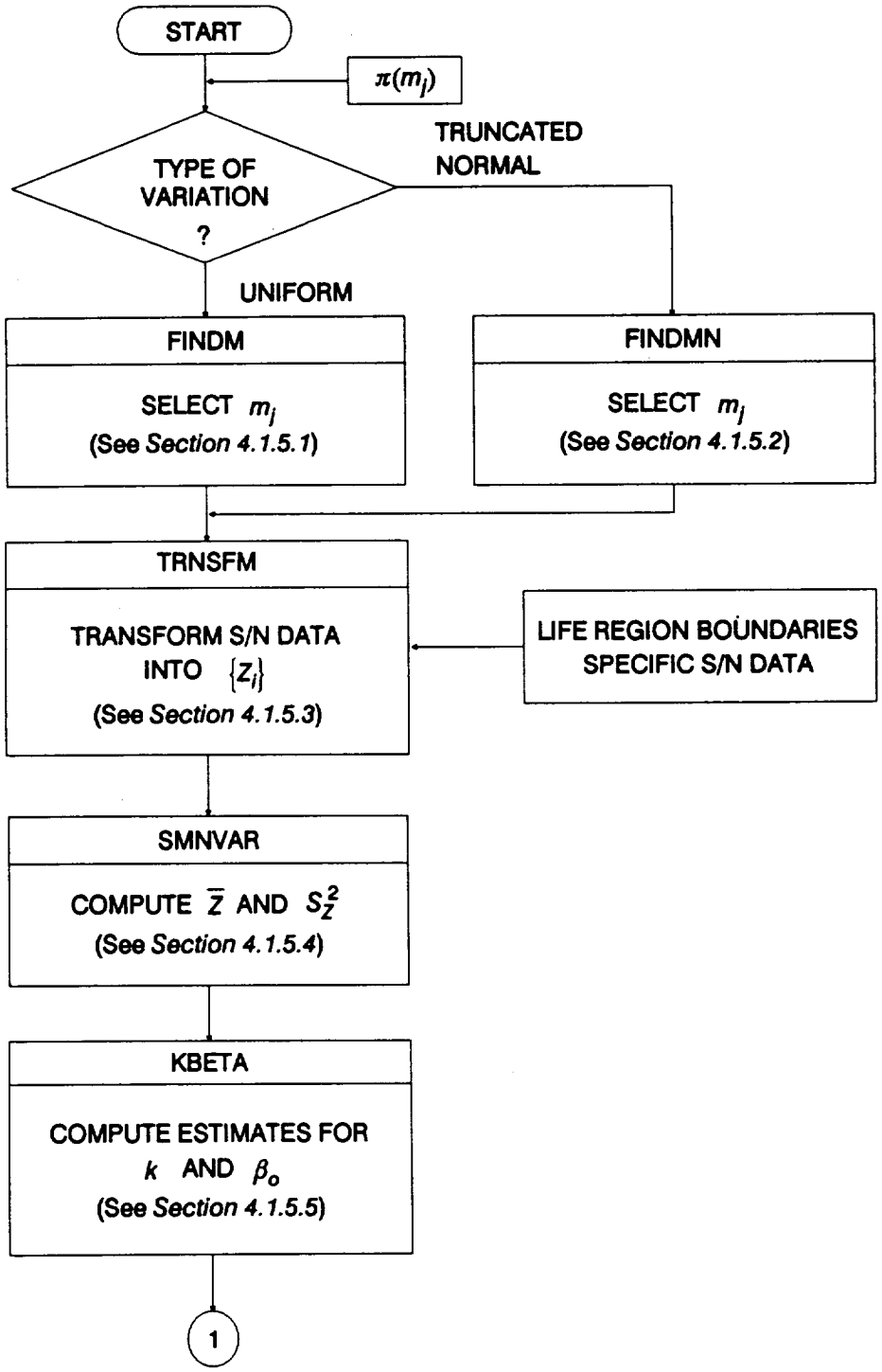

Figure 4-17 Flowchart for Subprogram PAREST

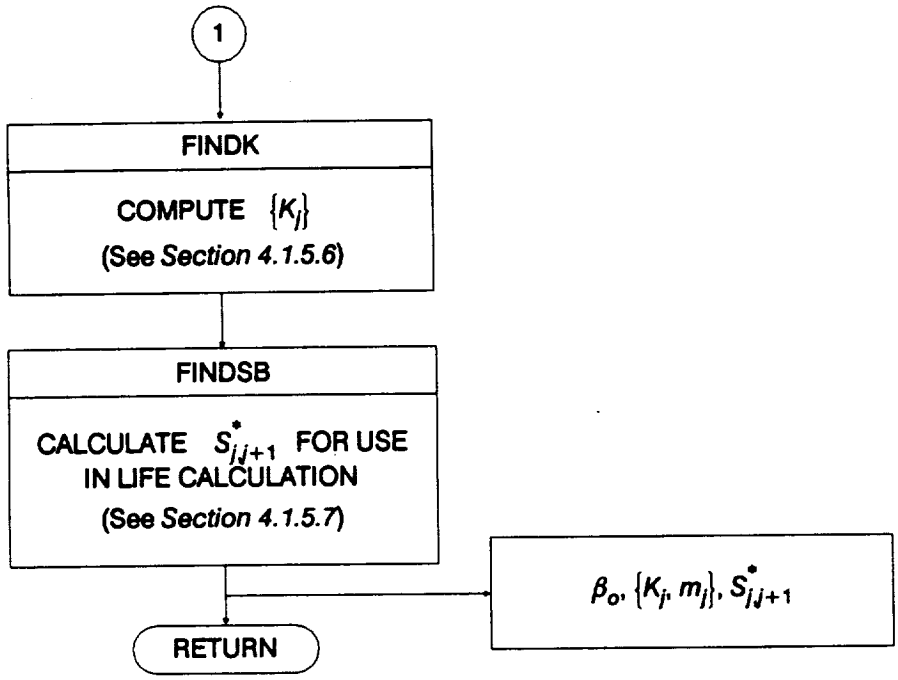

Figure 4-17 Flowchart for Subprogram PAREST (Cont'd)

The remaining calculations find the $\{K_j\}$ and β_o parameters consistent with the randomly selected $\{m_j\}$ and the specific material data set. The calculations begin by routine TRNSFM transforming the specific material S/N data.[27] The transformation produces the $\{Z_l\}$ as a function of the S/N data, the $\{m_j\}$, 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 β_o. Then, the $\{K_j\}$ 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 $\{m_l\}$ off the $\pi(m_l)$ for the Uniform distribution case. The subprogram begins by initializing the array that is to contain the $\{m_l\}$. 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_l is randomly selected off of $U(\max[m_{l-1}, L_l], U_l)$, where m_{l-1} is the randomly selected m in region $l-1$, L_l is the lower bound of $\pi(m_l)$, and U_l is the upper bound of $\pi(m_l)$.

4.1.5.2 Routine FINDMN

The flowchart for the FINDMN routine is given in *Figure 4-19*. The routine performs the random selection of the $\{m_l\}$ off the $\pi(m_l)$ for the truncated Normal distribution case. The subprogram begins by initializing the array that is to contain the $\{m_l\}$. 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 $N(m_{*1}, \sigma_{*1}^2)$, then FINDMN 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 $\pi(m_l)$ is not a point and l is not 1 then, m_l is randomly selected off of $N(m_{*l}, \sigma_{*l}^2)$, then FINDMN checks to see if the selected m is within the interval $[\max(m_{l-1}, L_l), U_l]$, where m_{l-1} is the randomly selected m in region $l-1$, L_l is the

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

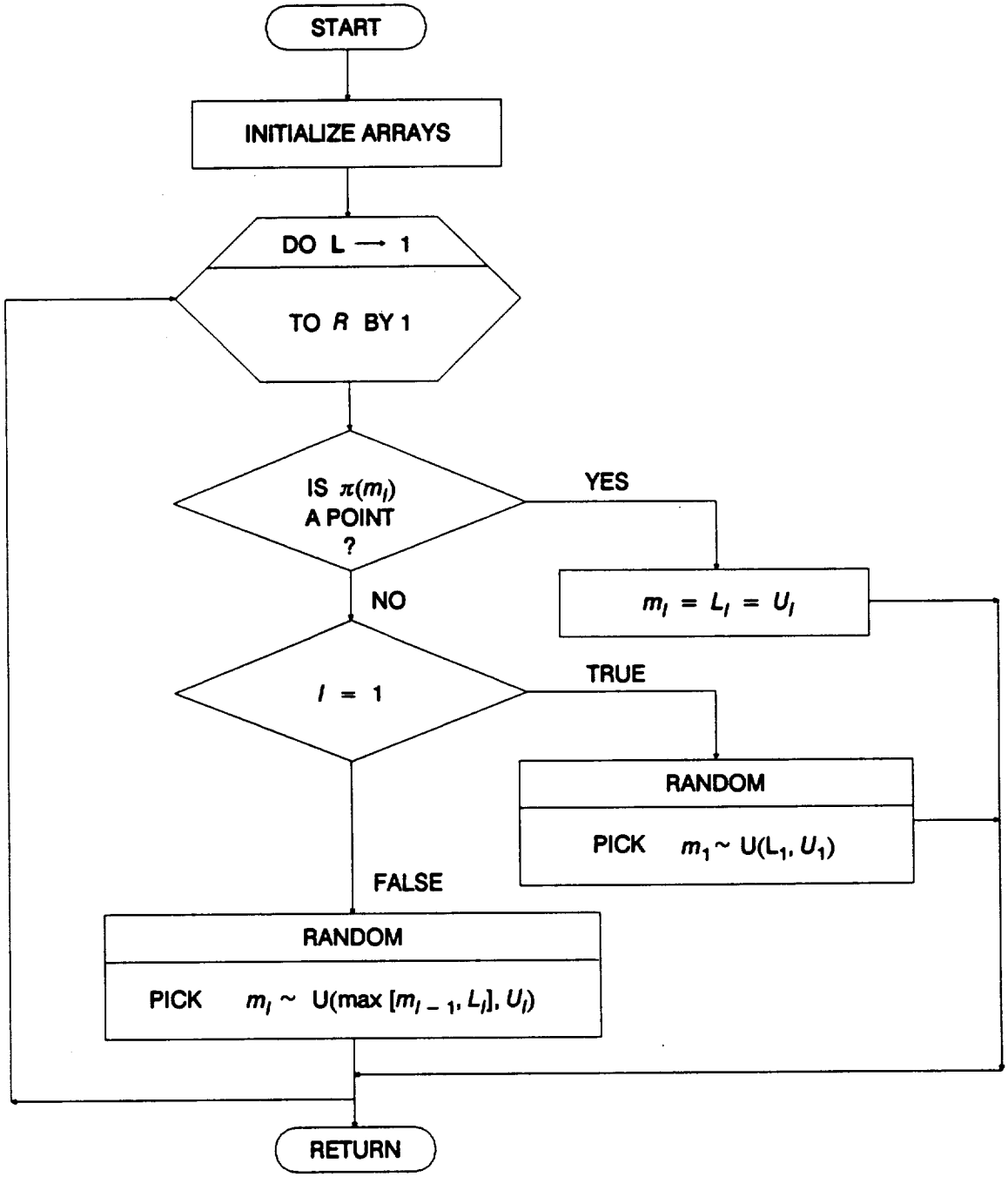

Figure 4-18 Flowchart for Subprogram FINDM, Uniform Distribution

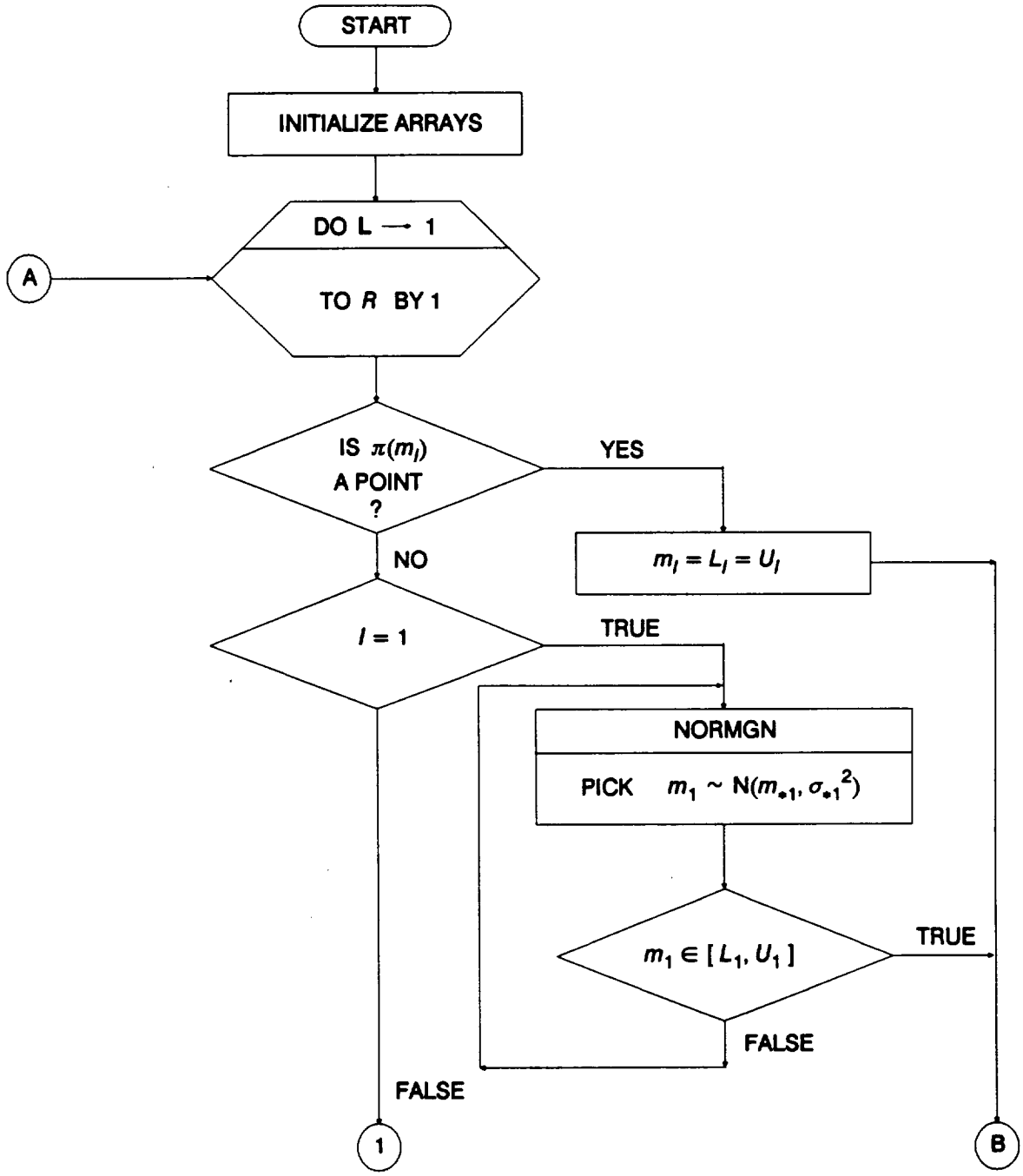

Figure 4-19 Flowchart for Subprogram FINDMN, Truncated Normal Distribution

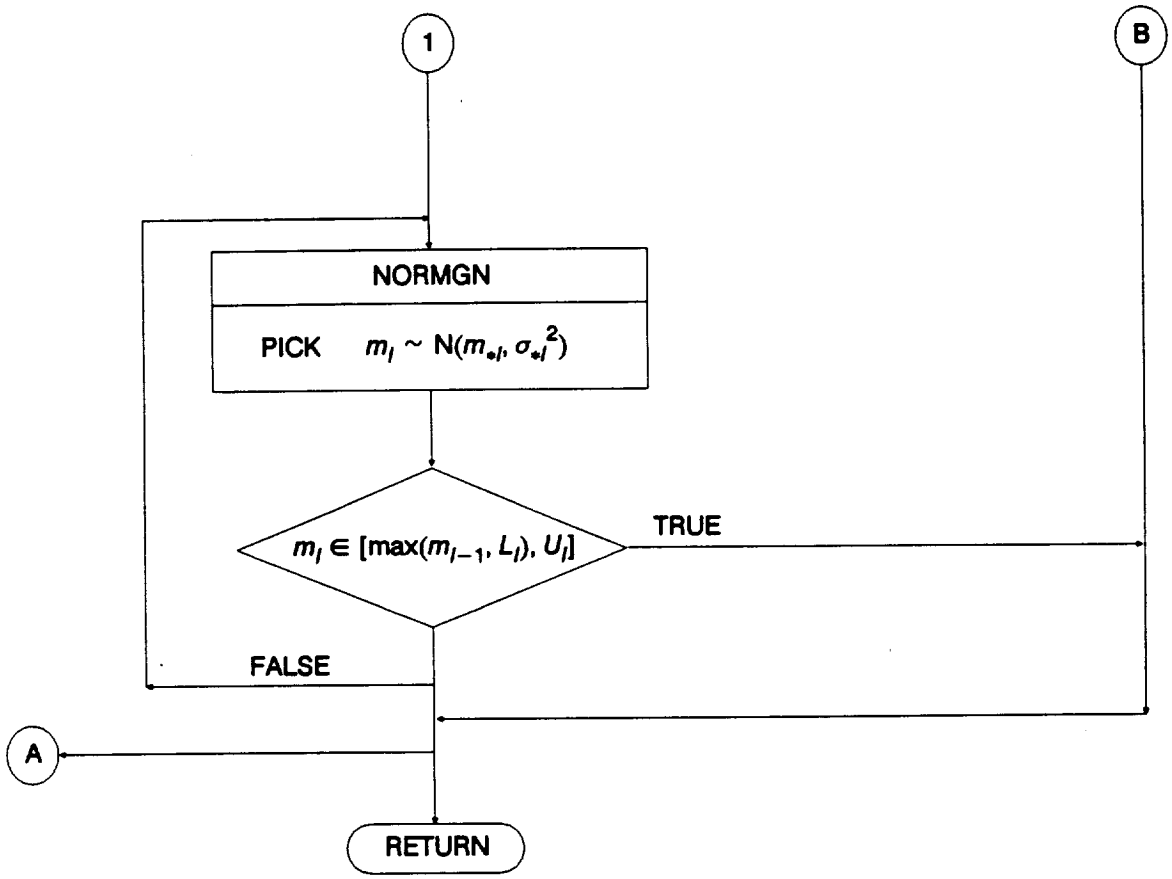

Figure 4-19 Flowchart for Subprogram FINDMN, Truncated Normal Distribution (Cont'd)

lower bound of $\pi(m_l)$, and U_l is the upper bound of $\pi(m_l)$. 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 $\{m_l\}$, and the life region boundaries $\{N^*_{l-1,l}\}$. 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 l, $l = 1, \ldots, R$

$$Z_k = \ln\left(S_k N_k^{\frac{1}{m_l}}\right)$$

Then for each life region to the left ll, $ll = 2, \ldots, l$

$$Z_k = Z_k \ln\left(S_k N^{*\left(\frac{1}{m_{ll-1}} - \frac{1}{m_{ll}}\right)}_{ll-1,ll}\right)$$

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:

$$\text{for the mean } \bar{Z} = \frac{1}{N_o}\sum_{i=1}^{N_o} Z_i$$

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

4.1.5.5 Routine KBETA

KBETA calculates $\hat{k}$ and β_o using *Equation 2-42* and the sample mean and variance obtained in routine SMNVAR where

$$\hat{k} = \bar{Z} \text{ and } \beta_o = \frac{\pi}{S_Z\sqrt{6}} .$$

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 $\{K_l\}$ as a function of $\hat{k}$, β_o, the $\{m_l\}$, and the life region boundaries $\{N^*_{l-1,l}\}$. The subprogram begins by initializing

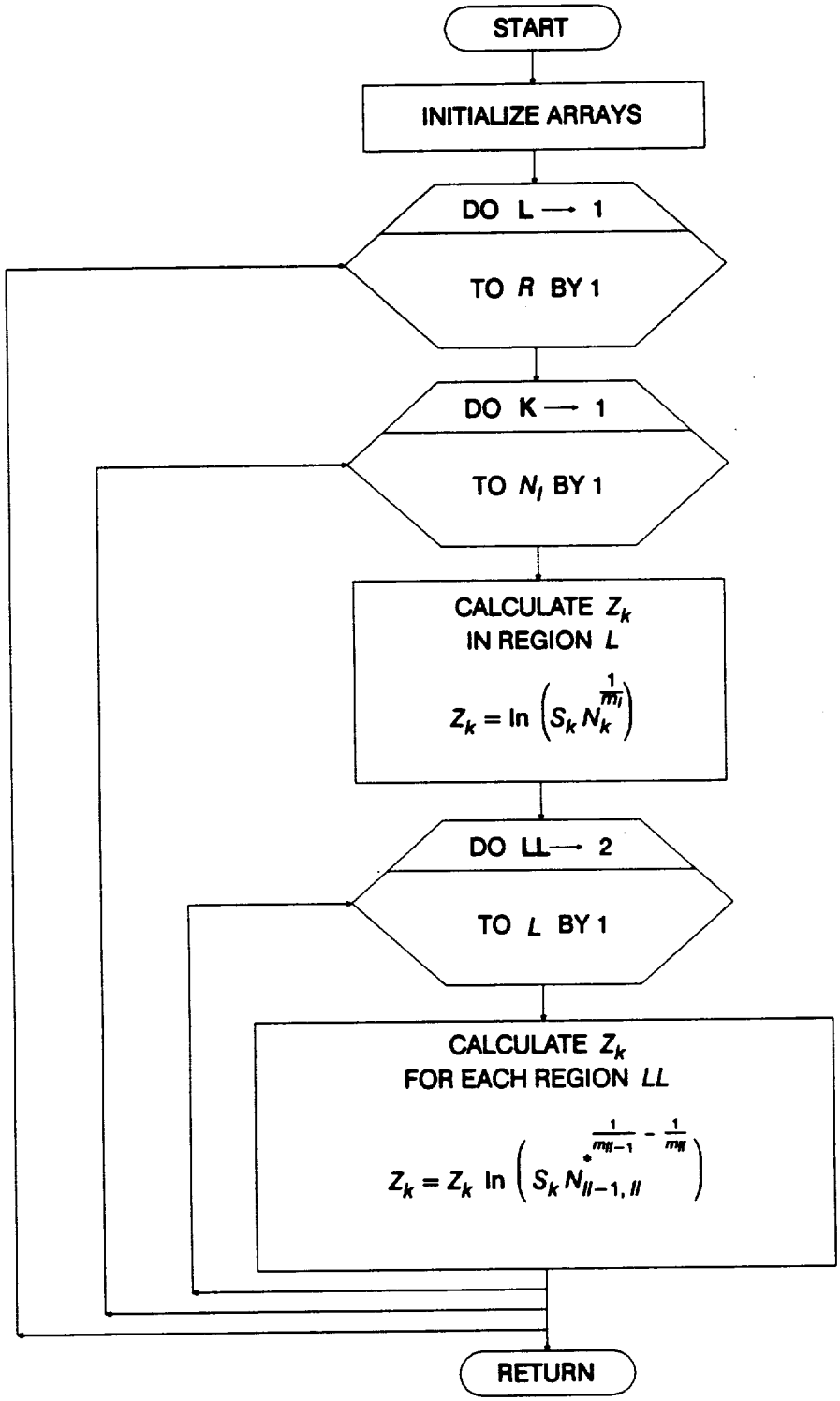

Figure 4-20 Flowchart for Subprogram TRNSFM

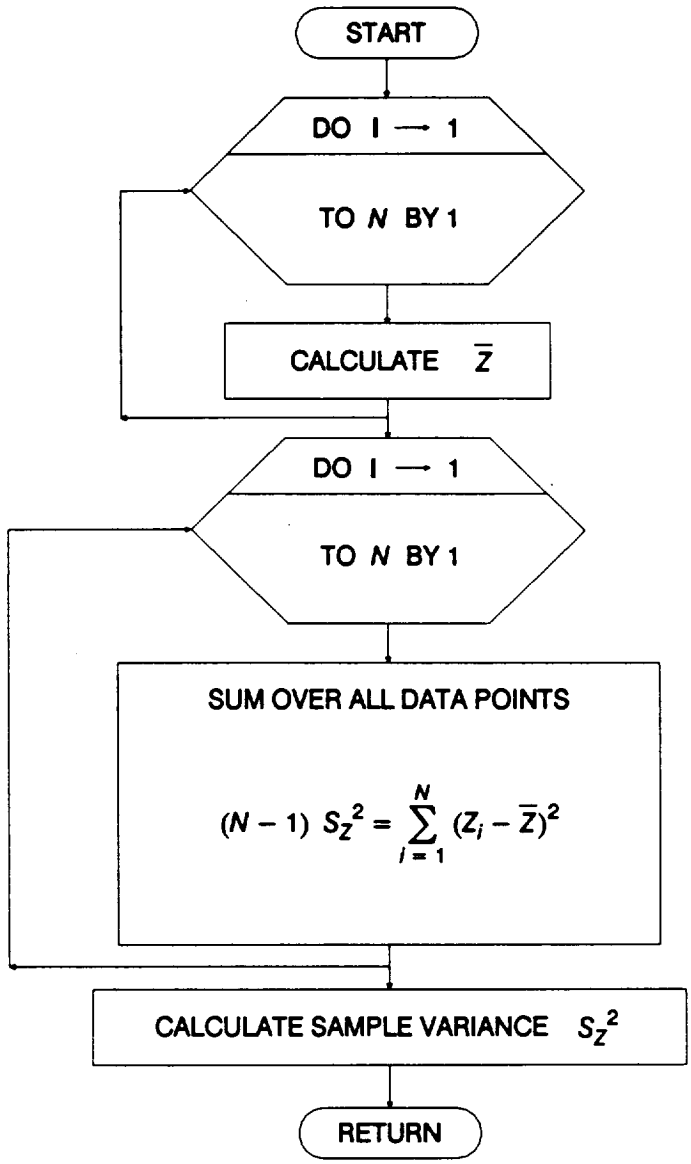

Figure 4-21 Flowchart for Subprogram SMNVAR

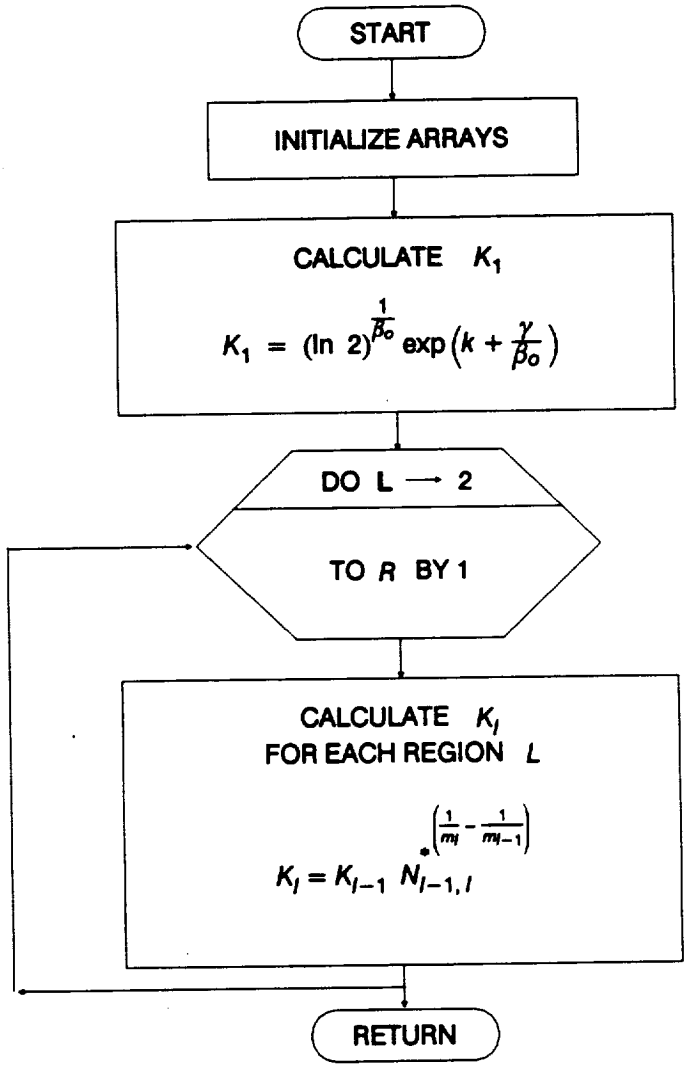

Figure 4-22 Flowchart for Subprogram FINDK

the array that is to contain the $\{K_l\}$. The remaining calculations are performed as follows. First, calculate K_1 given by *Equation 2-41*

$$K_1 = (\ln 2)^{1/\beta_o} \exp\left(k + \frac{\gamma}{\beta_o}\right)$$

where γ is Euler's Constant. Then, using *Equations 2-37* for each life region l, $l = 2, \ldots, R$

$$K_l = K_{l-1} N_{l-1,l}^{*\left(\frac{1}{m_l} - \frac{1}{m_{l-1}}\right)} .$$

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 $\{K_l\}$, β_o and k using *Equation 2-11*, with $l = 1, \ldots, R$

$$S_l^* = K_l N_l^{*(-1/m_l)} .$$

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

$$m_o = m_1 \frac{\ln K_1 - \ln S_0^* + \ln(\varphi \lambda_K^* Z)}{\ln S_o - \ln S_0^*} .$$

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_o is being used. If S_o is being used, the subprogram checks to see if the stress S is greater than or equal to S_o, 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 paremeters λ_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 φ 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 λ_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,

$$F = \left[K_P N^{-1/m_P} + K_E N^{-1/m_E}\right] \varphi \left[\lambda_K^* Z\right] - S$$

and the derivative is given by

$$\frac{dF}{dN} = -\left[\frac{K_P}{m_P} N^{(-1 - 1/m_P)} + \frac{K_E}{m_E} N^{(-1 - 1/m_E)}\right] \varphi \left[\lambda_K^* Z\right] .$$

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*.

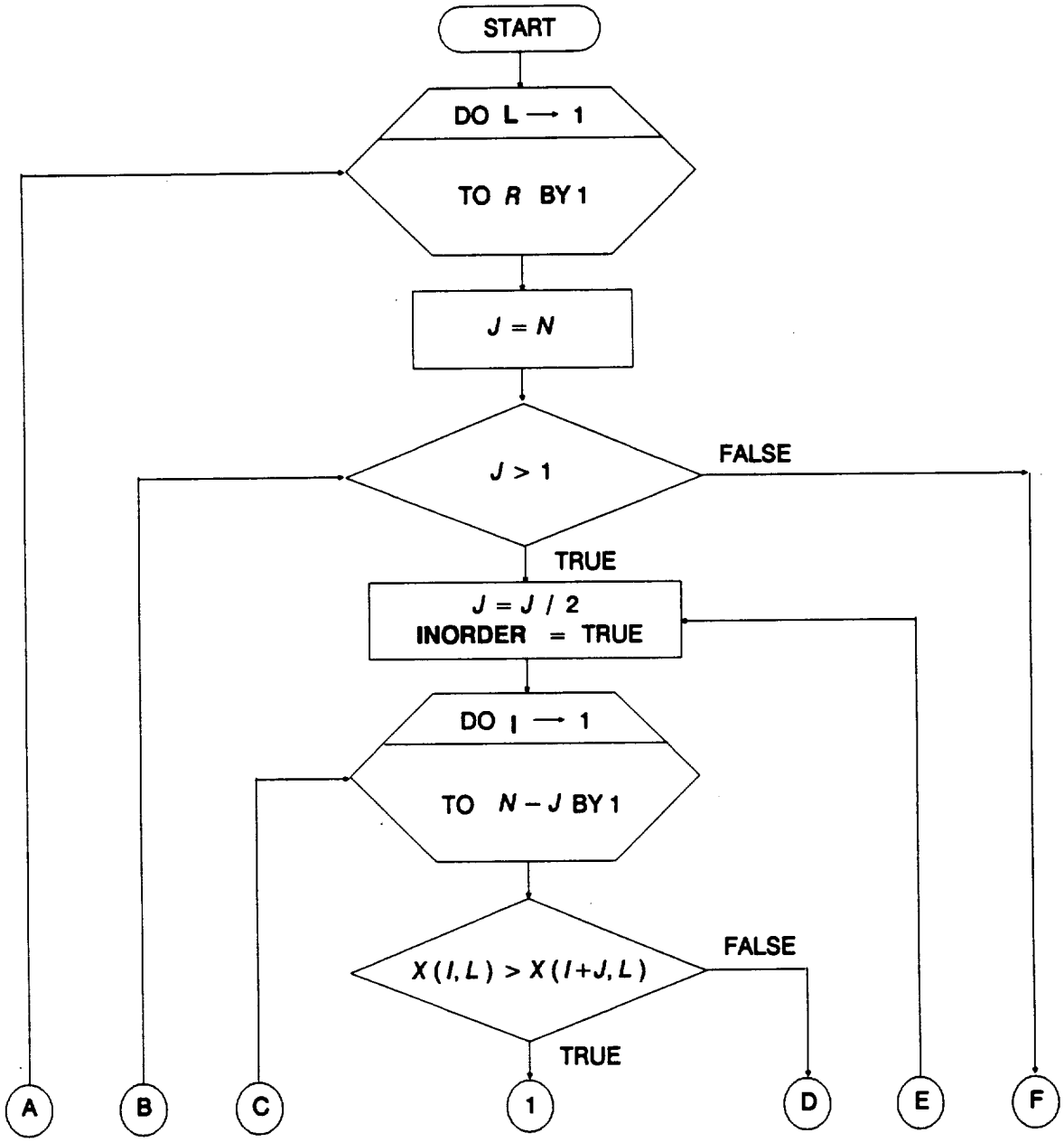

Figure 4-23 Flowchart for Subprogram SORTM

C-2

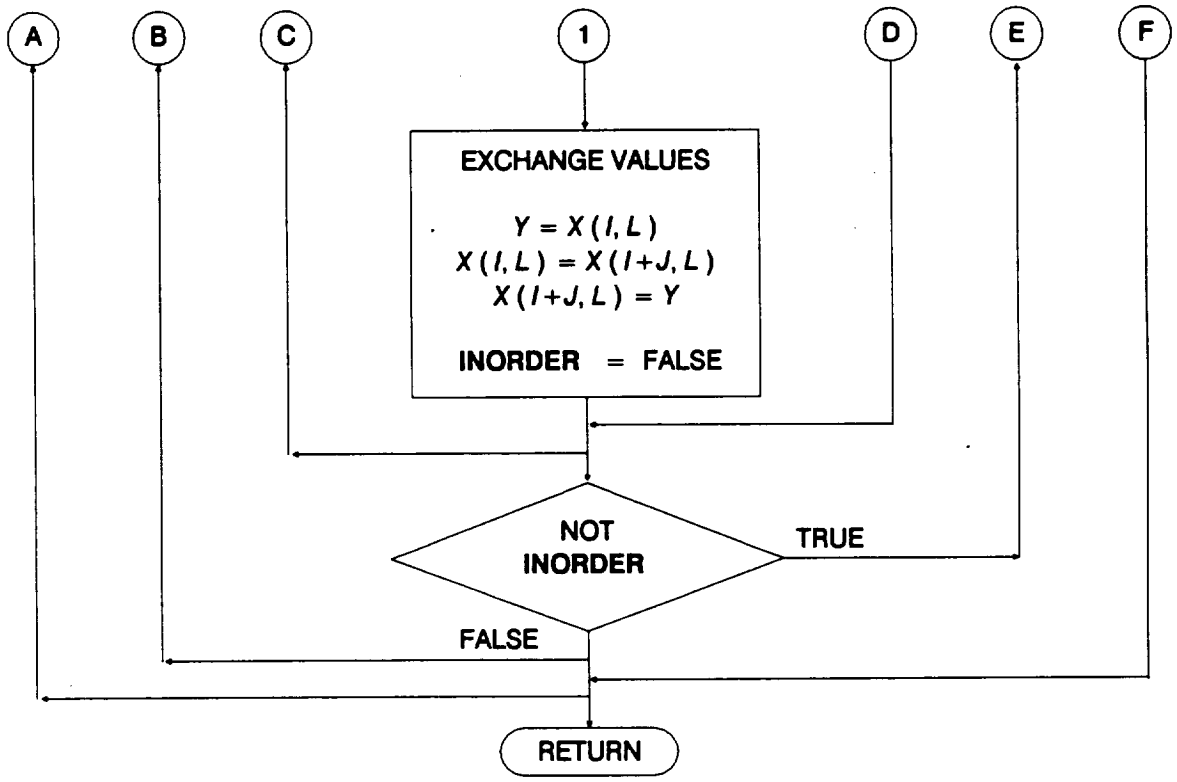

Figure 4-23 Flowchart for Subprogram SORTM (Cont'd)

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 5.A*.

4.2.2 BFIT Program

The prior failure distribution parameter β 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 β, 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:

NAME	TYPE	CONTENTS
BFITD	Input	Analysis indices
LOWLIF	Input	Sorted fatigue lives
BFITO	Output	Results
IOUTPR	Output	User-requested information

The indices which define the data base used to estimate β 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 β 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 $\ln(-\ln[1 - F(N)])$ on $\ln(N)$ to estimate β by b where

$$X_i = \ln N_i$$

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

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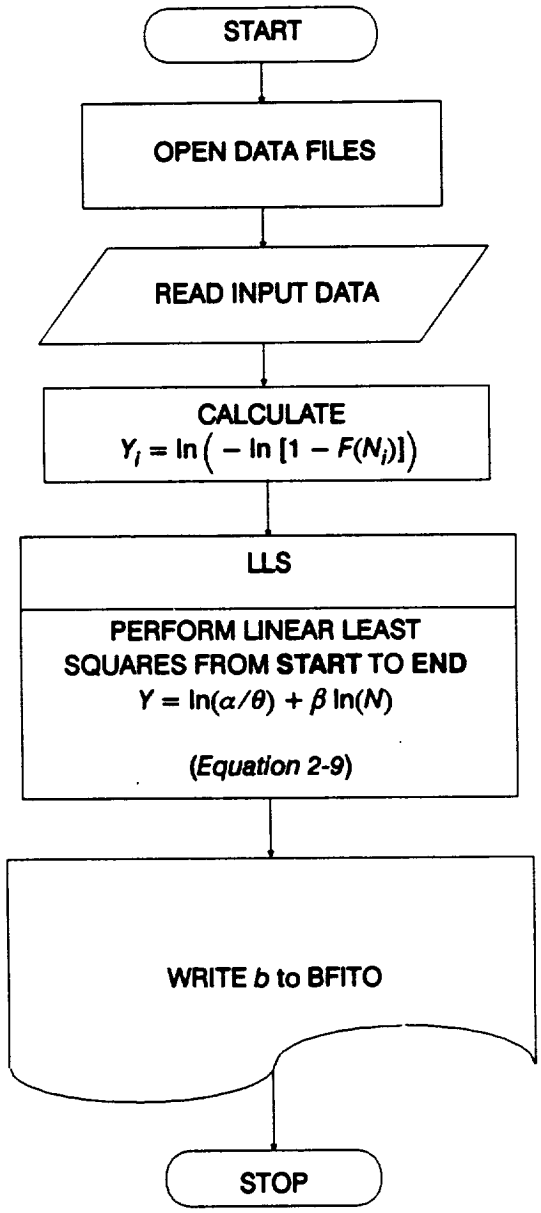

Figure 4-24 Flowchart for the Prior Failure Distribution Parameter β Estimation Program BFIT

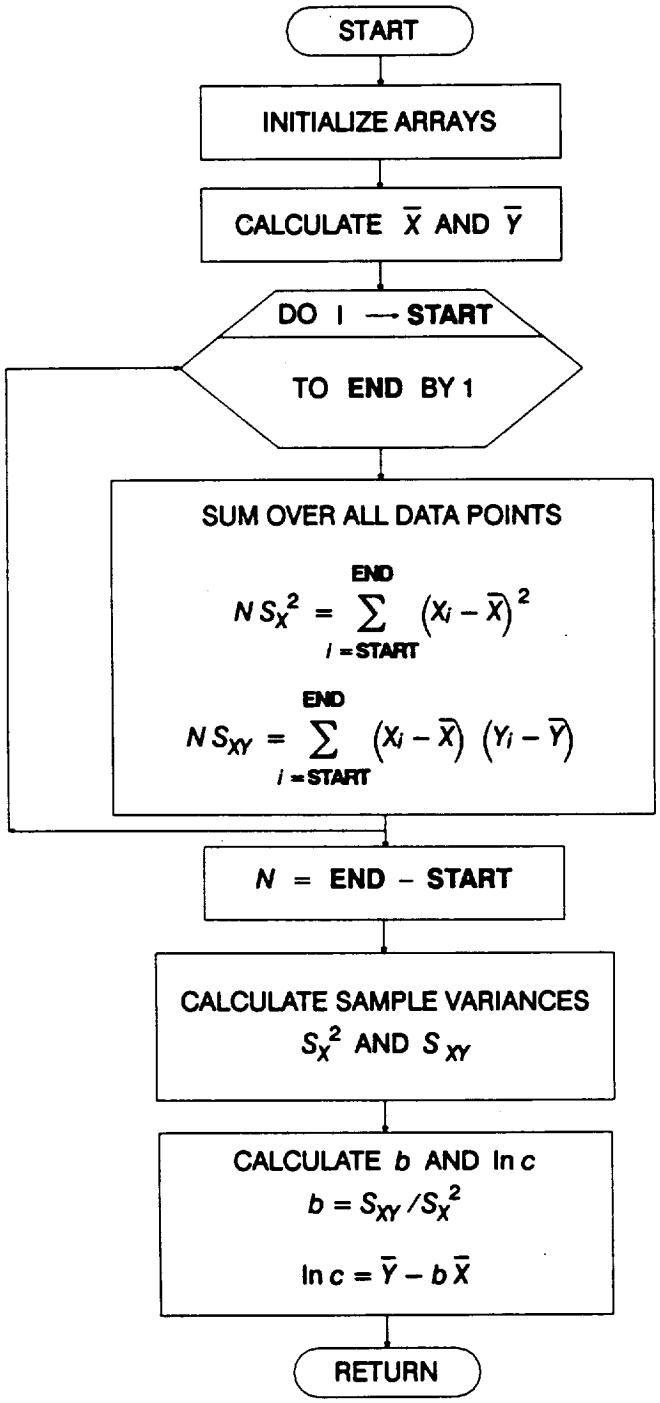

Figure 4-25 Flowchart for Subprogram LLS

LLS starts by initializing the arrays required for the calculations. Then the sample means $\bar{X}$ and $\bar{Y}$ are calculated. The sample variances are calculated as follows:

$$N S_X^2 = \sum_{i = \mathbf{START}}^{\mathbf{END}} \left(X_i - \bar{X}\right)^2$$

$$N S_{XY} = \sum_{i = \mathbf{START}}^{\mathbf{END}} \left(X_i - \bar{X}\right) \left(Y_i - \bar{Y}\right)$$

where N = **END** – **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*,

$$b = S_{XY}/S_X^2 \text{ and } \ln c = \bar{Y} - b\bar{X}$$

β 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 α and θ estimation procedure of *Section 2.1.1* is implemented as the FORTRAN program ABTFIT. This program is used to estimate α and θ, 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

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

is calculated for each failure time and LOWLIF is closed.

The estimate of β is provided exogenously or by the program BFIT described in *Section 4.2.2*. The estimates of the parameters α and θ 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.

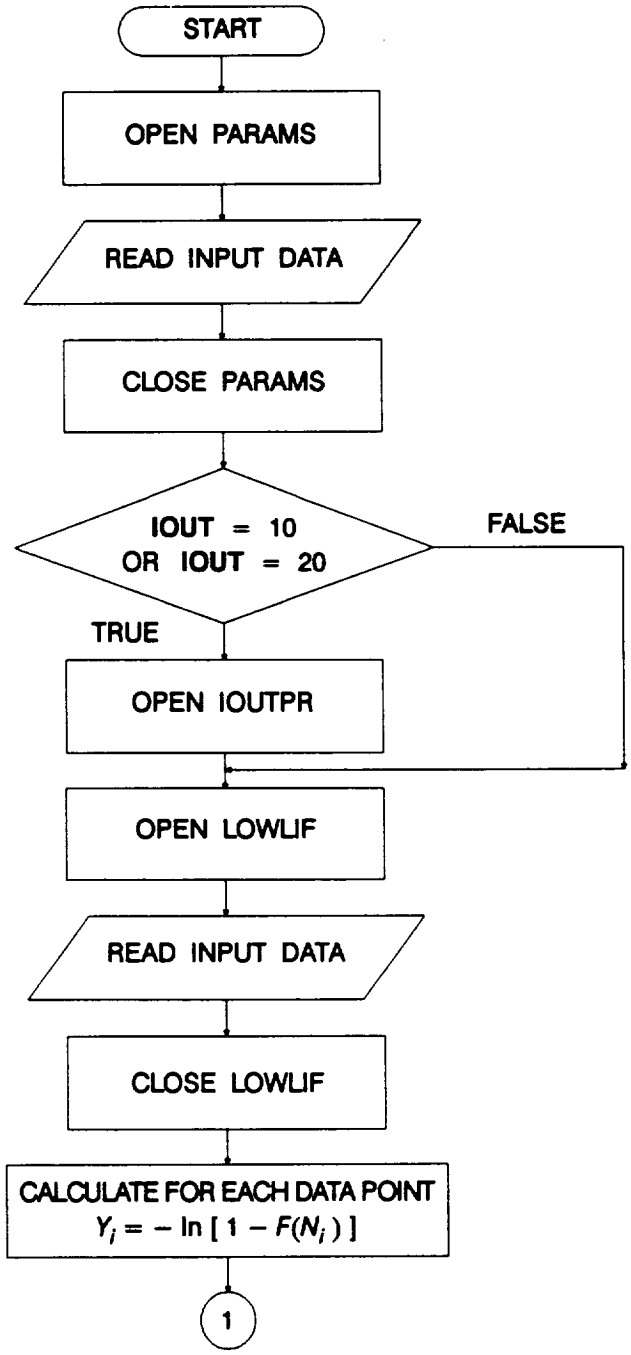

Figure 4-26 Flowchart for the Prior Failure Distribution Parameter Estimation Program ABTFIT

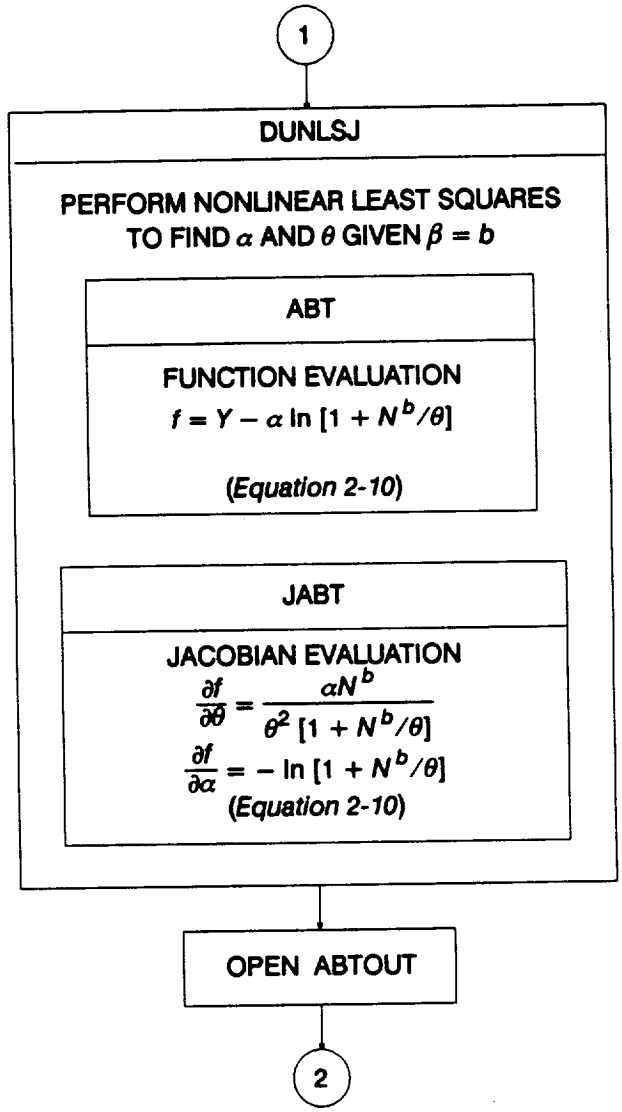

Figure 4-26 Flowchart for the Prior Failure Distribution Parameter Estimation Program ABTFIT (Cont'd)

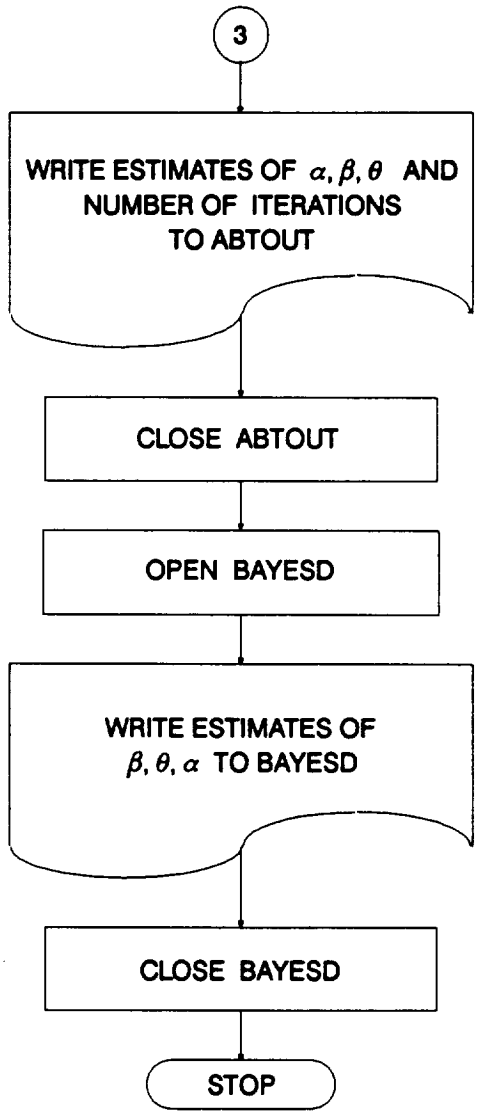

Figure 4-26 Flowchart for the Prior Failure Distribution Parameter Estimation Program ABTFIT (Cont'd)

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 θ and α 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 λ_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:

NAME	TYPE	CONTENTS
BAYESD	Input	Failure distribution parameters
LDAT	Input	Assurance level and λ bounds
LOUT	Output	Results
IOUTPR	Output	User-requested information

LZERO reads from file BAYESD the parameters α and θ derived for the failure life distribution using the program ABTFIT. Then **IOUT**, the desired assurance level **A**, and the bounds, λ_{lb} and λ_{ub}, on λ_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.

$F(\lambda_{lb})$ 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 $F(\lambda_{lb})$ 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.

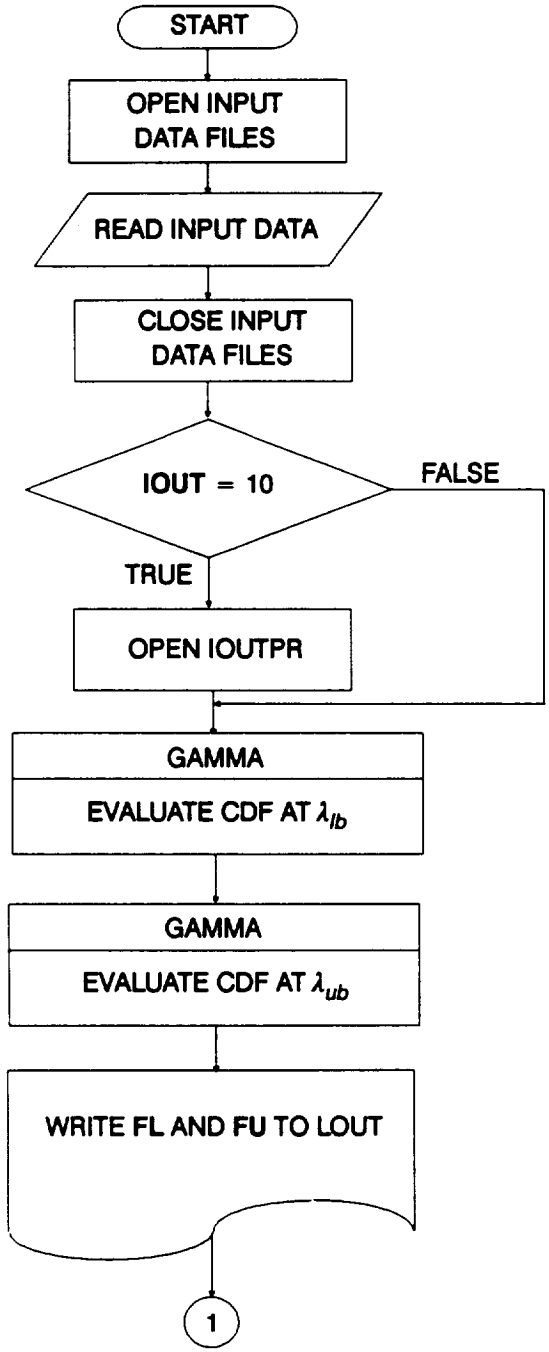

Figure 4-27 Flowchart for the Assurance Calculation Program LZERO

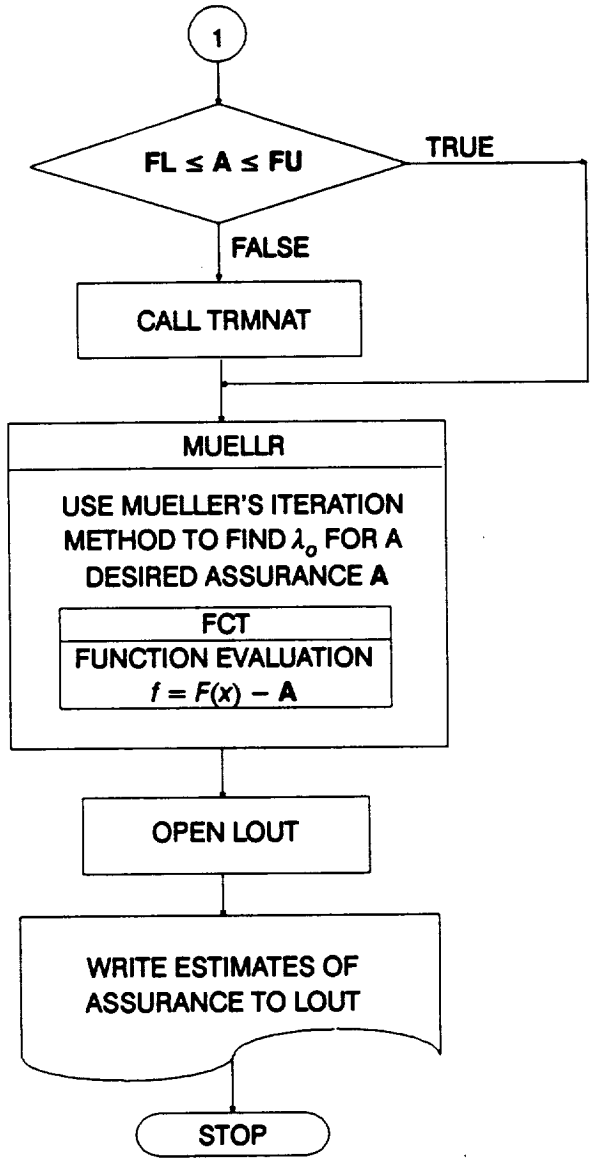

Figure 4-27 Flowchart for the Assurance Calculation Program LZERO (Cont'd)

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:

$$F(x) = (\theta x)^{\alpha} \exp(-\theta x) \sum_{i=0}^{\infty} \frac{(\theta x)^{i}}{\Gamma(\alpha + 1 + i)} \tag{4-1}$$

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

$$F(x) = \sum_{i=0}^{NS} \exp\Big(- \ln [\, \Gamma(\alpha + 1 + i) \,] + (i + \alpha) \ln [\, \theta x \,] - \theta x \Big) \tag{4-2}$$

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.

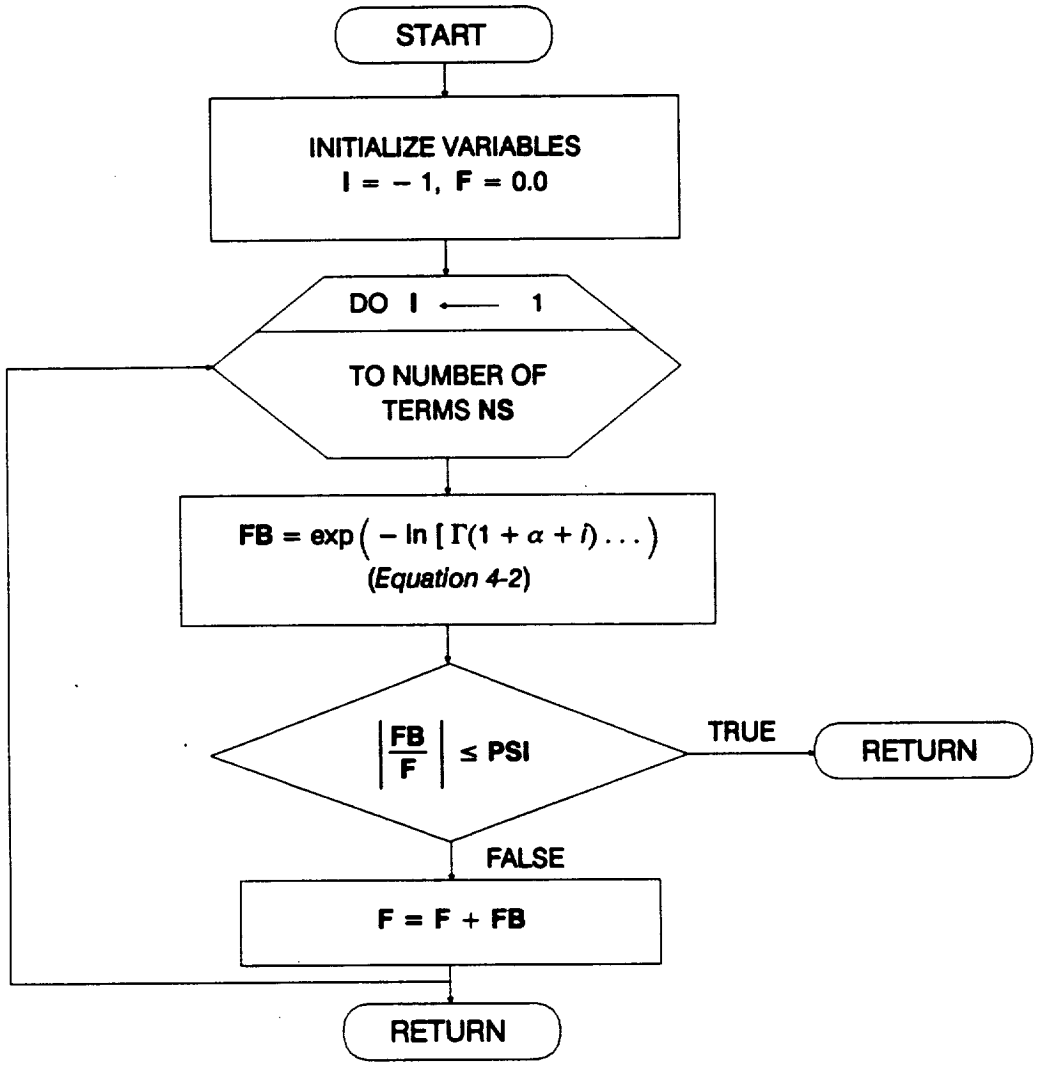

Figure 4-28 Flowchart for Subprogram GAMMA

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:

NAME	TYPE	CONTENTS
BAYESD	Input	Prior failure distribution parameters and operating experience
BAYESO	Output	Echo of input data and results of analysis
UBAYES	Output	Posterior failure distribution parameters

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 α' and θ' 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 β, θ', and α' 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%.

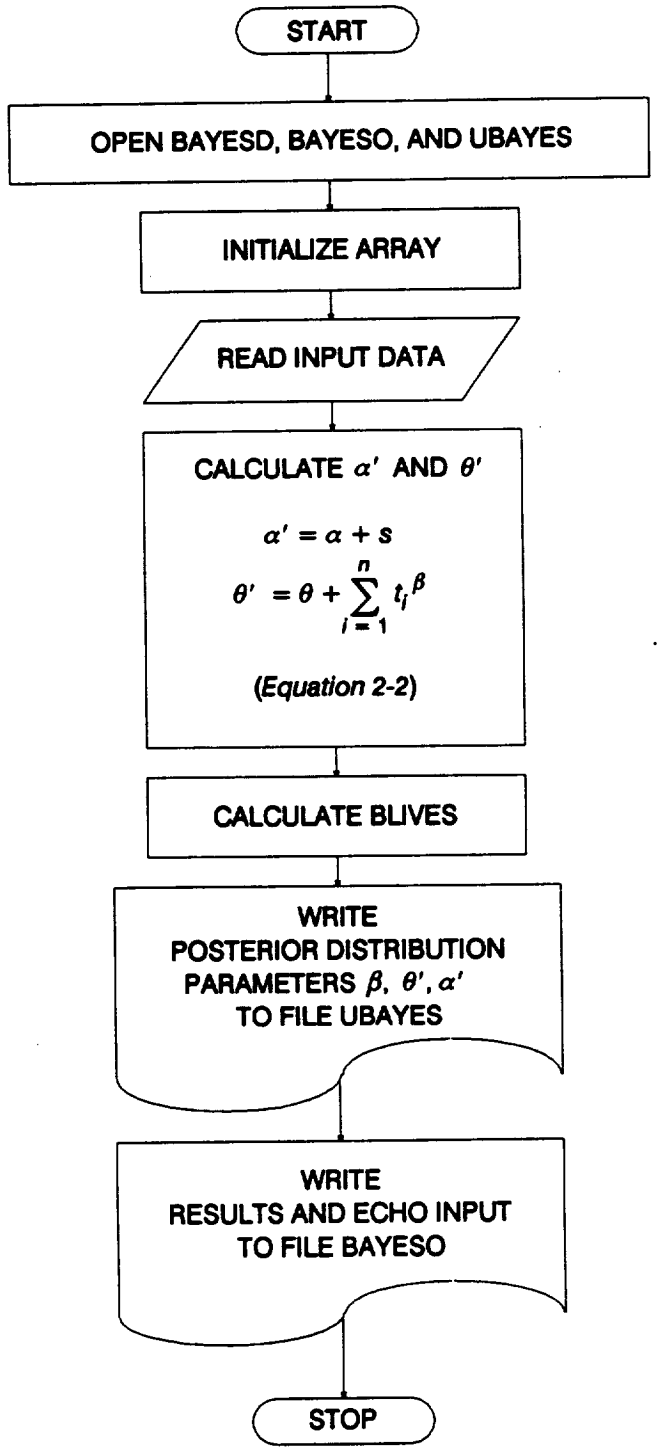

Figure 4-29 Flowchart for the Bayesian Statistical Procedure Program BAYES

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, σ^2) 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 $X_1 \sim$ Gamma(α) and $X_2 \sim$ Gamma(β) are independently distributed, Johnson and Kotz **[4]**, pp.181-182.

$$g(y) = y^{\alpha - 1}(1 - y)^{\beta - 1}\frac{\Gamma(\alpha + \beta)}{\Gamma(\alpha)\,\Gamma(\beta)} \qquad 0 \le y \le 1$$

That standard Beta distribution can be related to the Beta distribution we use, *Equation 2-54*

$$f(x) = \frac{(x-a)^{\rho\theta}(b-x)^{(1-\rho)\theta}}{(b-a)^{\theta+1}} \frac{\Gamma(\theta+2)}{\Gamma(\rho\theta+1)\,\Gamma[(1-\rho)\theta+1]}$$

$$a \le x \le b \qquad 0 \le \rho \le 1 \qquad \theta \ge 0$$

by the transformations

$$X = a + (b-a)\,Y$$

$$\alpha = \rho\theta + 1$$

$$\beta = (1-\rho)\,\theta + 1$$

4.4.6 WEIBGN Routine

The Weibull(β, η) 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 η and β 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:

NAME	TYPE	CONTENTS
NBSIN	Input	Generation parameters
IOUTPR	Output	Intermediate calculations
User-Specified	Output	Narrow-band and sinusoidal time histories

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, σ_{Nk}^2) variates; however, for reference time histories the

[31] The AR(1) process is described in *Section 2.1.4*.

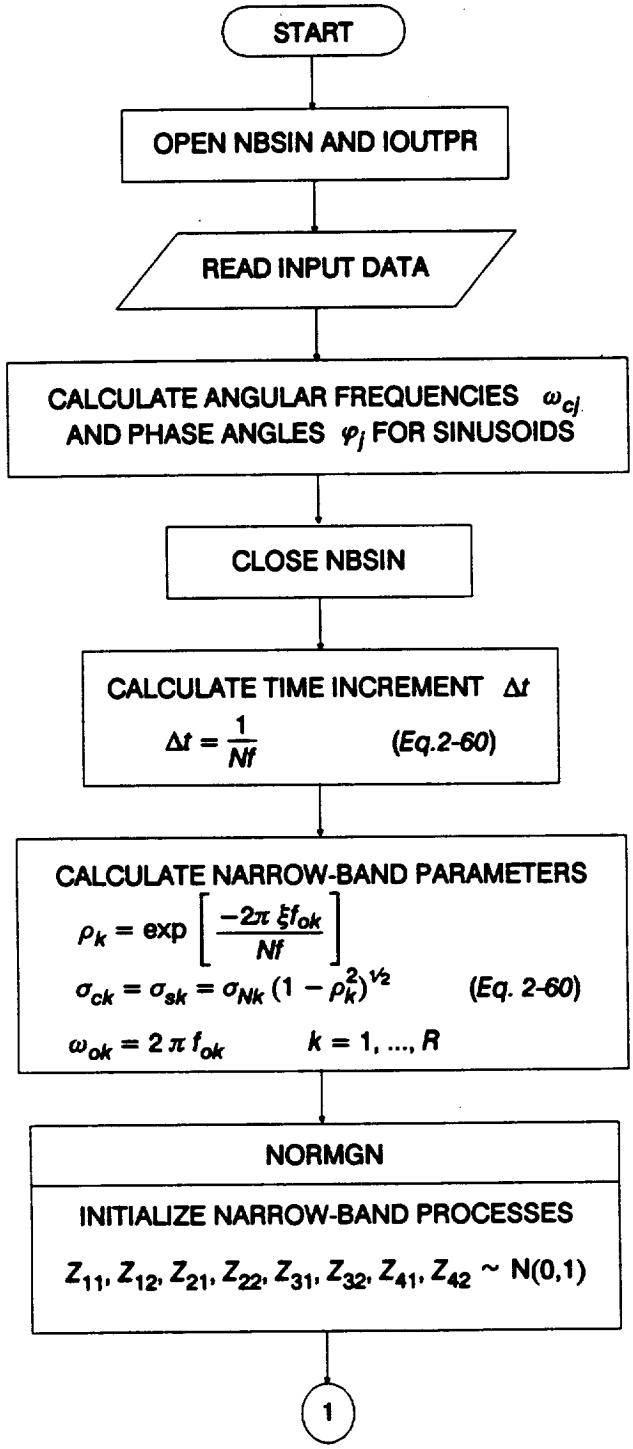

Figure 4-30 Flowchart for the Time History Generation Program NBSIN

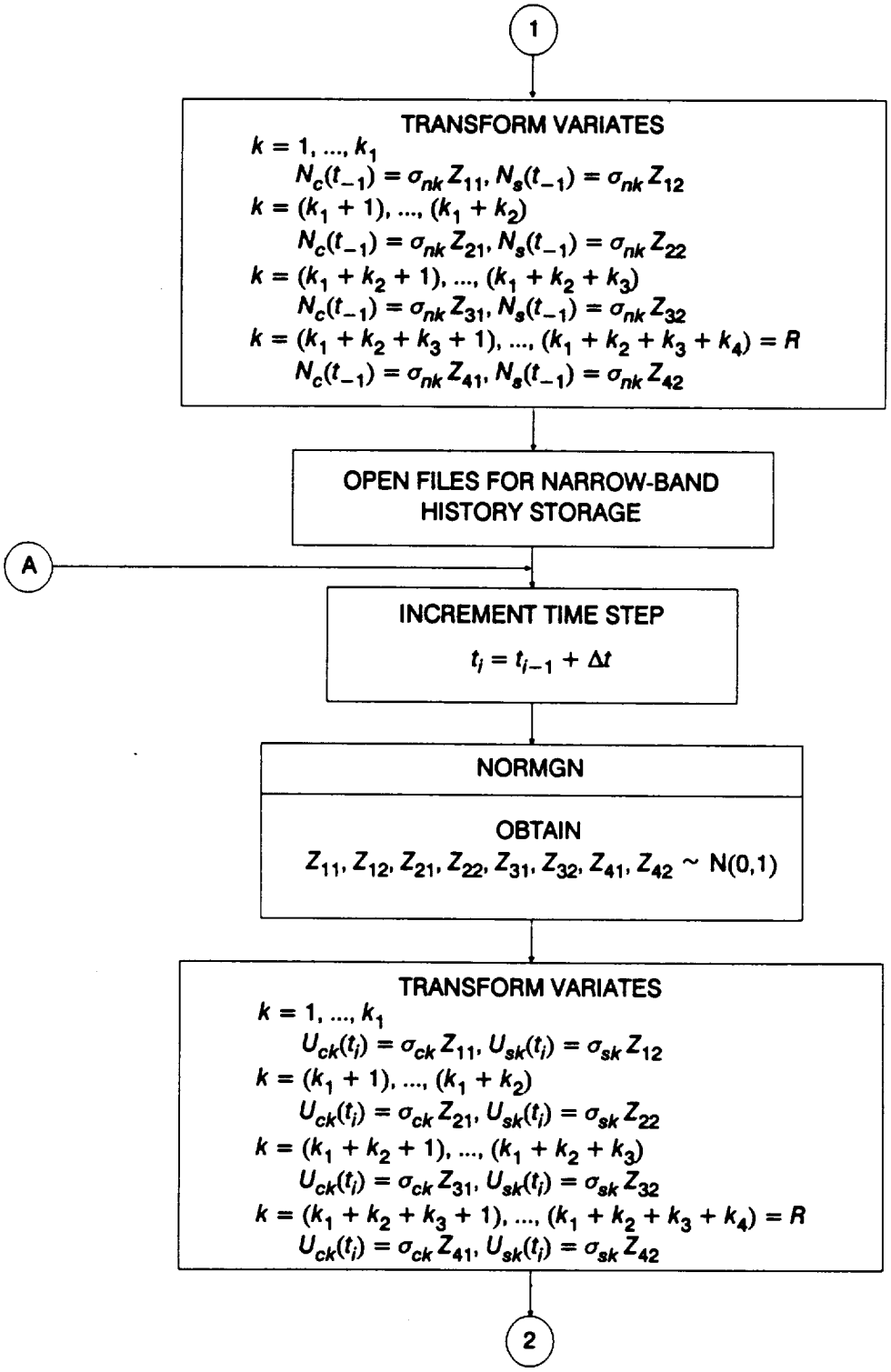

Figure 4-30 Flowchart for the Time History Generation Program NBSIN (Cont'd)

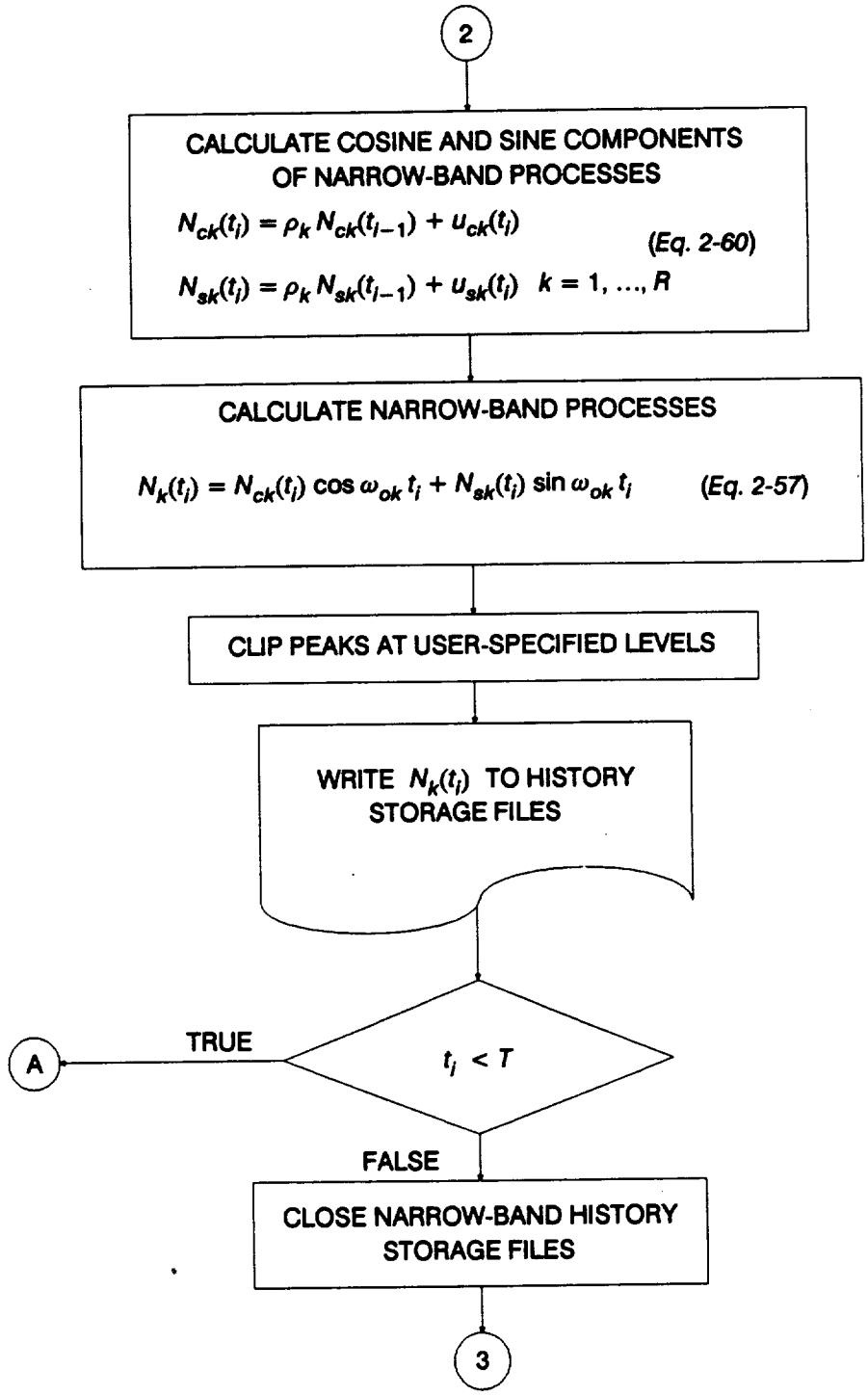

Figure 4-30 Flowchart for the Time History Generation Program NBSIN (Cont'd)

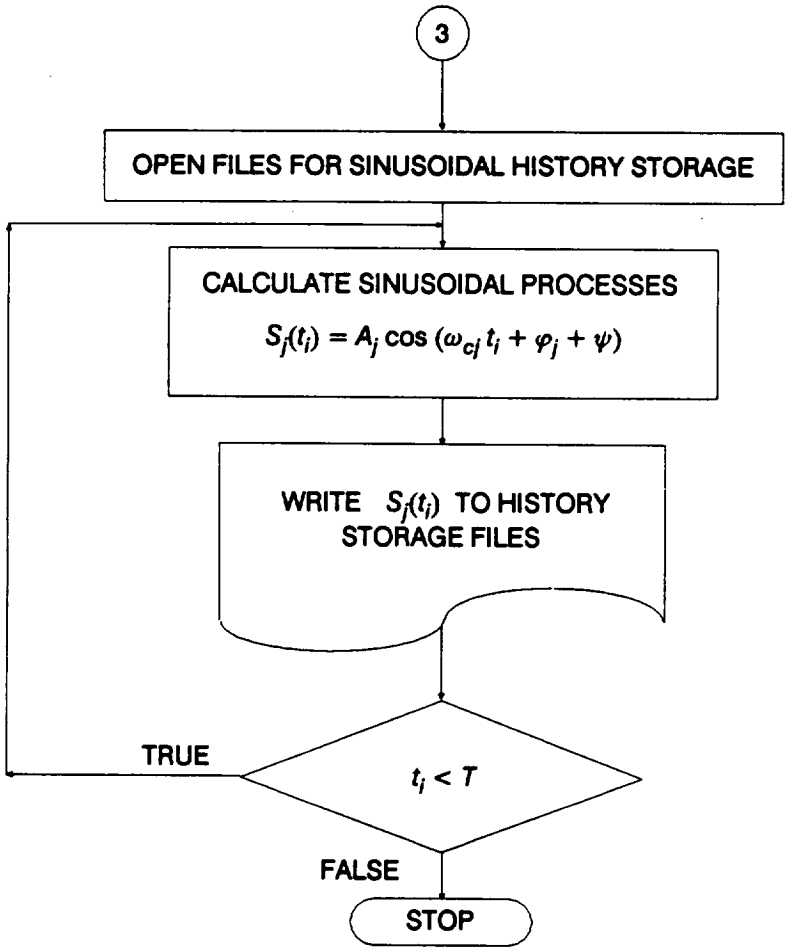

Figure 4-30 Flowchart for the Time History Generation Program NBSIN (Cont'd)

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, σ_{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

[1] Miles, R. F., The RANDOM Computer Program: A Linear Congruential Random Number Generator, JPL Publication 85-98, JPL Document 5101-277, Feb. 15, 1986.

[2] Abramowitz, M., and Stegun, I. A., editors, Handbook of Mathematical Functions, National Bureau of Standards, Applied Mathematics Series 55, Issued June 1964, Ninth Printing, November 1970 with corrections.

[3] Fishman, George S., "Sampling From the Gamma Distribution on a Computer," Communications of the ACM, Volume 19, Number 7, July 1976, Pages 407-409.

[4] Johnson, N. L., and Kotz, S., Distributions in Statistics: Continuous Univariate Distributions - 1, Houghton Mifflin Company, 1970.

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.

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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.[1] They are:

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

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 ρ and θ 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*.

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1 Files RELATD and RELATO are opened in INFAGG.

2 Hyperparameters are discussed in *Section 2.1.1*.

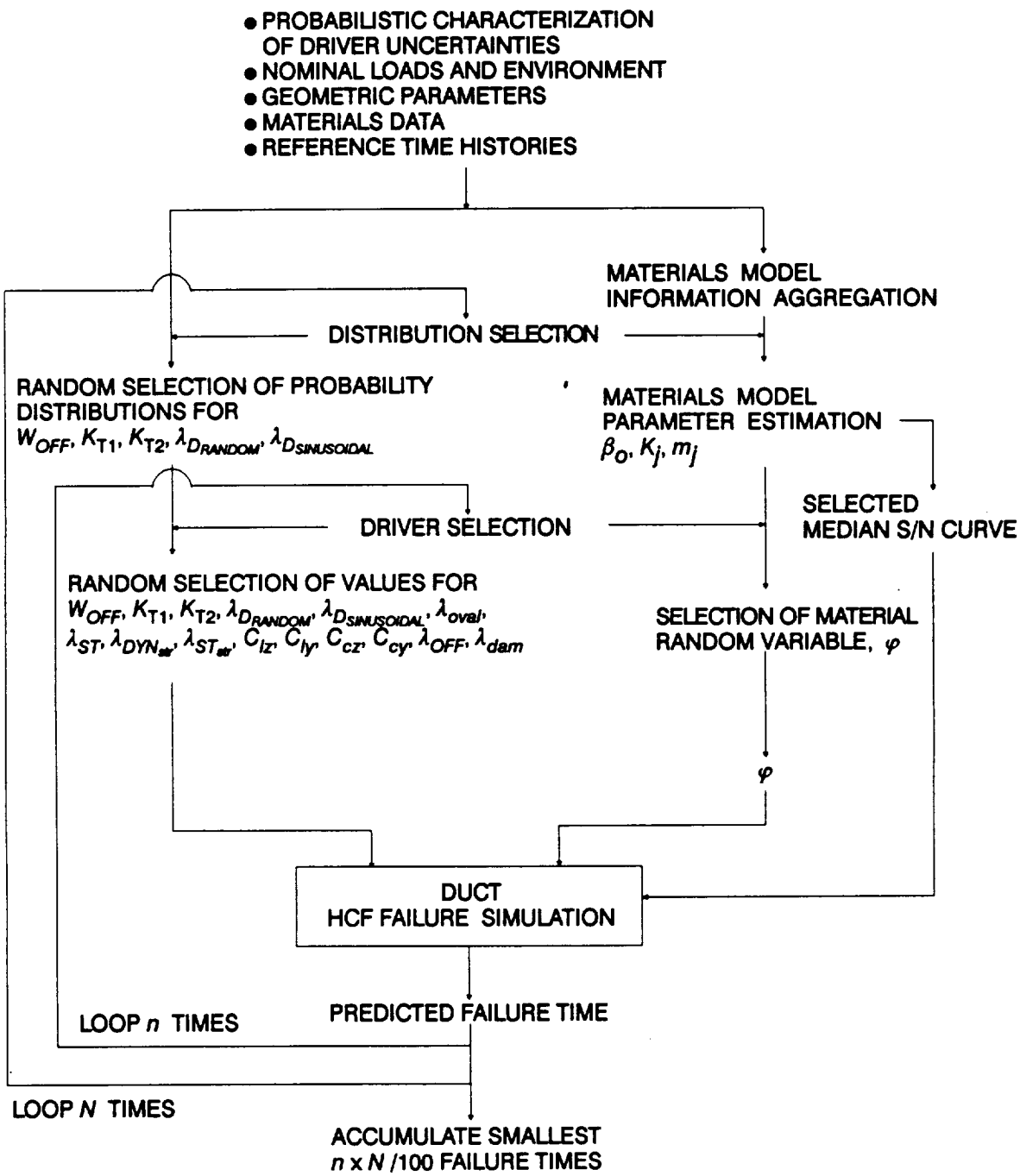

Figure 5-1 Structure of the Probabilistic Failure Model for the Elbow Ducts with Welds

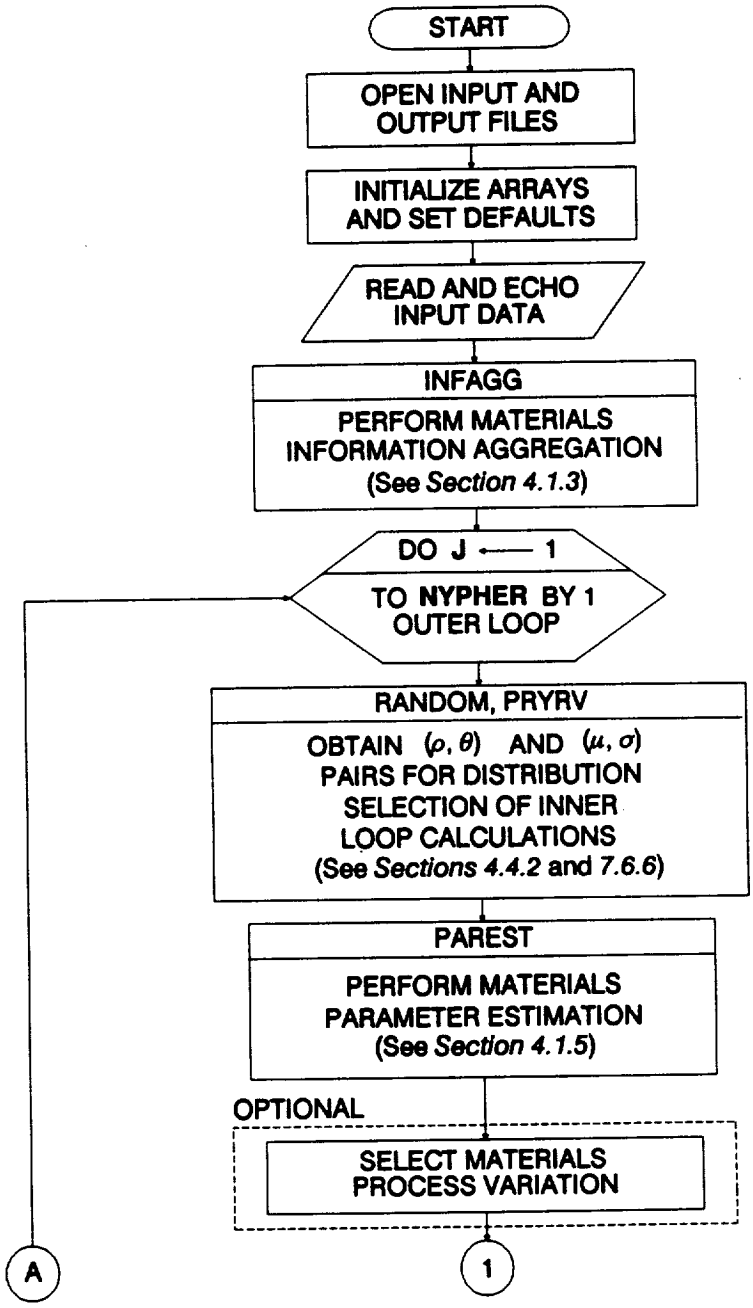

Figure 5-2 Main Flowchart for the Duct Analysis Program DCTHCF

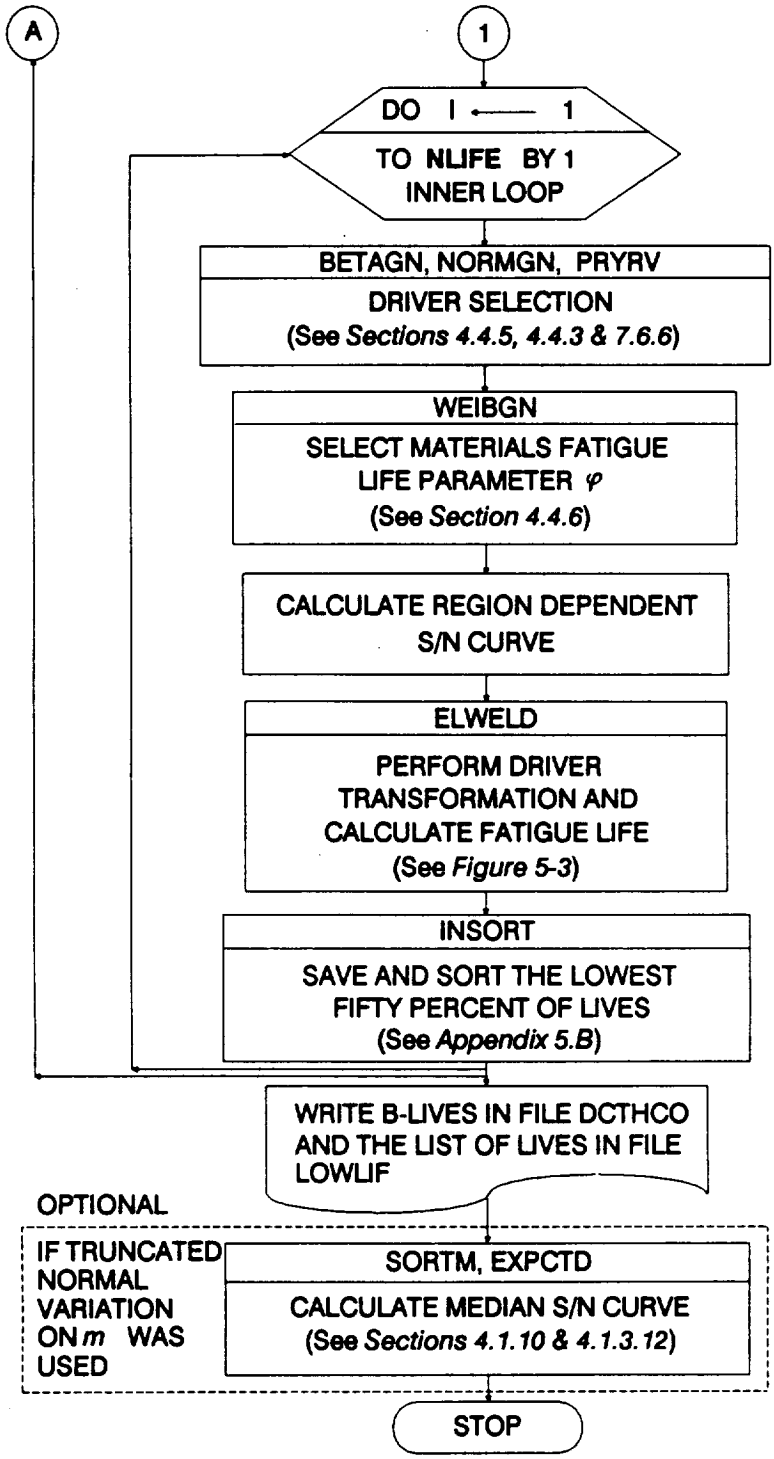

Figure 5-2 Main Flowchart for the Duct Analysis Program DCTHCF (Cont'd)

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.

LOCATION	POSITION	ROUTINE
1	Exterior Surface	M2L1
2	Interior Surface	M2L2

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 β 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 γ_{lz}, γ_{cz}, γ_{ly}, and γ_{cy} 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.

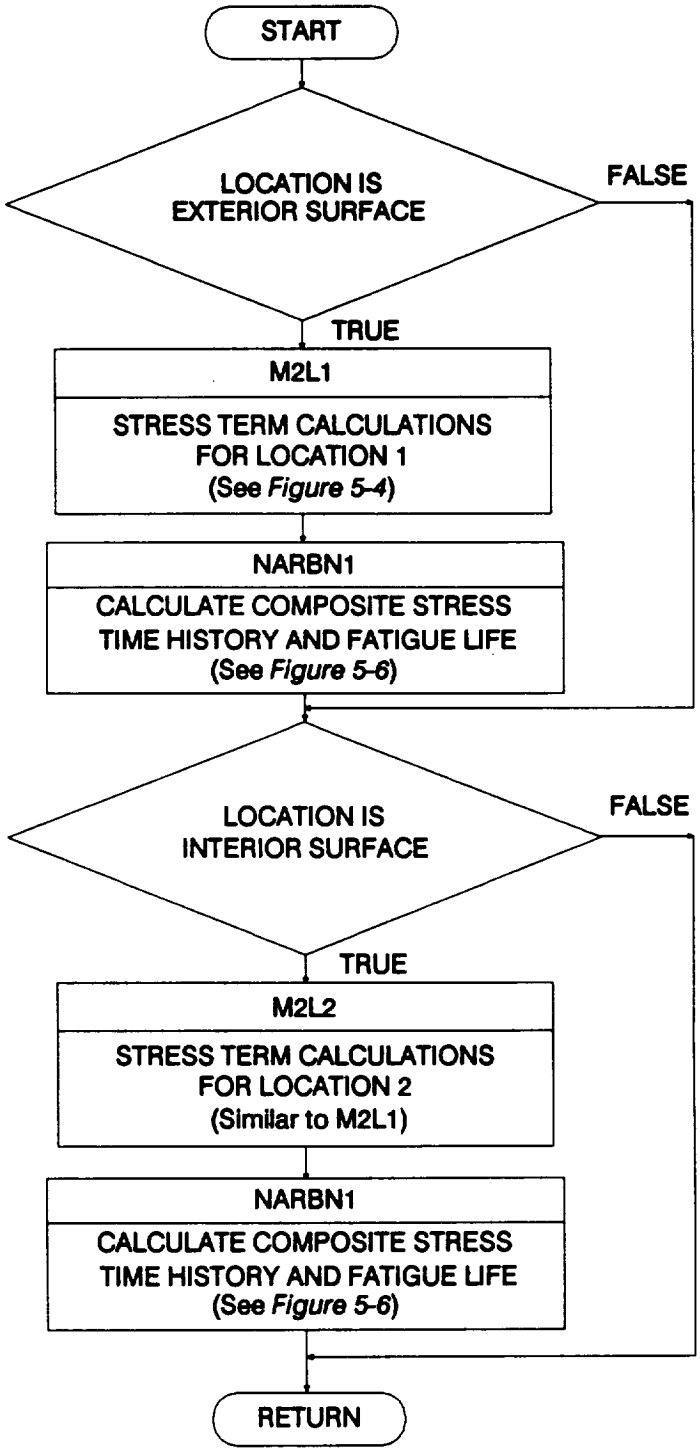

Figure 5-3 Flowchart for the Subprogram ELWELD

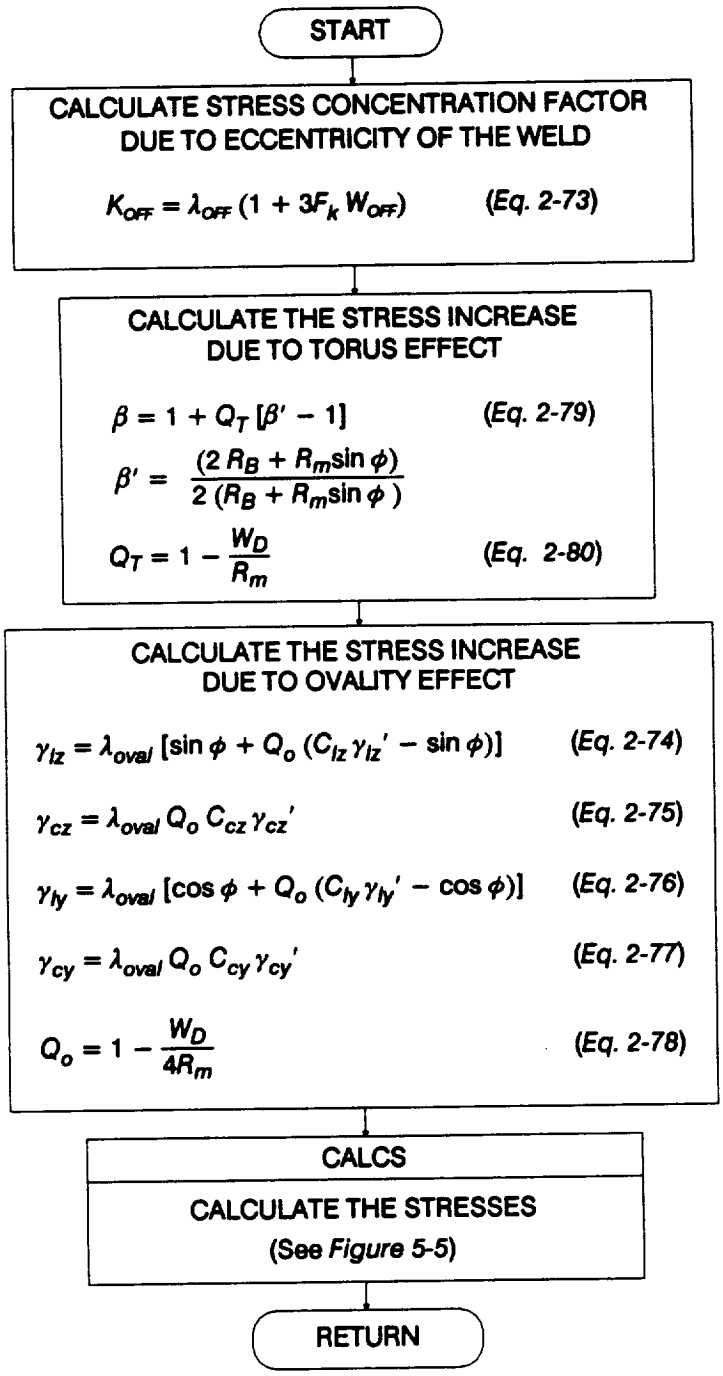

Figure 5-4 Flowchart for the Subprogram M2L1

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 γ_{lz}, γ_{cz}, γ_{ly}, γ_{cy}, and the angular position ϕ. 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 σ_{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

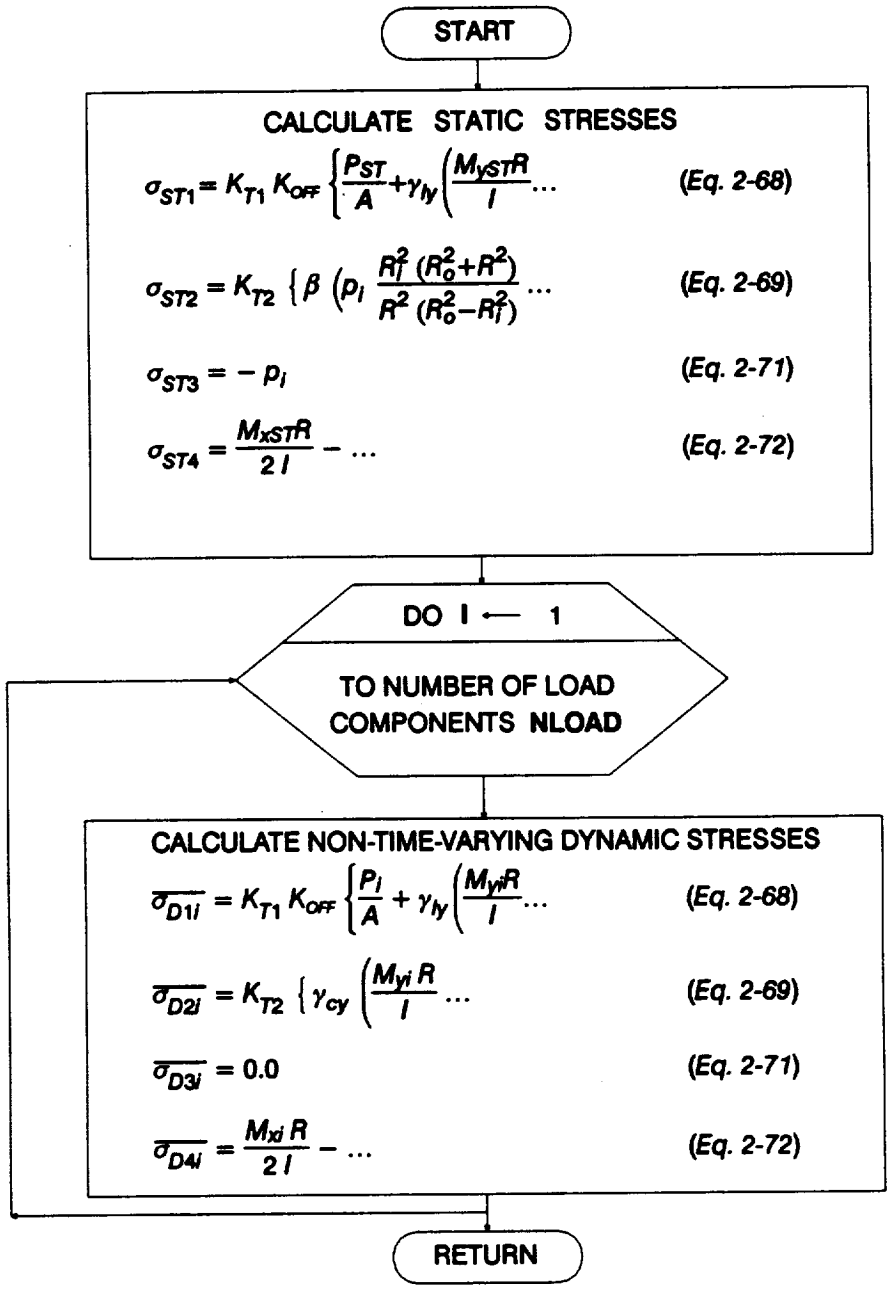

Figure 5-5 Flowchart for the Subprogram CALCS

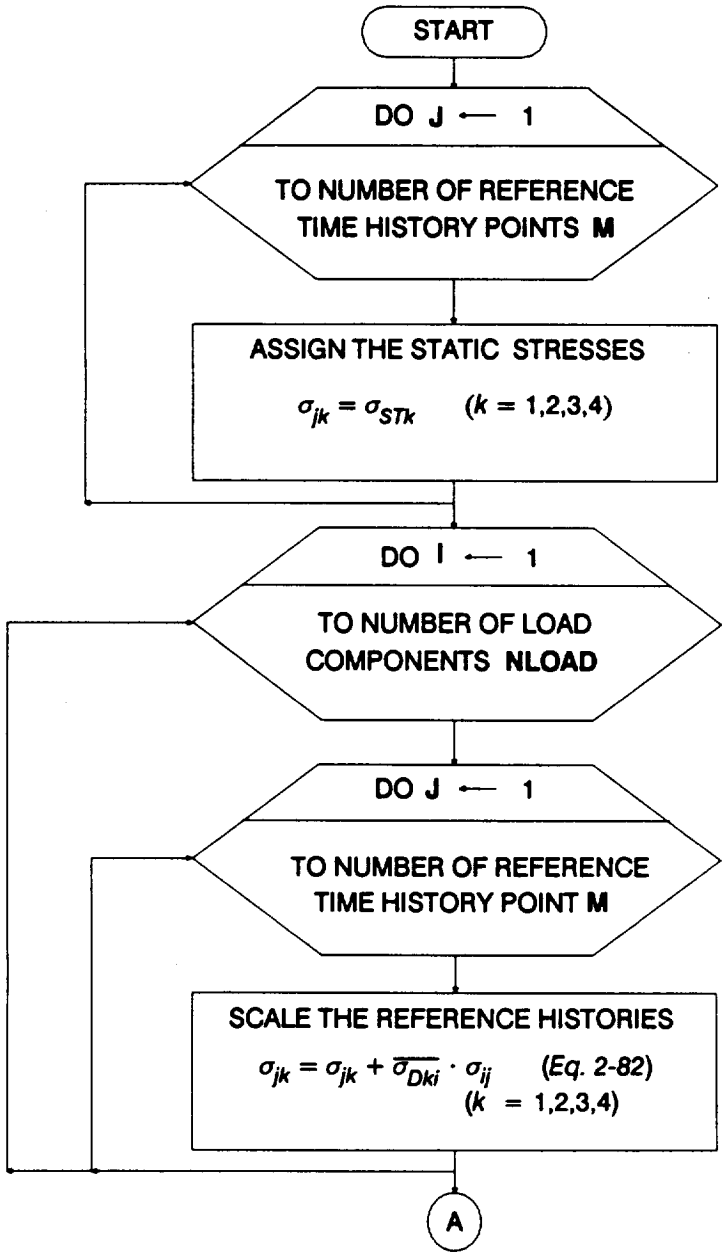

Figure 5-6 Flowchart for the Subprogram NARBN1

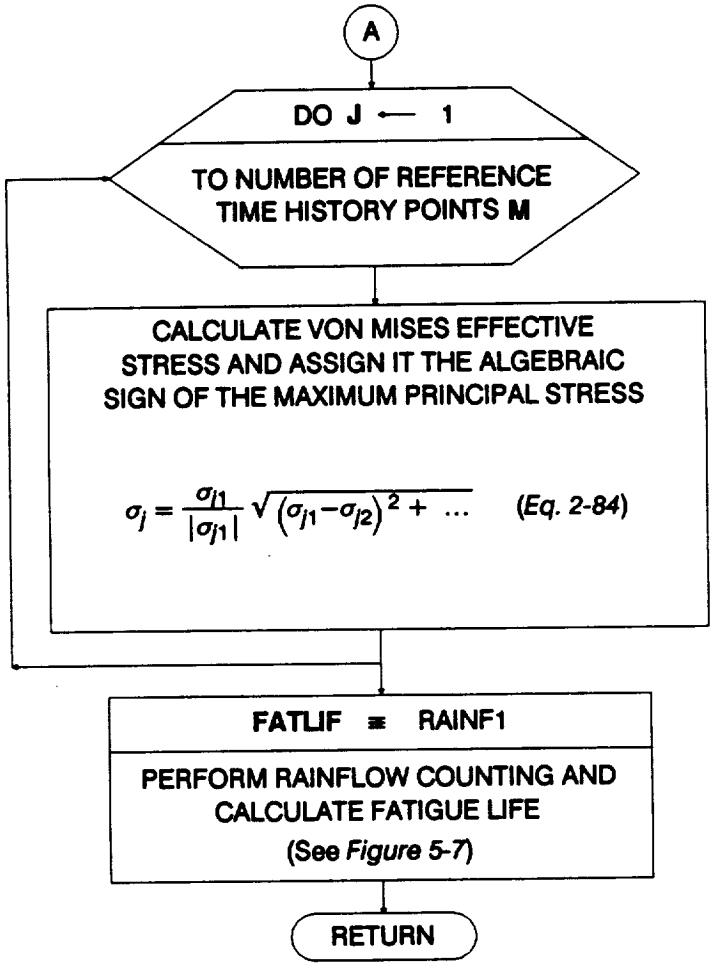

Figure 5-6 Flowchart for the Subprogram NARBN1 (Cont'd)

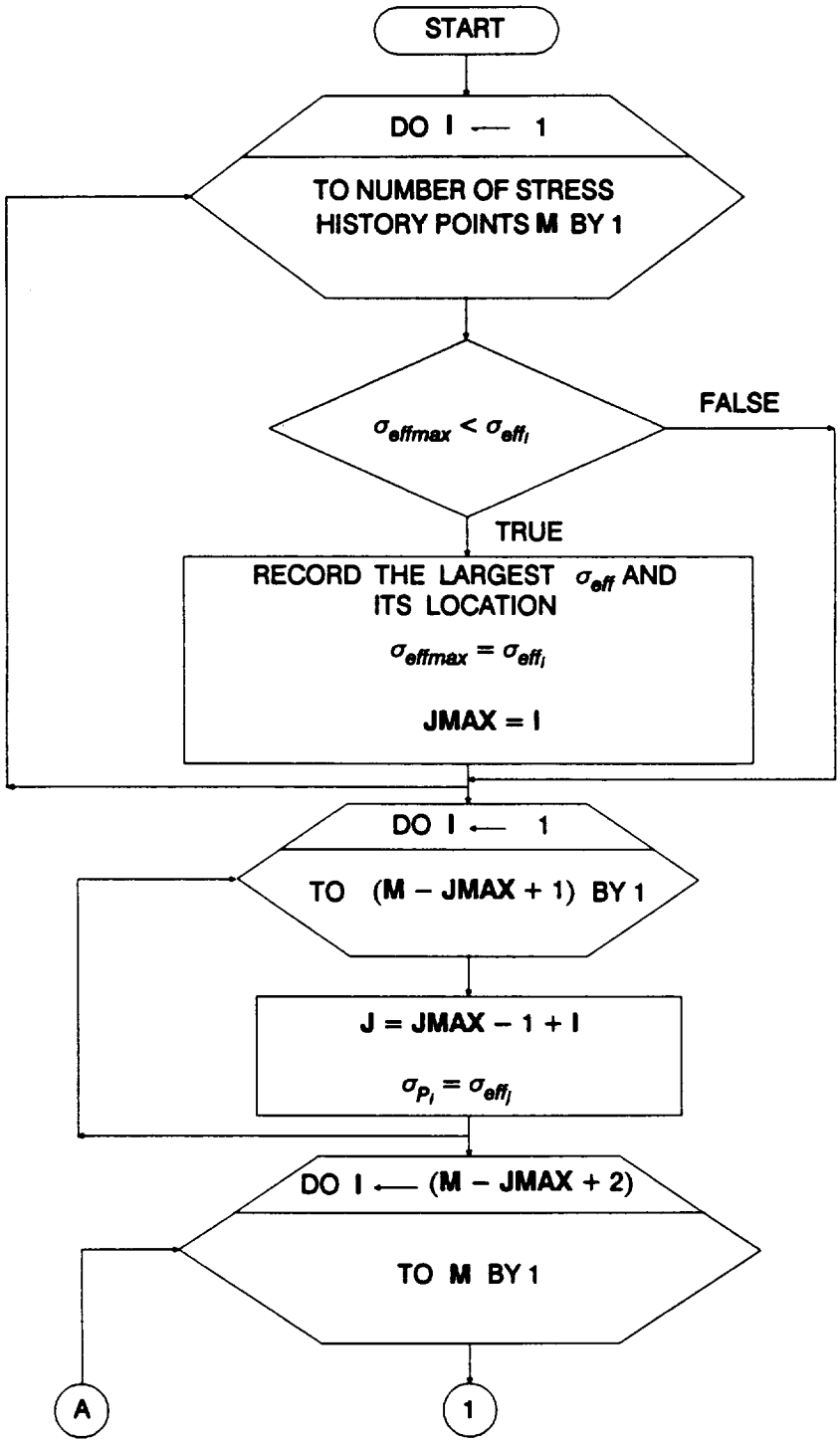

Figure 5-7 Flowchart for Subprogram RAINF1

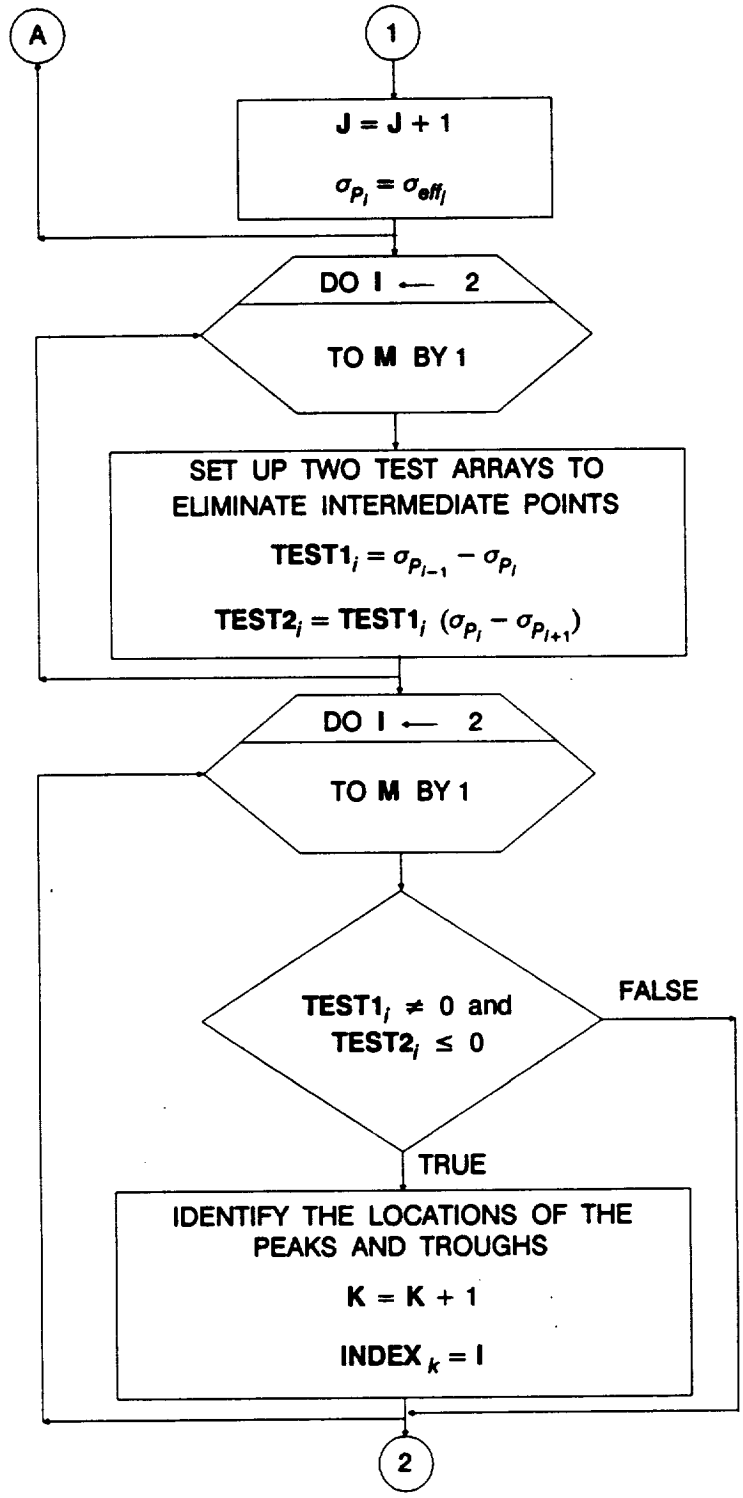

Figure 5-7 Flowchart for Subprogram RAINF1 (Cont'd)

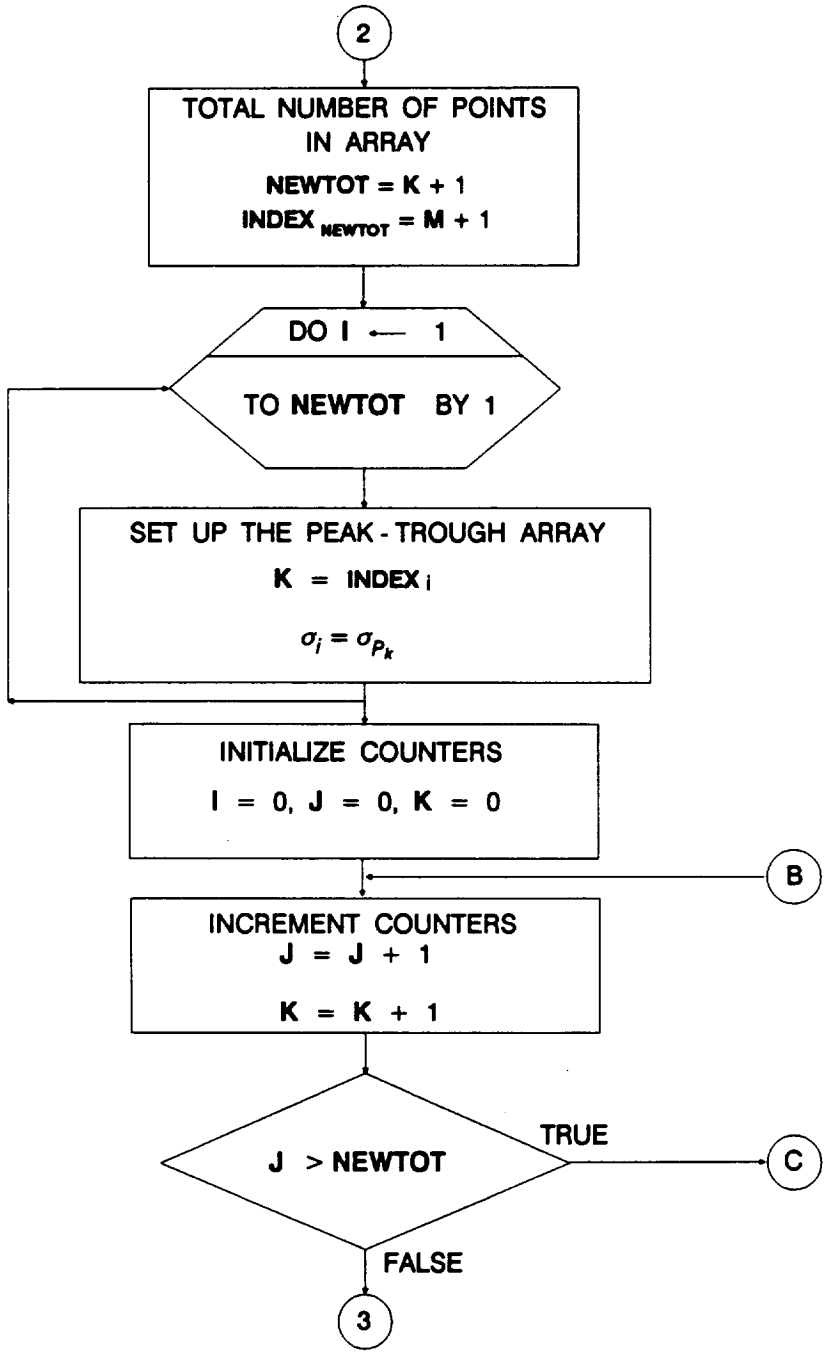

Figure 5-7 Flowchart for Subprogram RAINF1 (Cont'd)

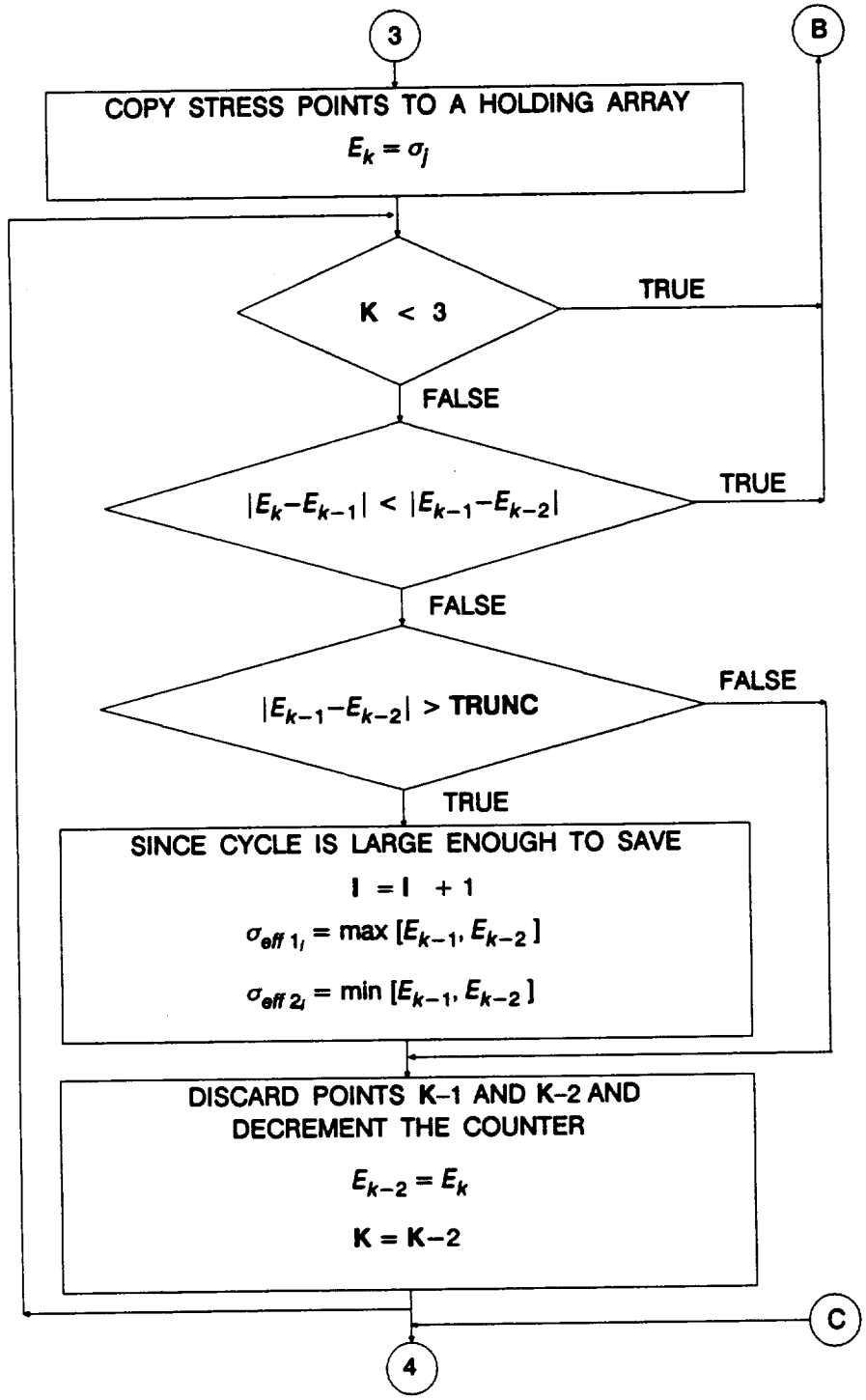

Figure 5-7 Flowchart for Subprogram RAINF1 (Cont'd)

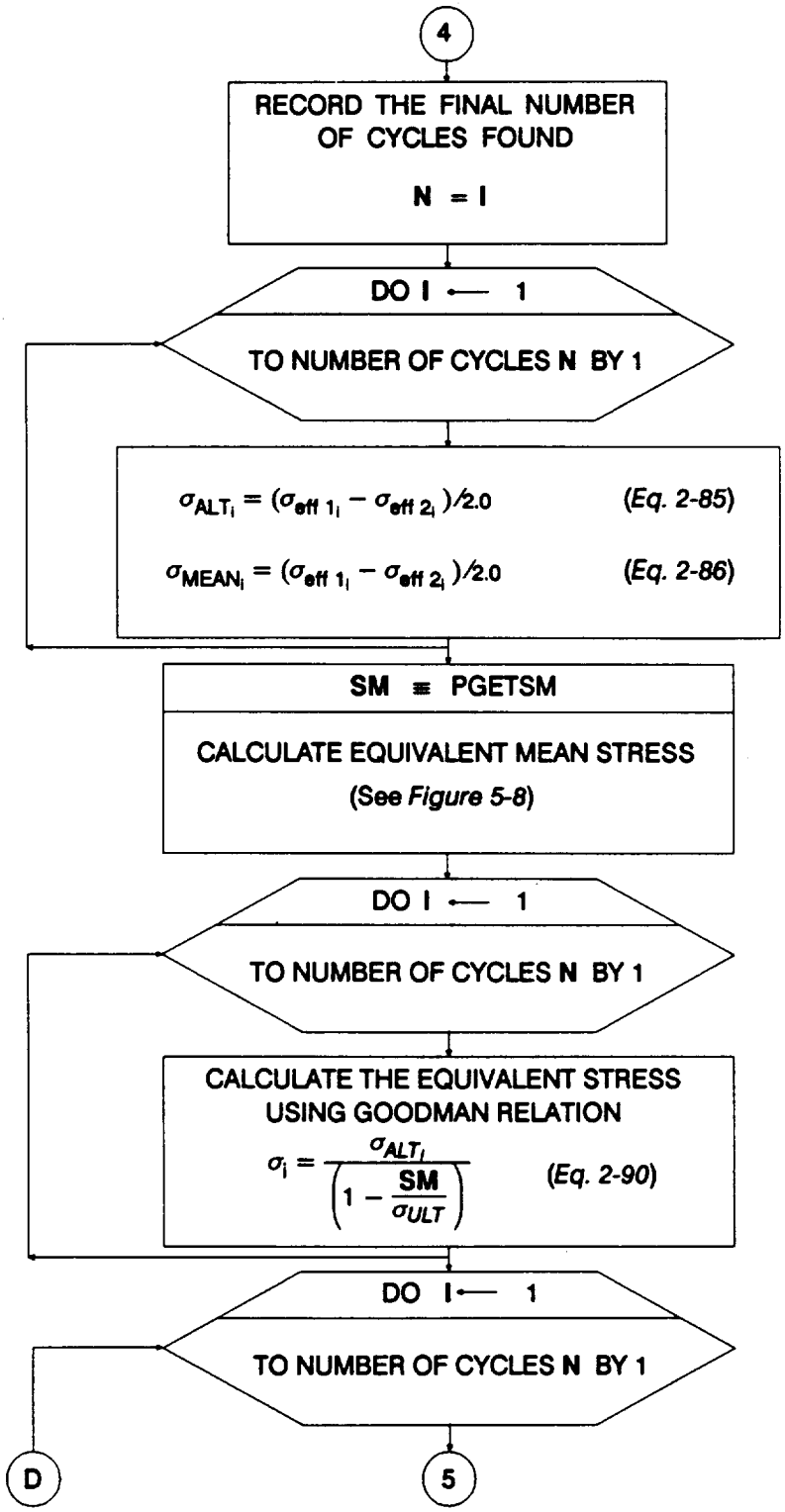

Figure 5-7 Flowchart for Subprogram RAINF1 (Cont'd)

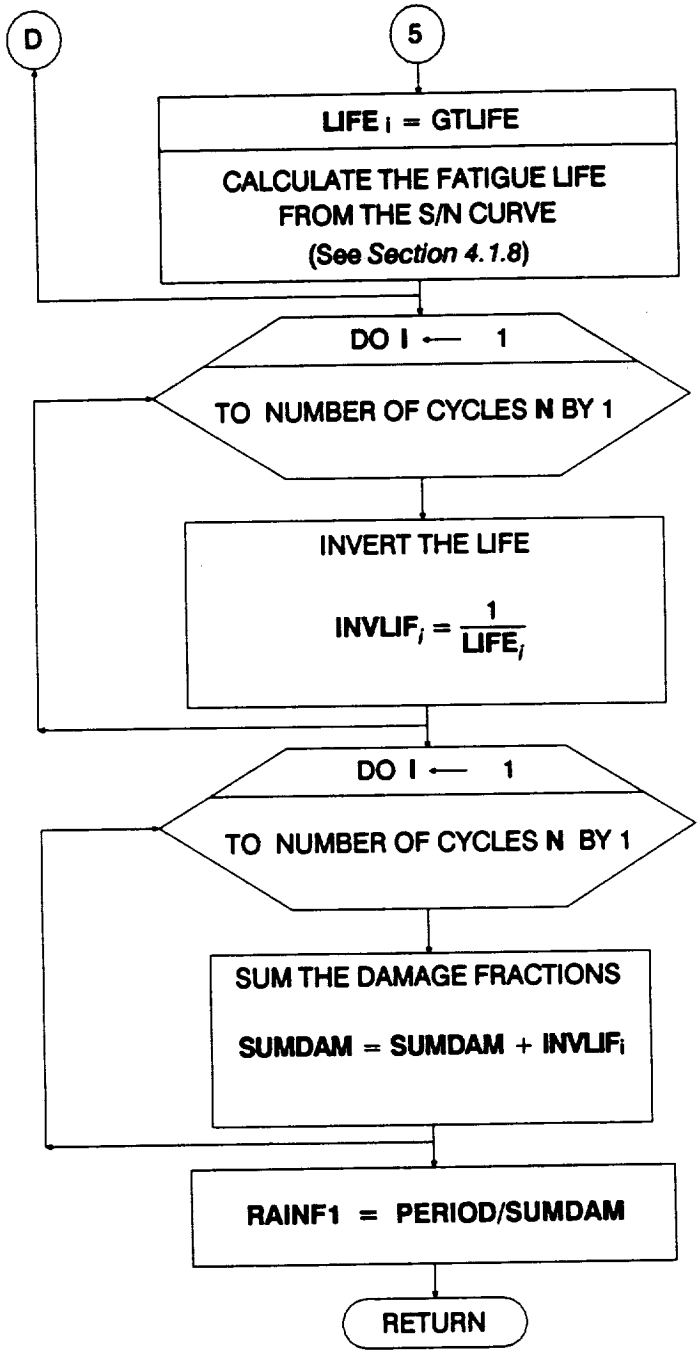

Figure 5-7 Flowchart for Subprogram RAINF1 (Cont'd)

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 HEXHCF Program

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

5.1.3.1 Main Routine

The main flowchart for the HEXHCF program is given in *Figure 5-10.* The program starts by opening the input and output files.[3] They are:

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

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.

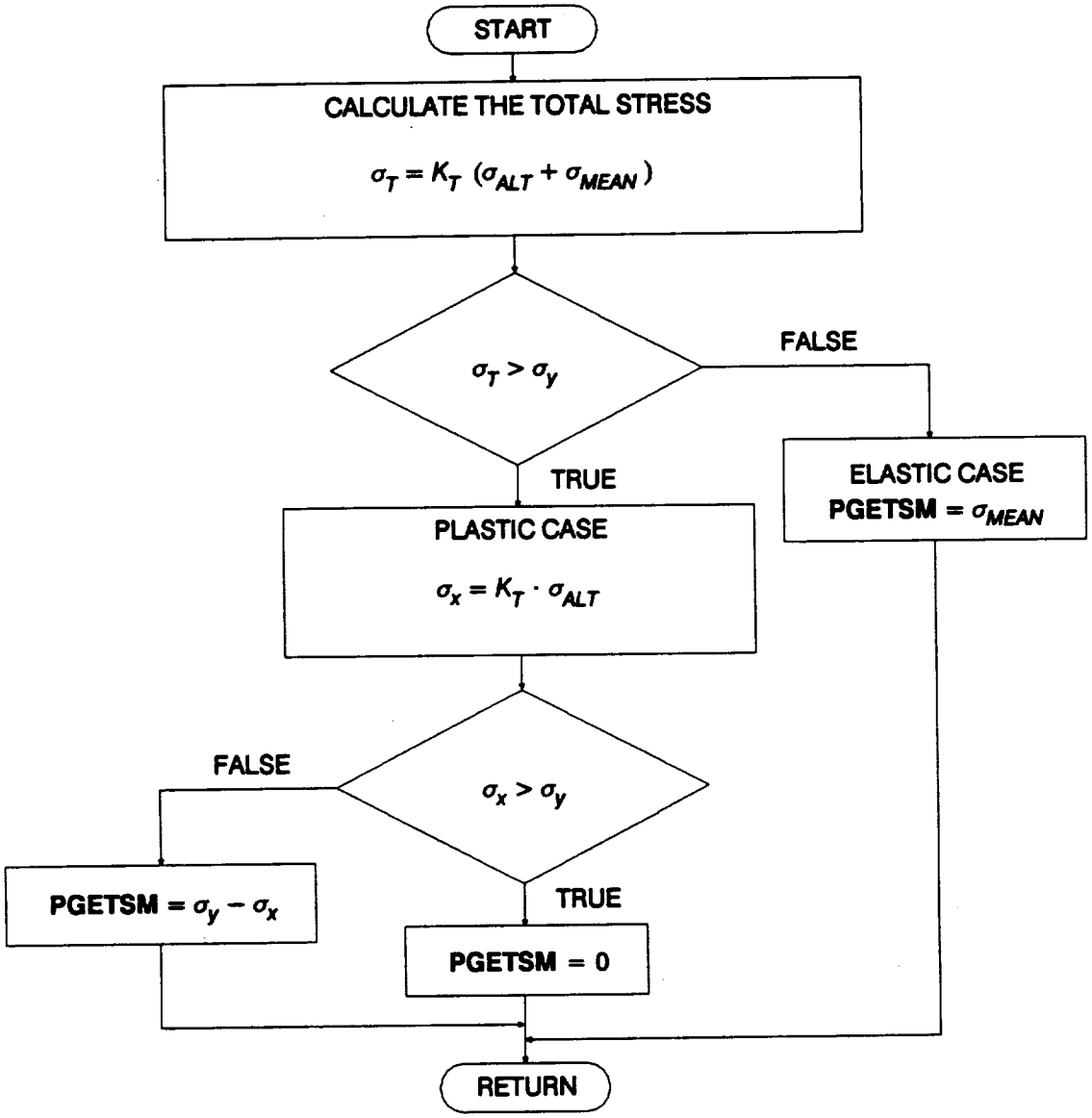

Figure 5-8 Flowchart for Subprogram PGETSM

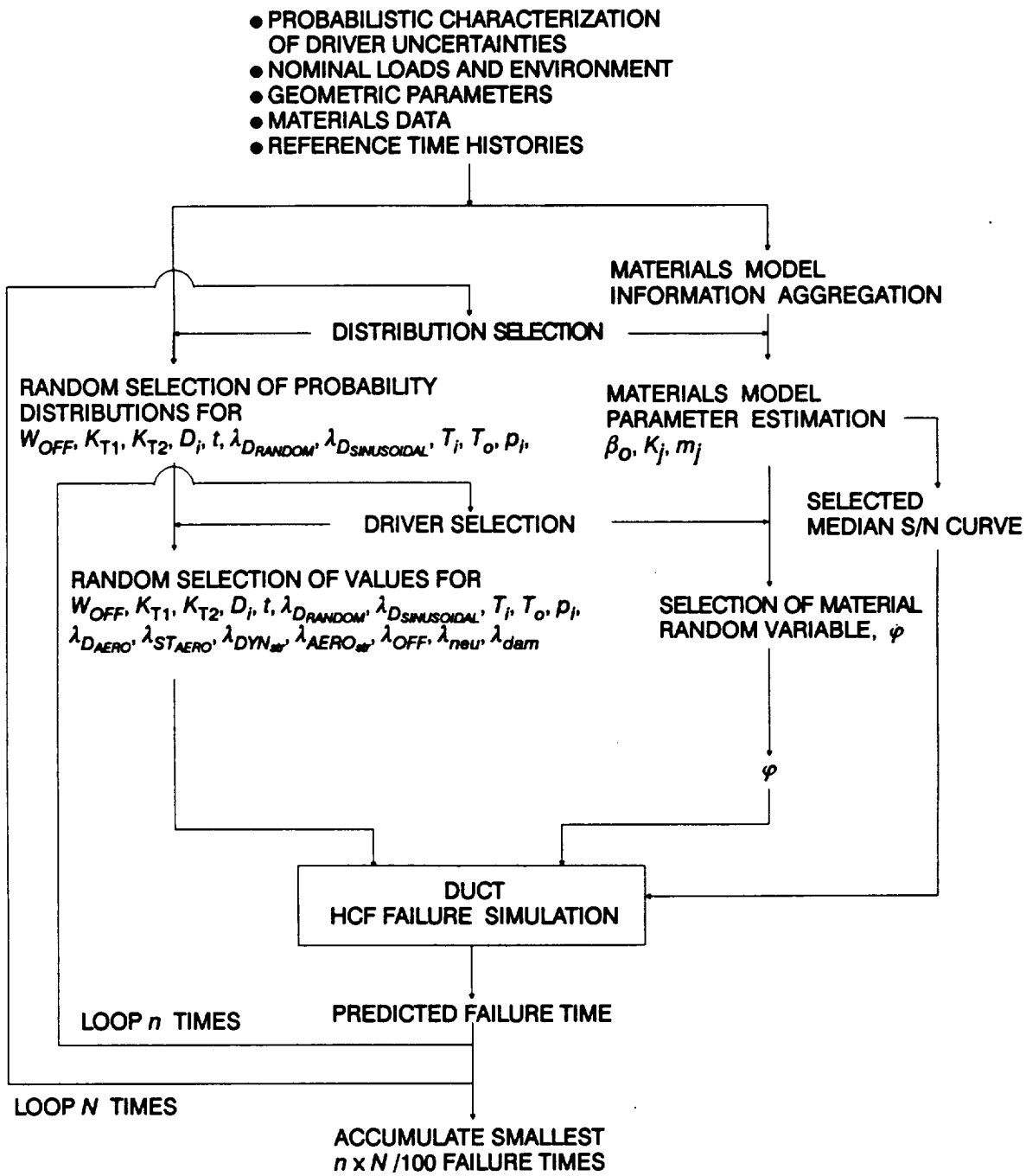

Figure 5-9 Structure of the Probabilistic Failure Model for Straight Ducts with Welds and Temperature Differences Across the Wall

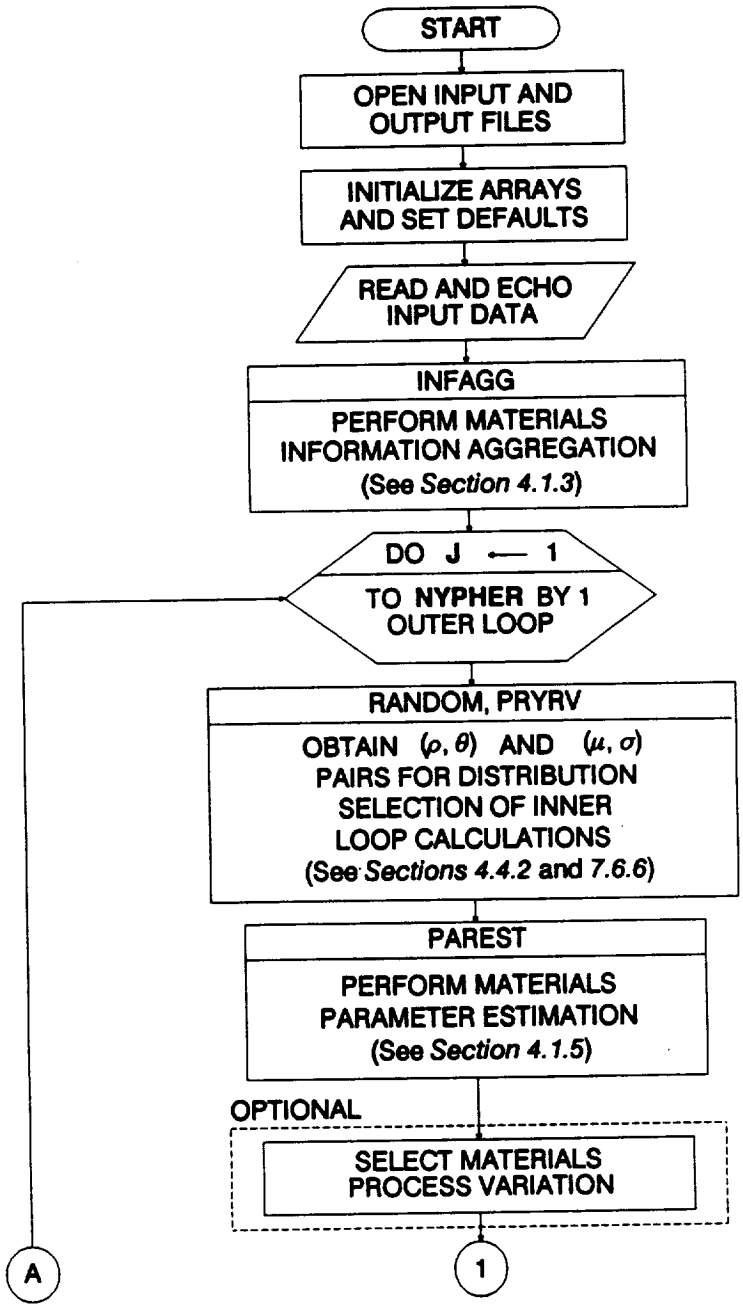

Figure 5-10 Main Flowchart for the HEX Coil Analysis Program HEXHCF

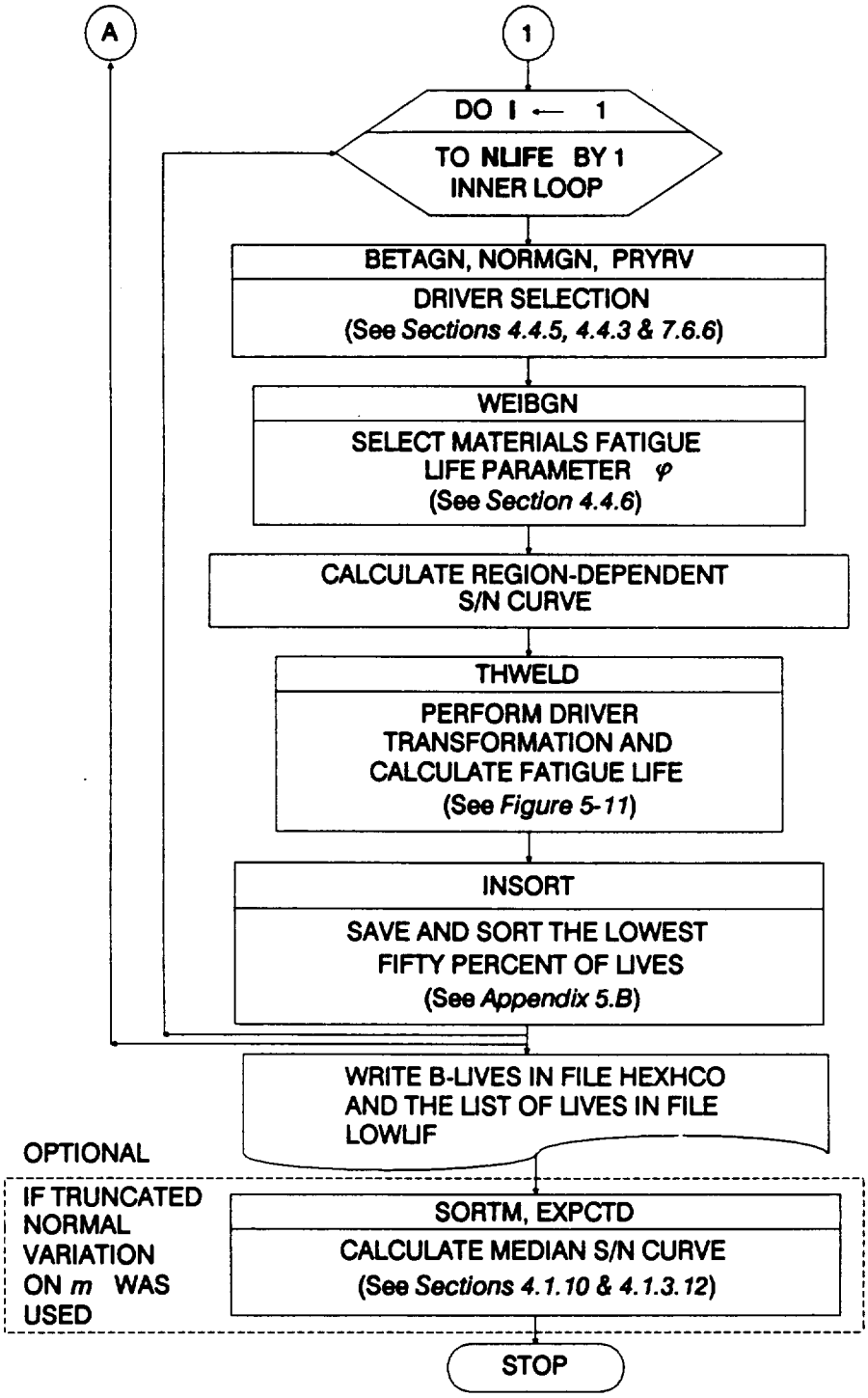

Figure 5-10 Main Flowchart for the HEX Coil Analysis Program HEXHCF (Cont'd)

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 ρ and θ 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.

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[4] Hyperparameters are discussed in *Section 2.1.1.*

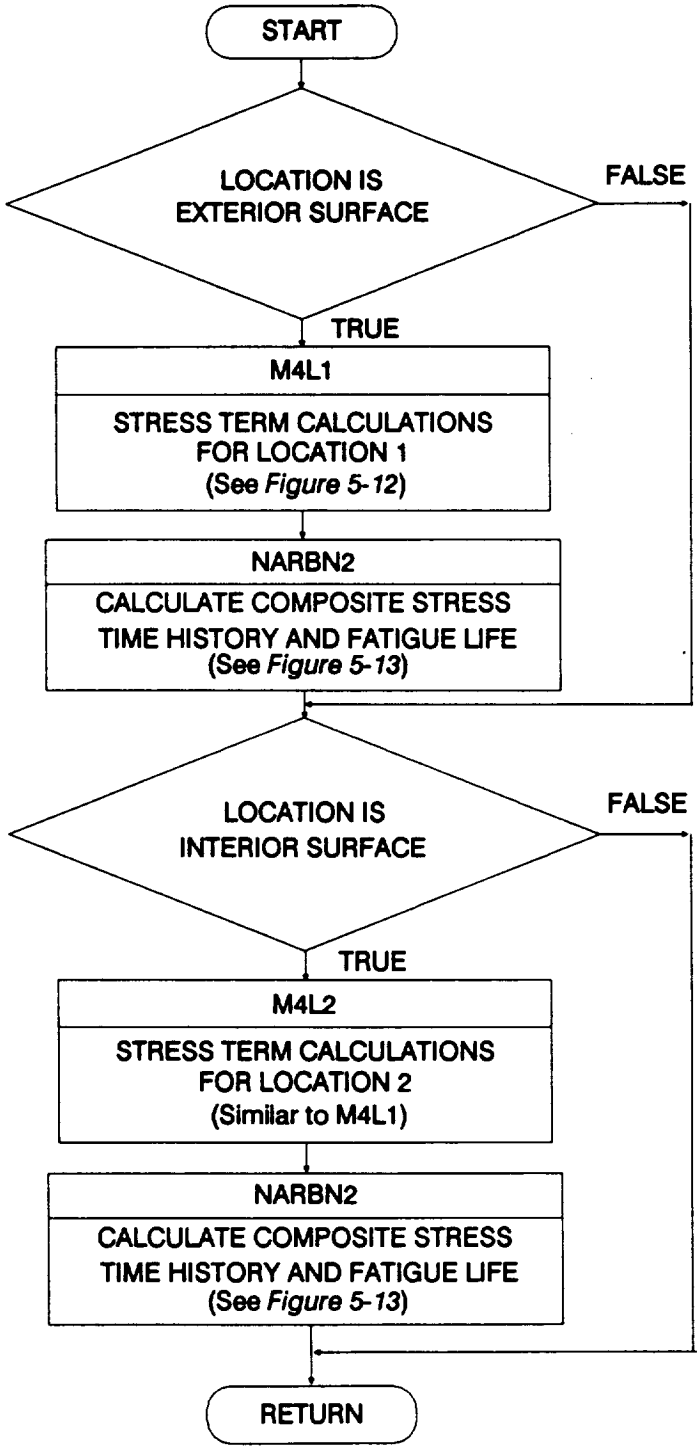

Figure 5-11 Flowchart for Subprogram THWELD

LOCATION	POSITION	ROUTINE
1	Exterior Surface	M4L1
2	Interior Surface	M4L2

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 $\gamma_{lz} = \sin\phi$, $\gamma_{ly} = \cos\phi$, $\gamma_{cz} = \gamma_{cy} = 0$, 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 ΔT.

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.

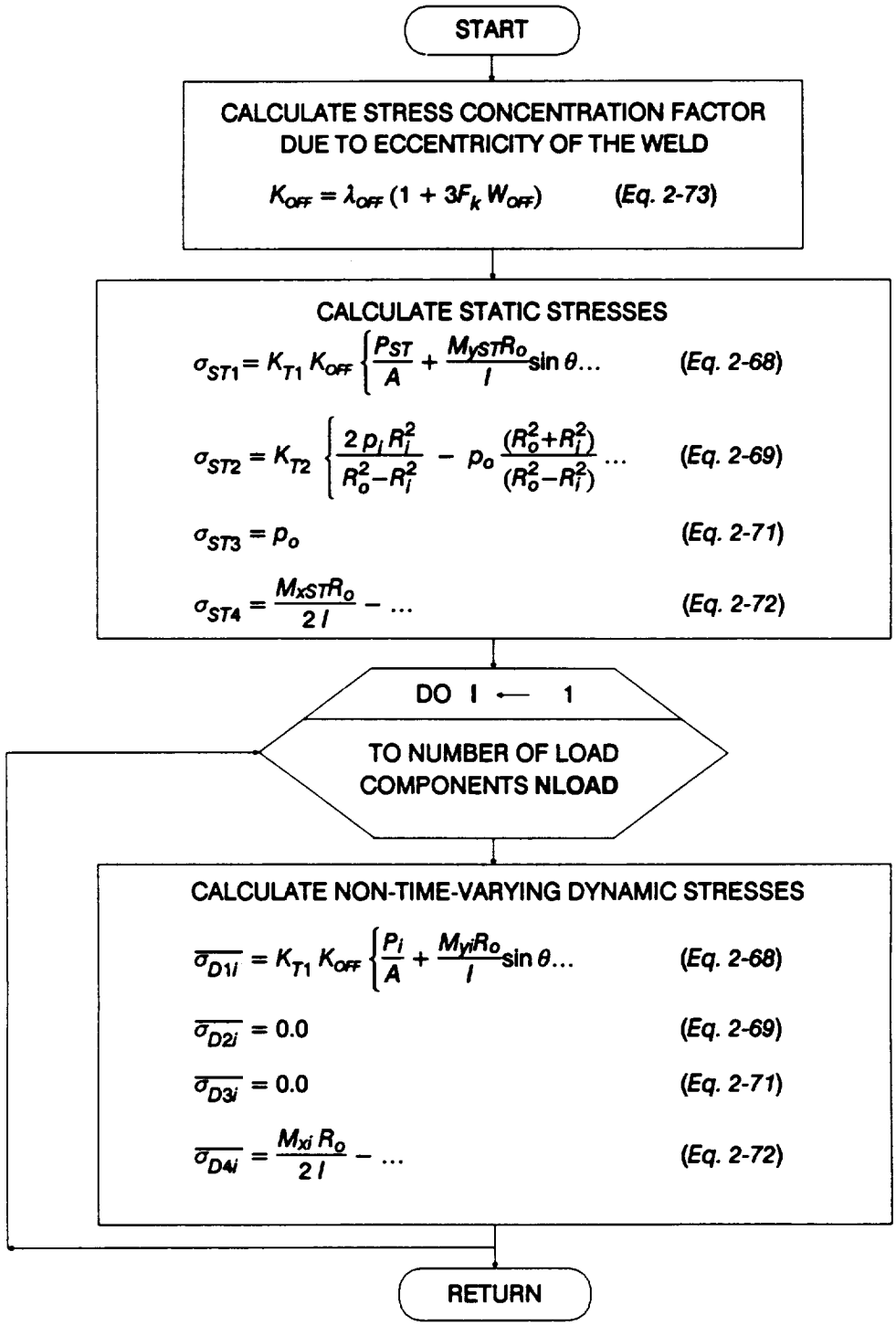

Figure 5-12 Flowchart for Subprogram M4L1

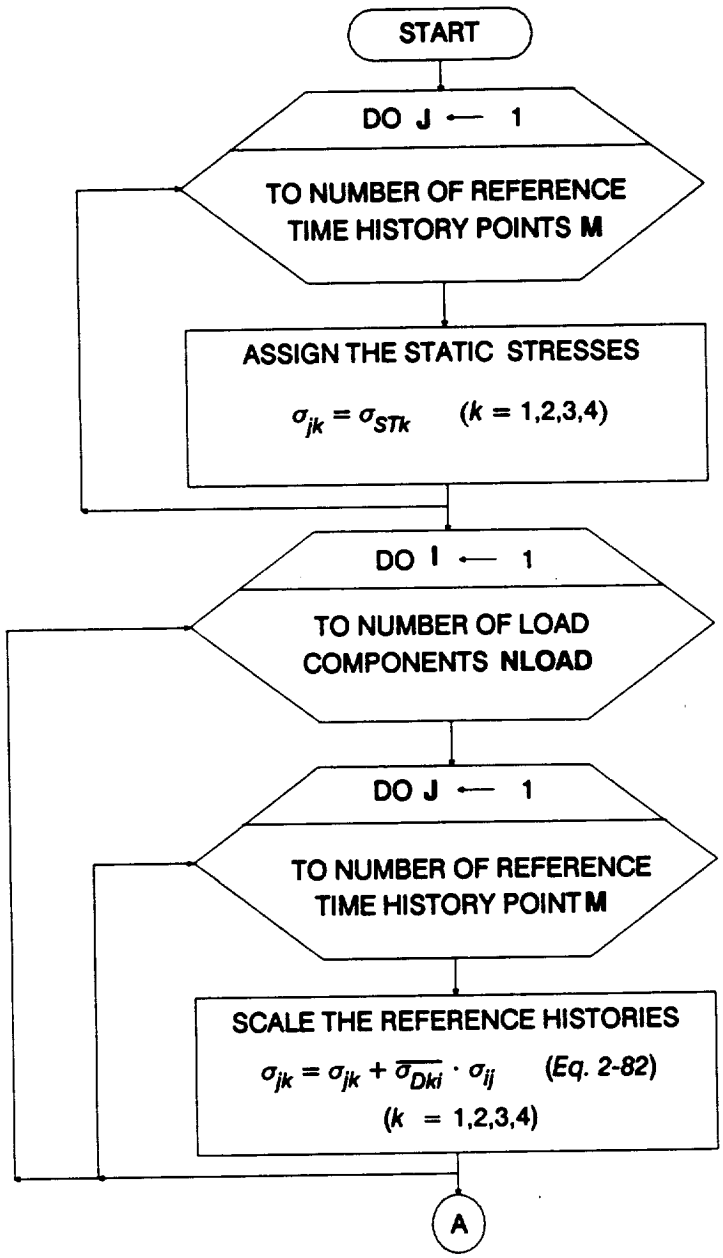

Figure 5-13 Flowchart for the Subprogram NARBN2

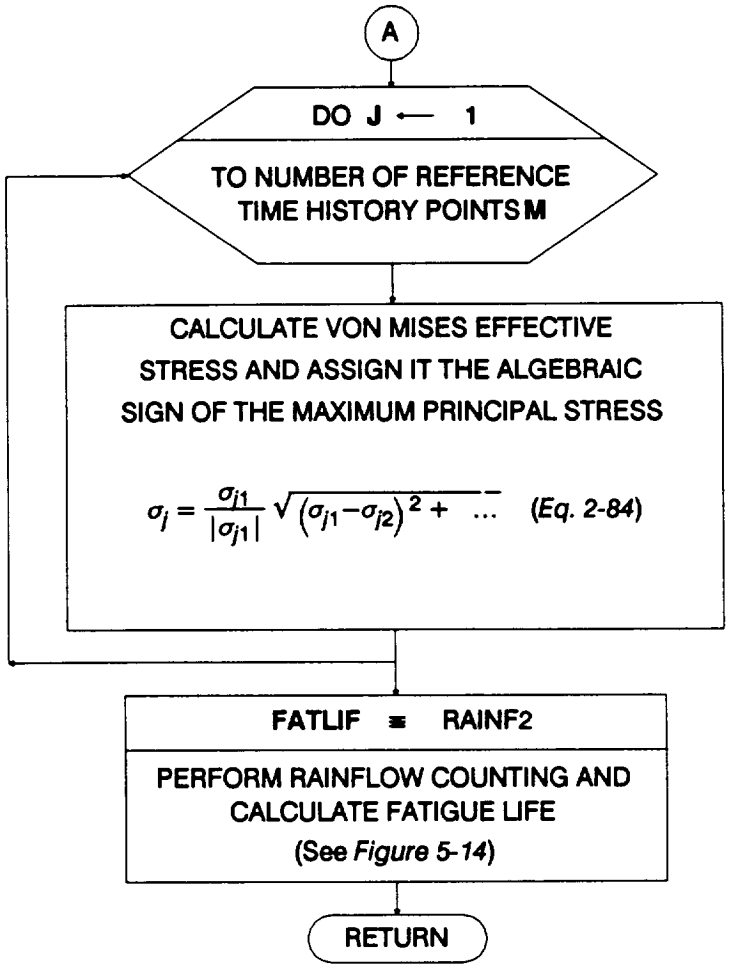

Figure 5-13 Flowchart for Subprogram NARBN2 (Cont'd)

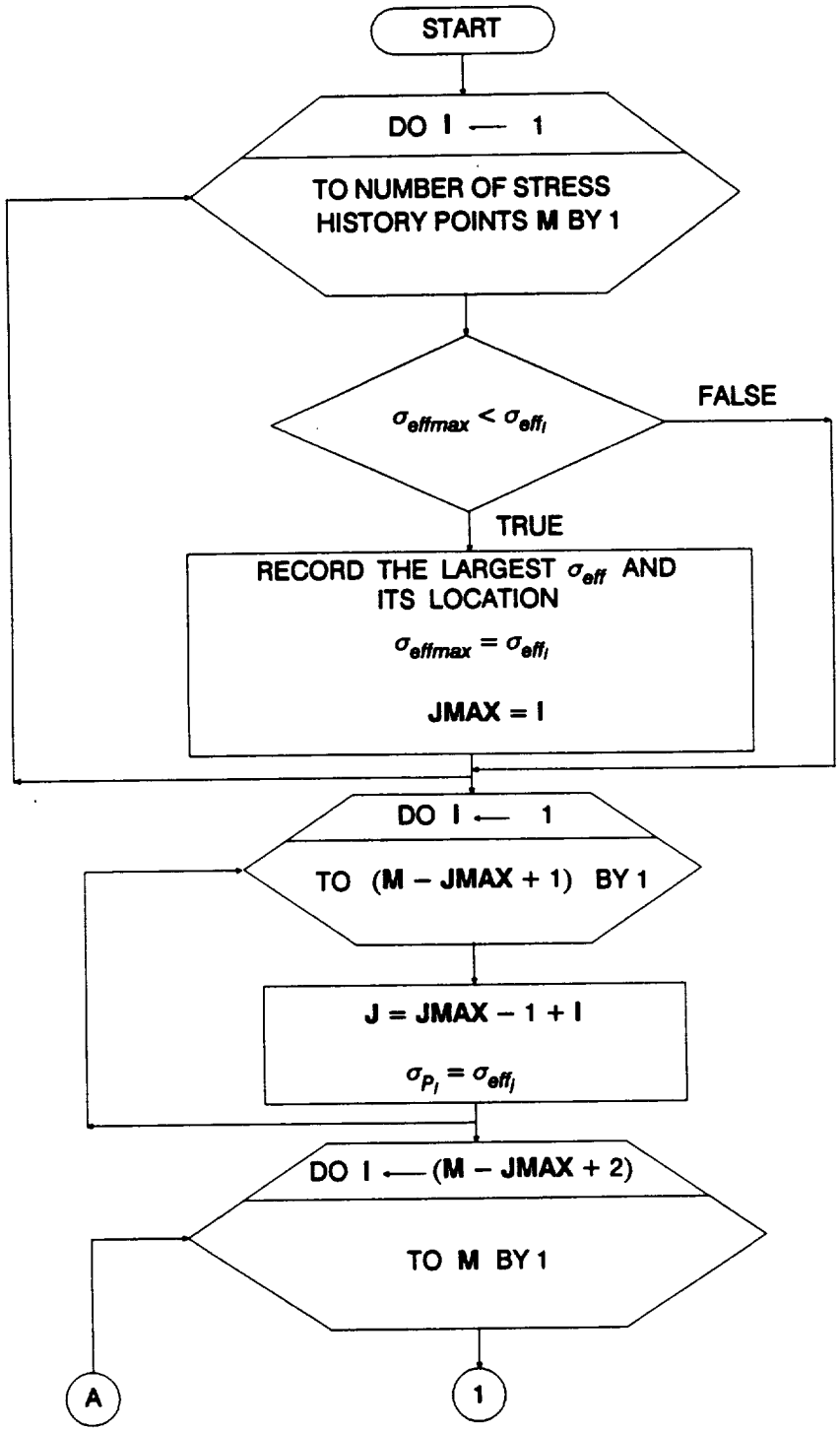

Figure 5-14 Flowchart for Subprogram RAINF2

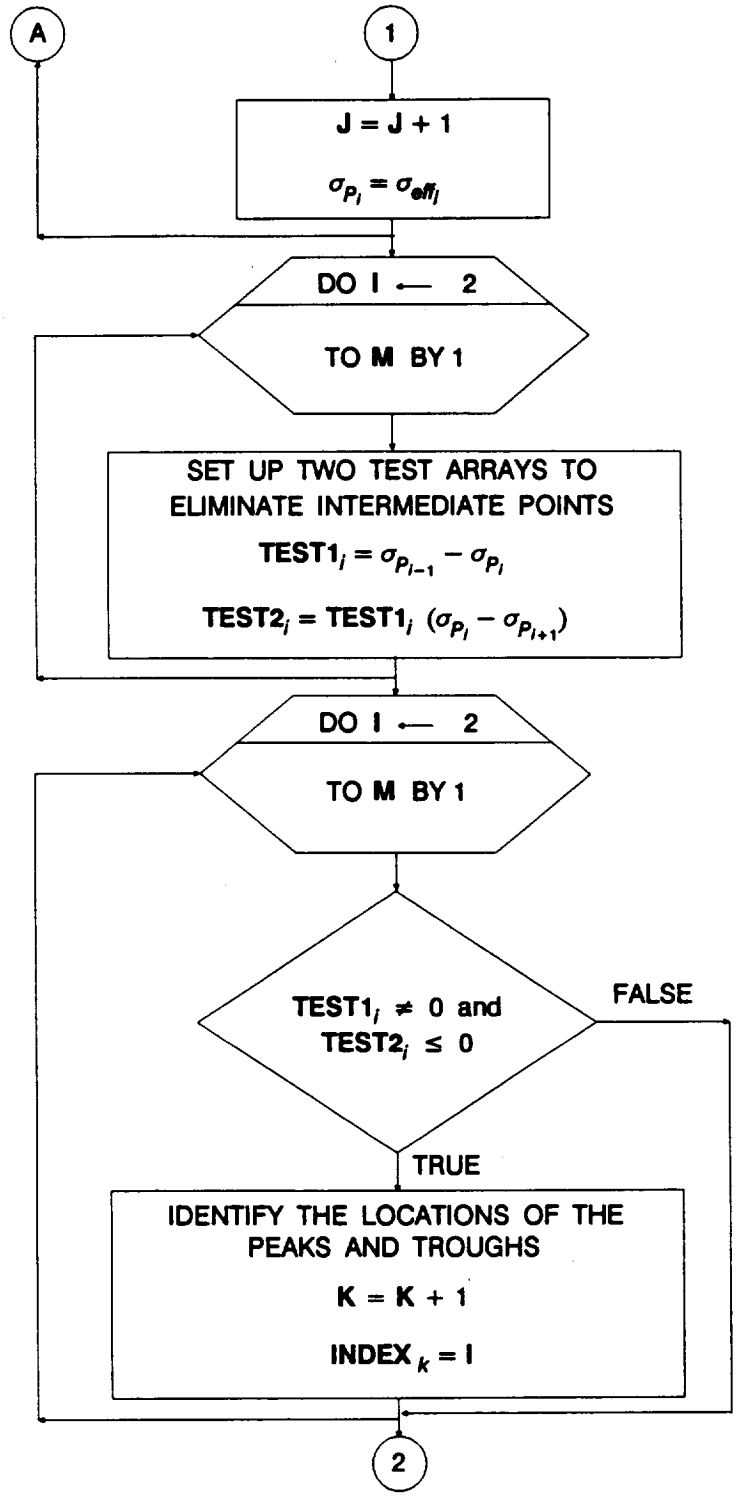

Figure 5-14 Flowchart for Subprogram RAINF2 (Cont'd)

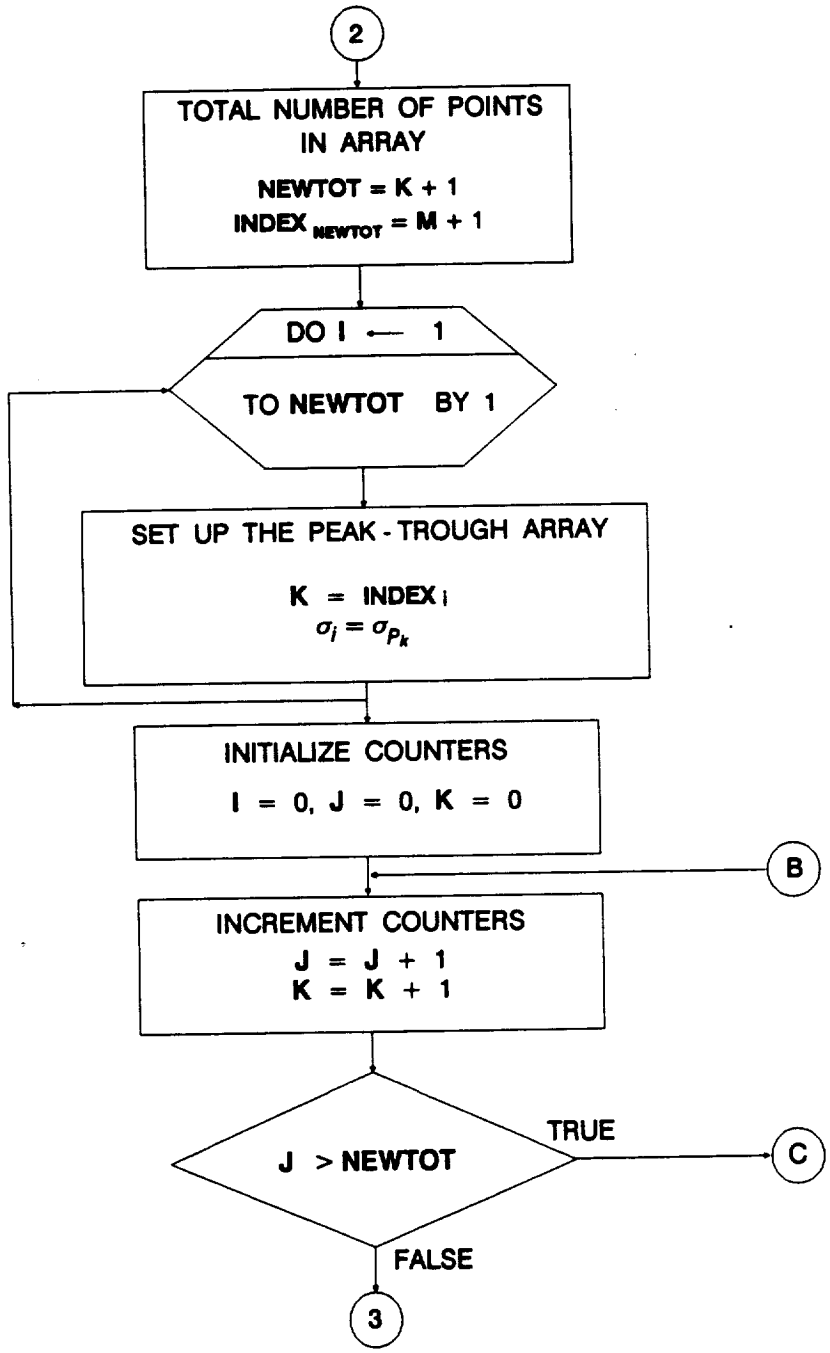

Figure 5-14 Flowchart for Subprogram RAINF2 (Cont'd)

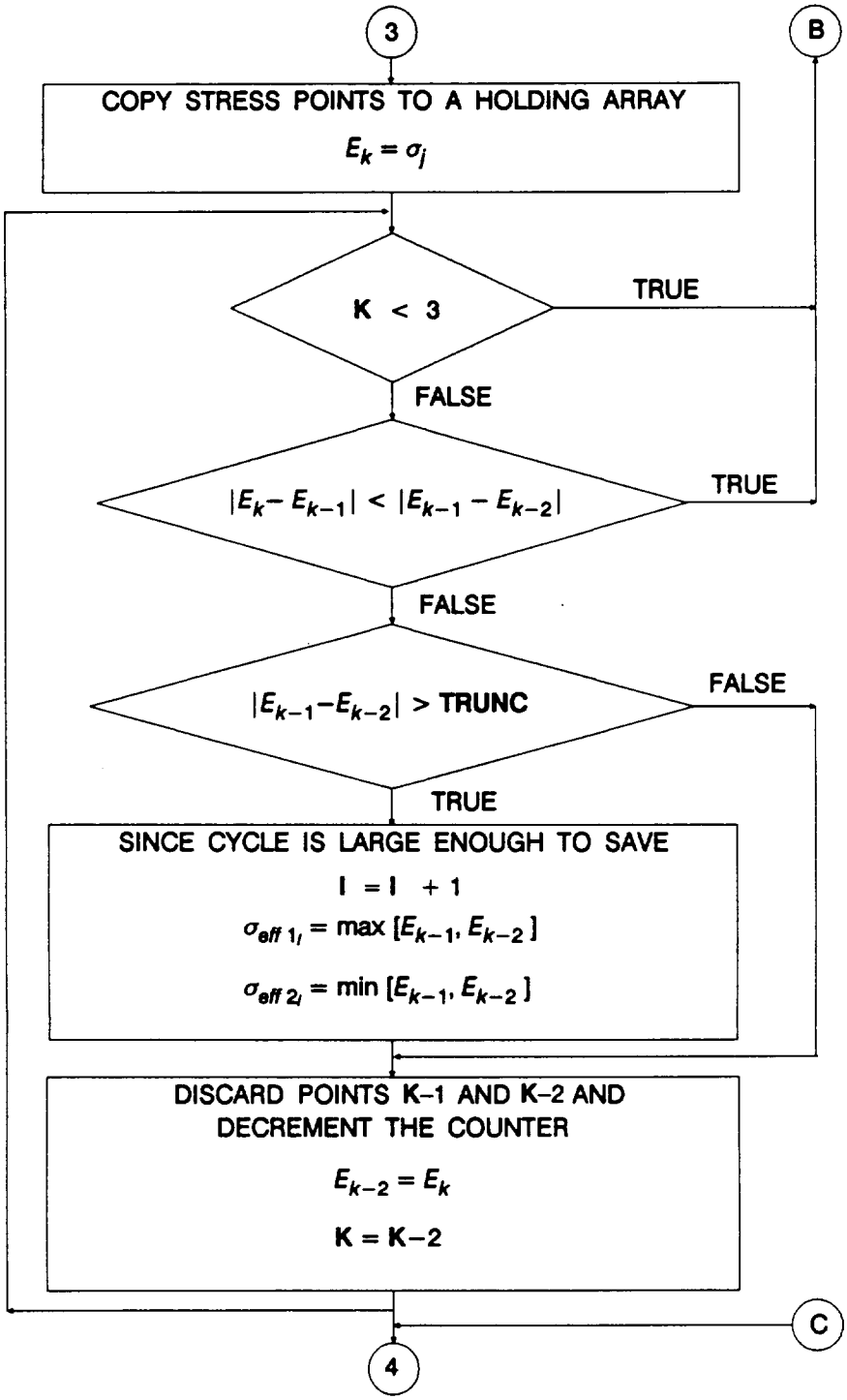

Figure 5-14 Flowchart for Subprogram RAINF2 (Cont'd)

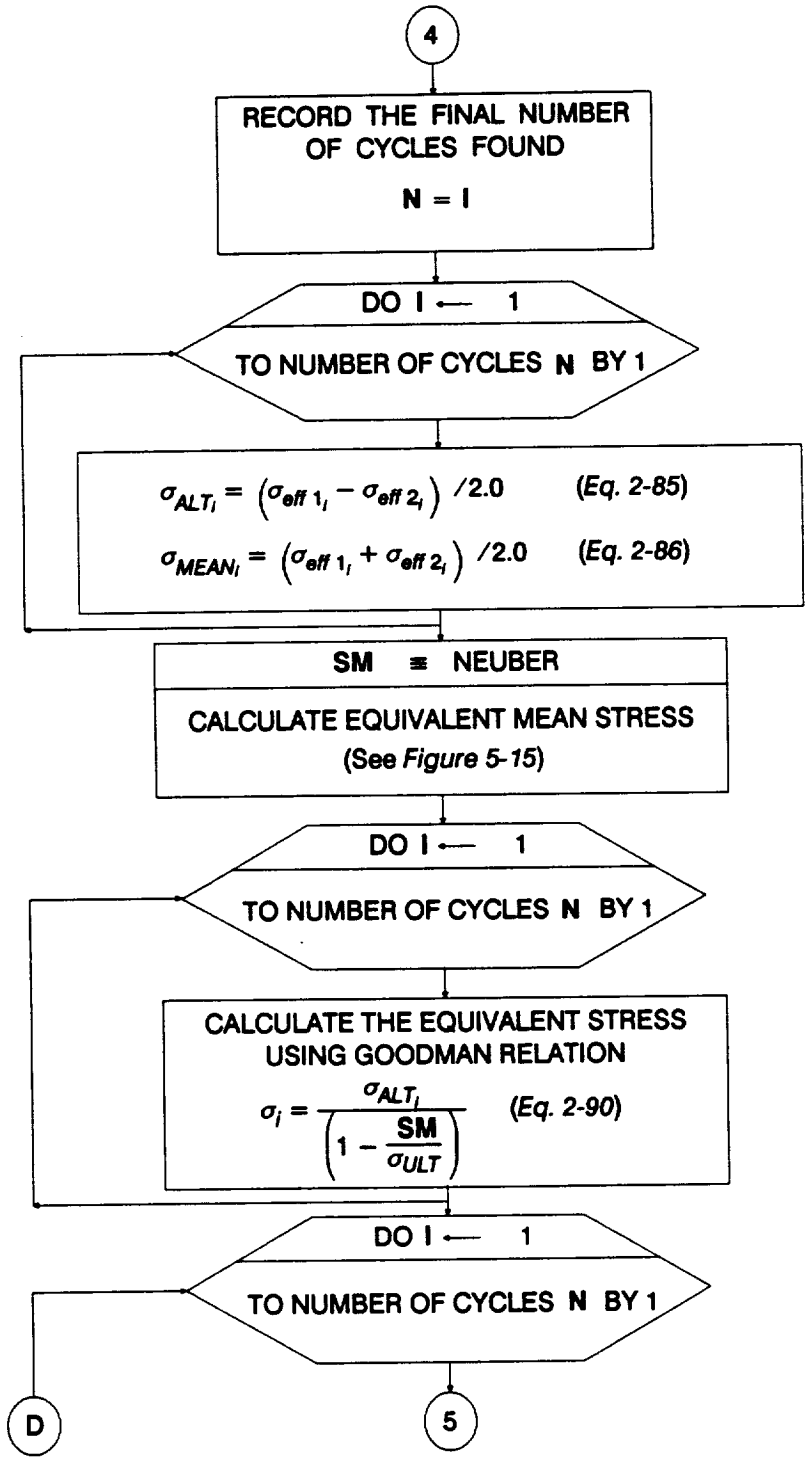

Figure 5-14 Flowchart for Subprogram RAINF2 (Cont'd)

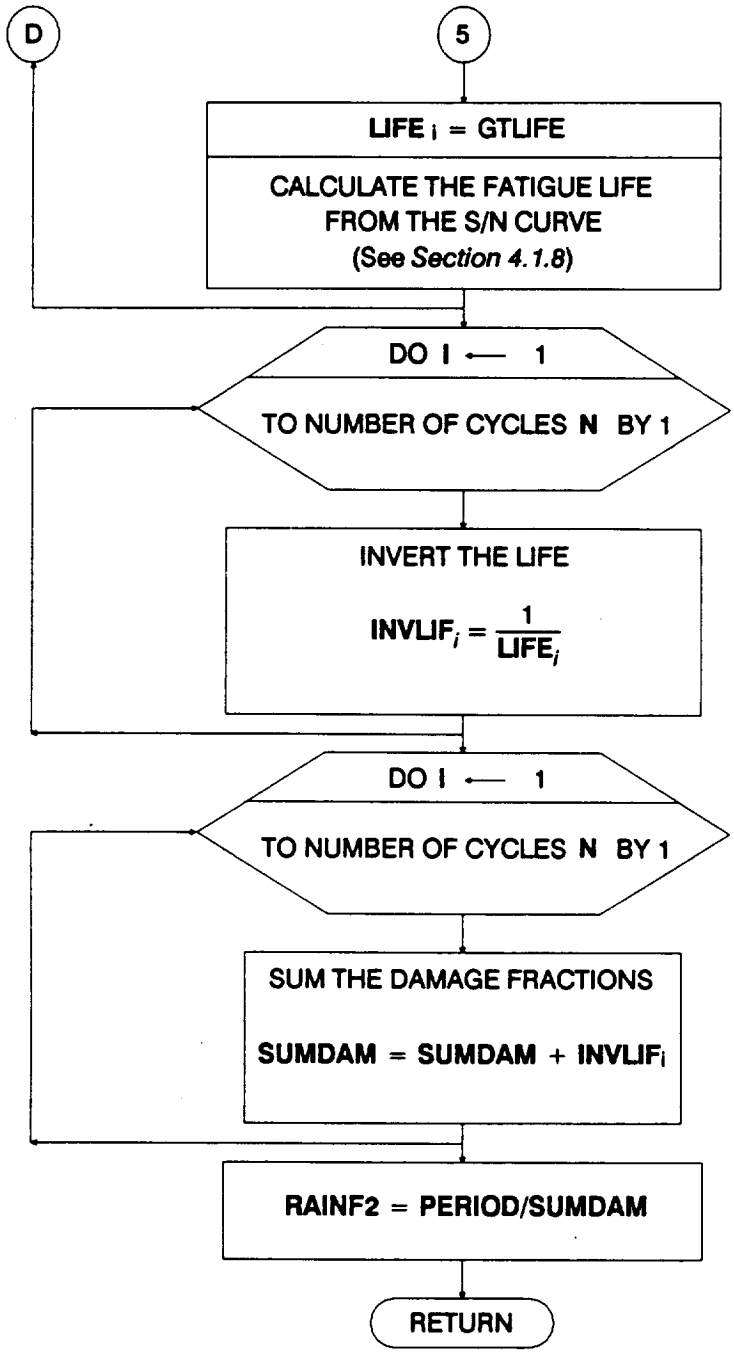

Figure 5-14 Flowchart for Subprogram RAINF2 (Cont'd)

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.*

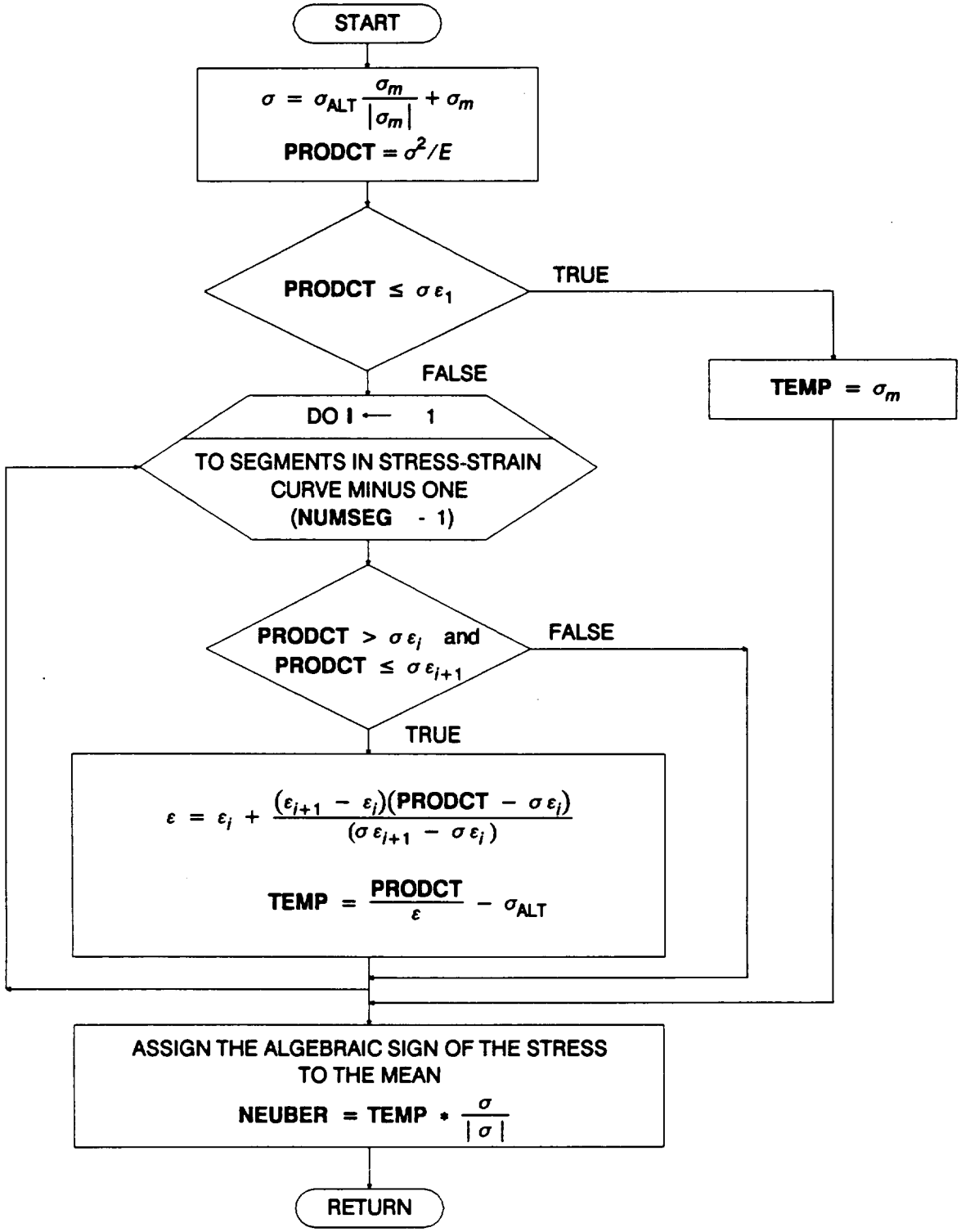

Figure 5-15 Flowchart for Subprogram NEUBER

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:[5]

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

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.

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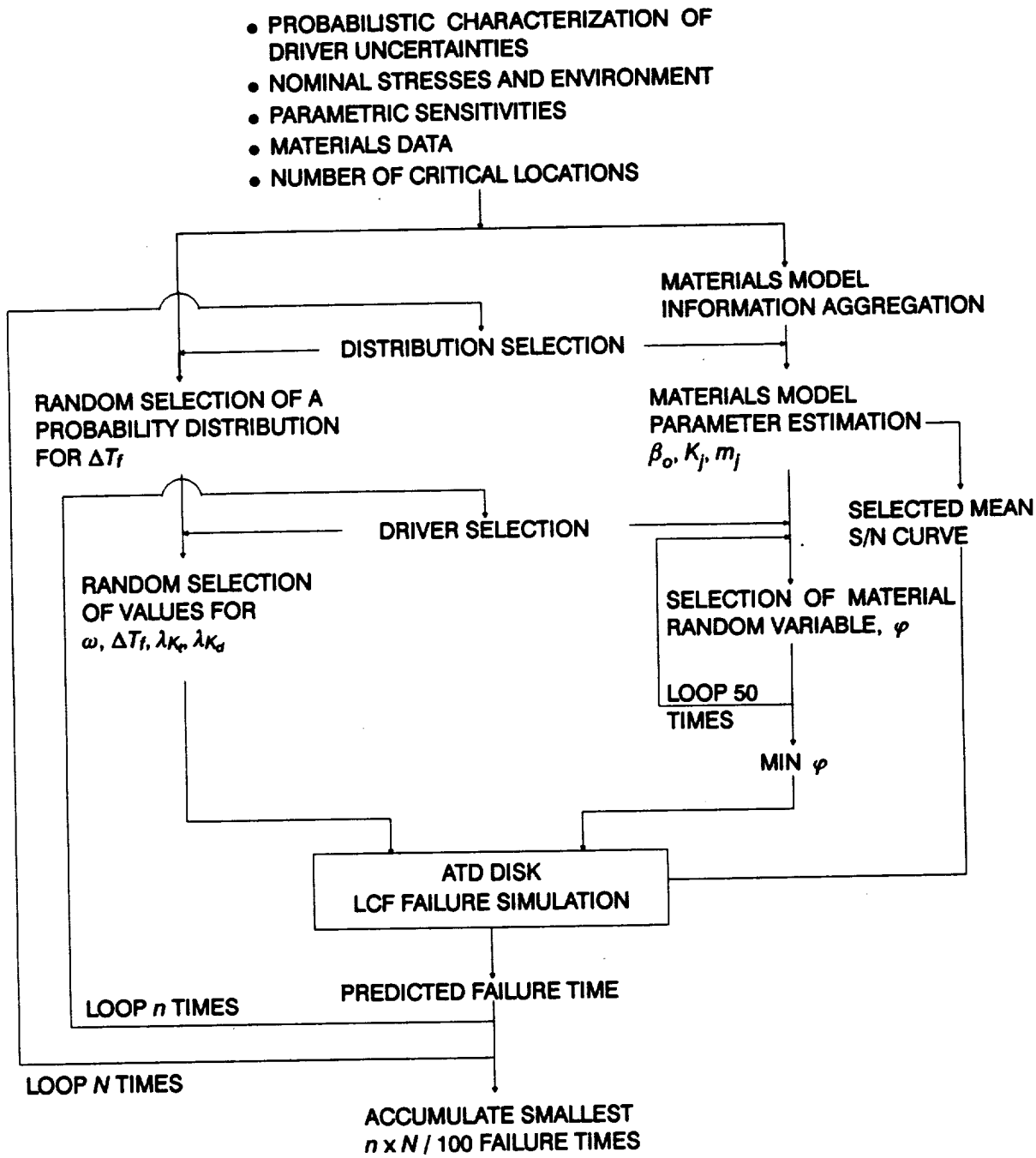

Figure 5-16 Structure of the Probabilistic Failure Model for the ATD-HPFTP Second Stage Turbine Disk

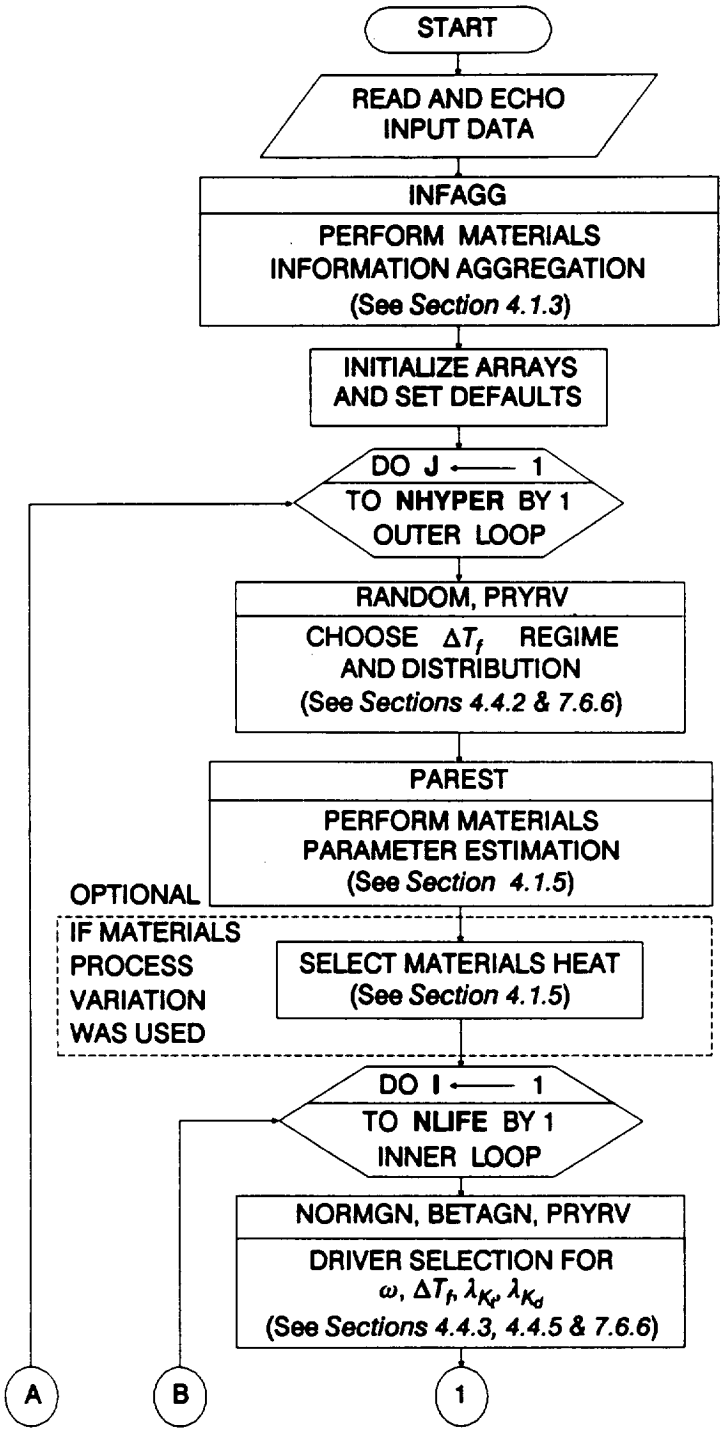

Figure 5-17 Main Flowchart for the ATD Disk LCF Analysis Program TRBPWA

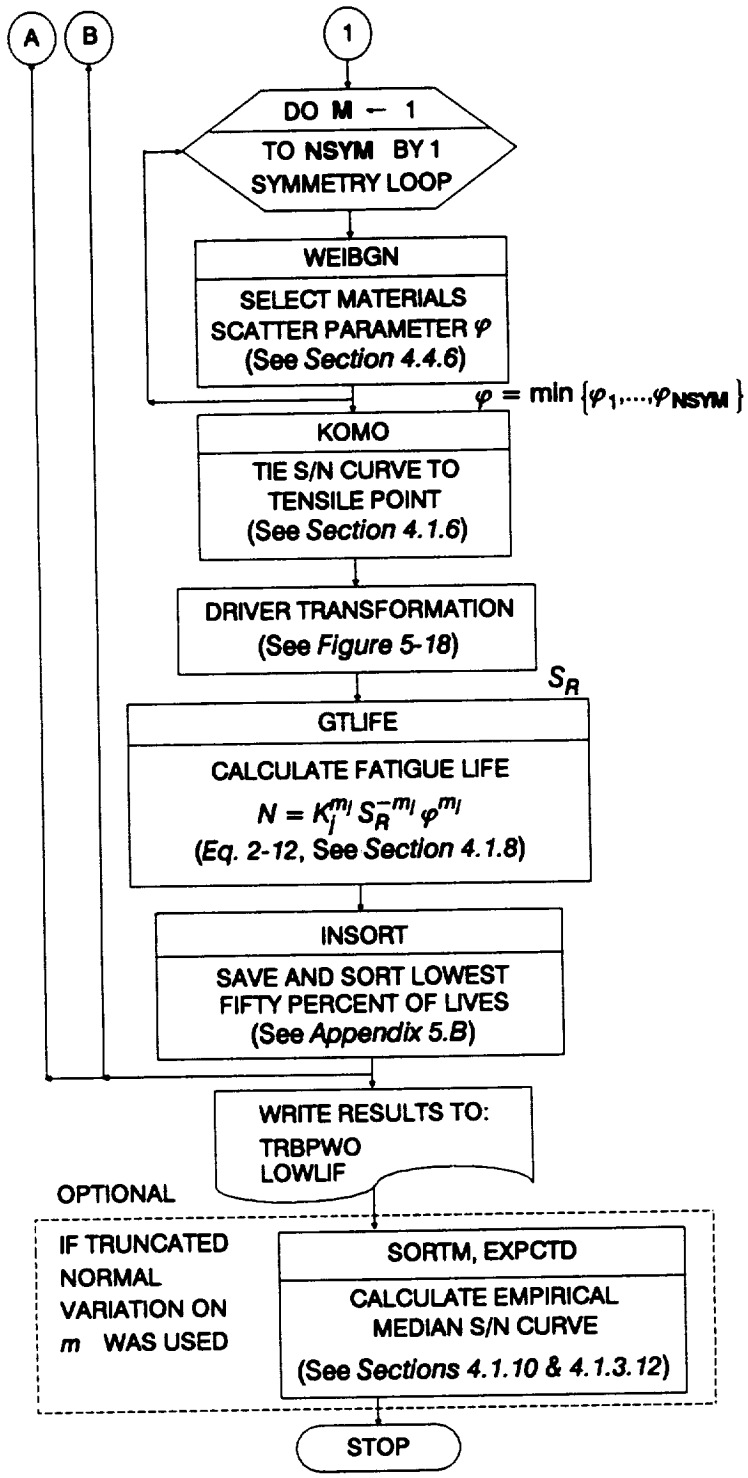

Figure 5-17 Main Flowchart for the ATD Disk LCF Analysis Program TRBPWA (Cont'd)

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 ρ and θ for ΔT_f; 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 ω, ΔT_f, λ_{K_t} and λ_{K_d} 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 φ is found from the minimum of 50 draws of a Weibull distribution. Calls to WEIBGN provide the 50 values of φ. 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 LOWLIF. 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

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[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, λ_m and λ_G by using the parametric relationships of *Equations 2-94* through *2-98* and the values of ω and ΔT_f. Then C_S, λ_m, λ_G; the nominal stresses S_{M_o}, S_{m_o} and S_{G_o}; and the model accuracy factors λ_{K_t} and λ_{K_d} 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.

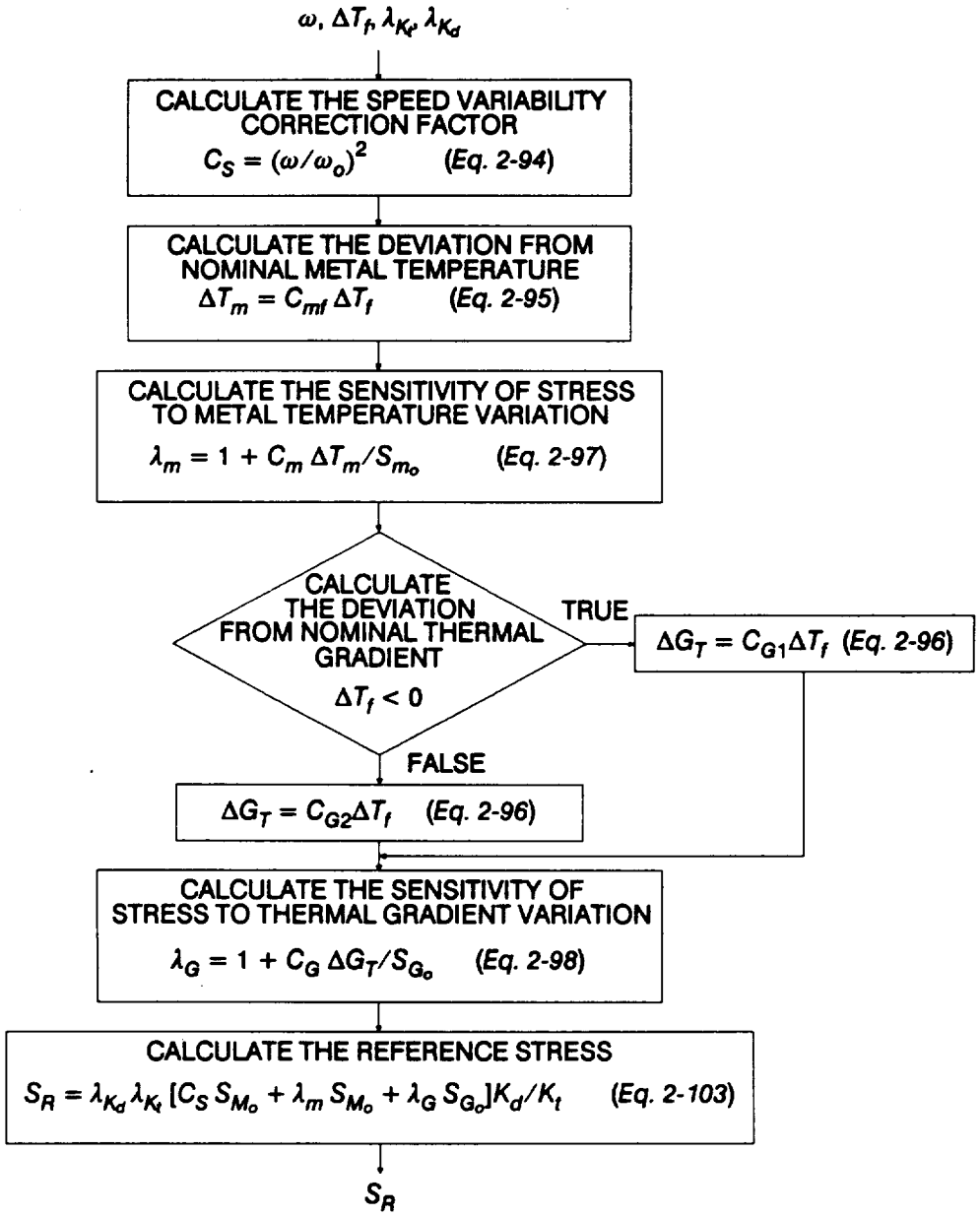

Figure 5-18 Flowchart of Driver Transformation

Appendix 5.A
Program Flowchart Symbols

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

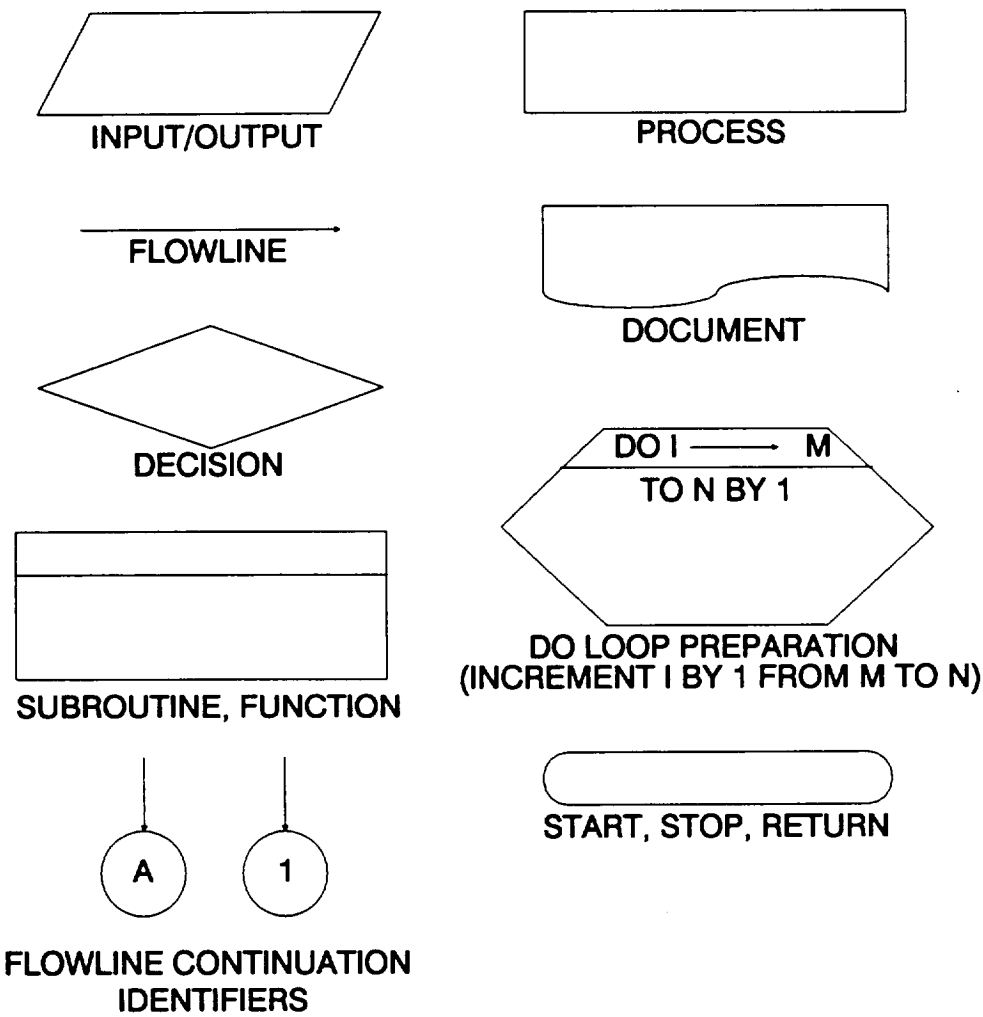

Figure 5-19 Program Flowchart Symbols

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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.

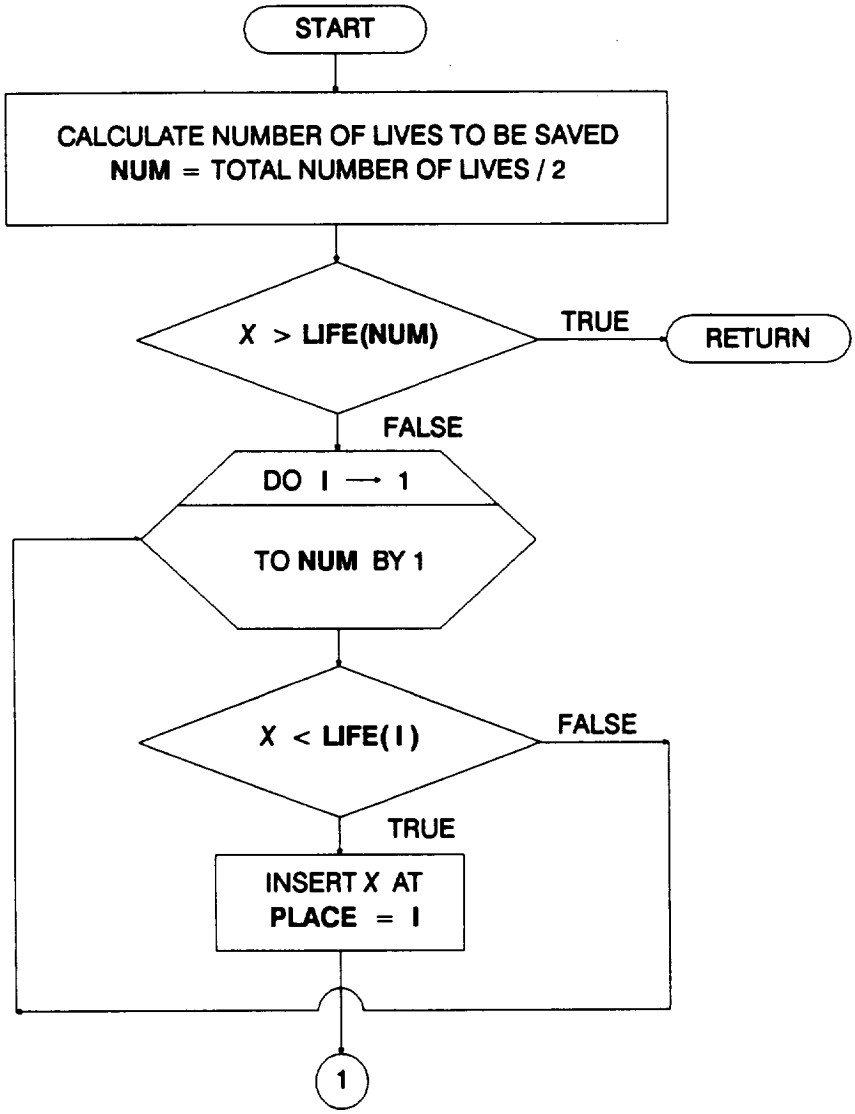

Figure 5-20 Flowchart for Subprogram INSORT

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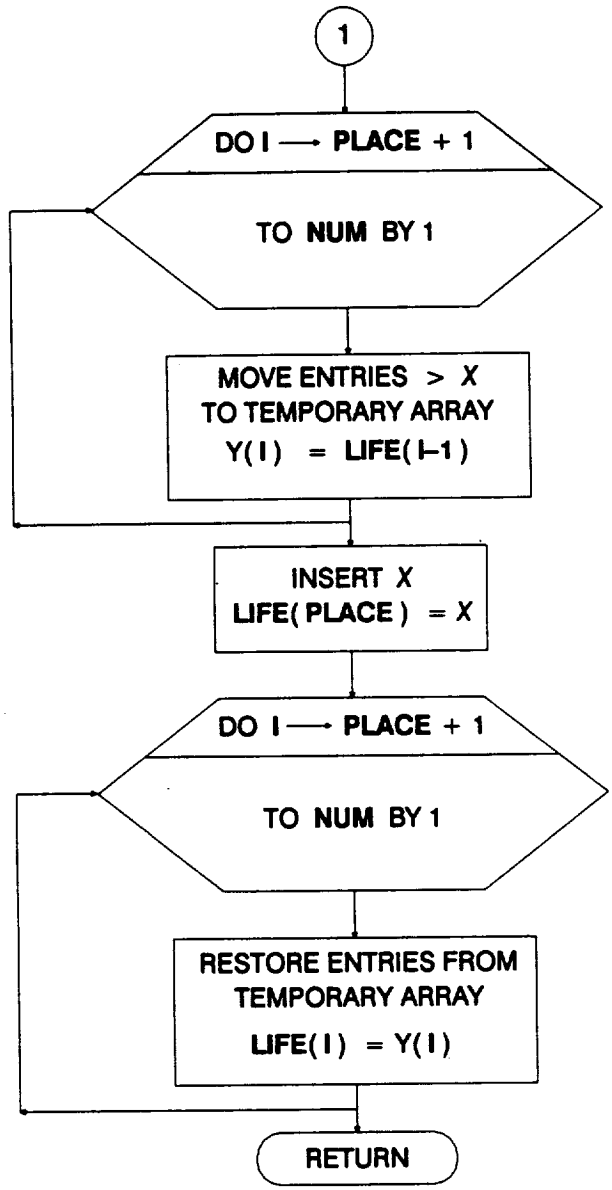

Figure 5-20 Flowchart for Subprogram INSORT (Cont'd)

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

6-2

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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 <u>underlined</u> 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	Output dump controller
1	Inner loop size
20000	Outer loop size
2	Type of S/N variation
0	Request for truncated Normal median S/N curve
0	Controls materials process variation
10	Number of B-lives

Decimal equivalent of percentages for B-lives

0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009	0.010

Weld offset two Beta distribution information

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					

Outer diameter weld axial stress concentration factor Beta distribution information

1.20	3.50	0.08696	0.3478	10.	10.

Inner diameter weld axial stress concentration factor Beta distribution information

1.04	1.43	0.30	0.70	0.5	10.

Outer diameter geometric axial stress concentration factor Beta distribution information

1.20	1.34	0.30	0.70	0.5	10.

2.00	2.00	0.15	0.866667	Narrow-band random load scale factor
2.00	2.00	0.20	0.933333	Sinusoidal load scale factor
0.90	1.10			Static load scale factor
0.80	1.20			Dynamic stress analysis accuracy factor
0.90	1.10			Static stress analysis accuracy factor
0.40	0.60			In-plane axial stress carryover factor
0.40	0.60			Out-of-plane axial stress carryover factor
0.40	0.60			In-plane circumferential stress carryover factor
0.40	0.60			Out-of-plane circumferential stress carryover factor
0.85	1.15			Ovality effect analysis accuracy factor
0.80	1.20			Weld offset accuracy factor
-1.38629	0.95166			Damage accumulation model accuracy factor
14				Number of dynamic loads

Figure 6-1 Format for File DCTHCD

Static loads: P, M_x, M_y, M_z, V_y, V_z

8130.00	20900.00	42010.00	42010.00	3805.00	3805.00

Dynamic loads: file name, load type, P, M_x, M_y, M_z, V_y, V_z

'NBP'	1	237.675	0.00	0.00	0.00	0.00	0.00
'NBT'	1	0.00	103.41	0.00	0.00	0.00	0.00
'NBM3'	1	0.00	0.00	0.00	626.175	0.00	0.00
'NBV3'	1	0.00	0.00	0.00	0.00	0.00	34.075
'SIN1'	2	4.889461	1.88731	3.002265	8.618995	13.91015	0.829459
'SIN2'	2	17.2329	12.6415	0.182346	38.4677	54.89455	2.90558
'SIN3'	2	3.117695	2.764815	4.45821	29.7981	4.905385	0.691592
'SIN4'	2	1.107417	0.856604	1.17435	3.663675	1.350412	0.414575
'SIN5'	2	10.23887	11.81905	137.38	28.5843	6.0813	13.24209
'SIN6'	2	2.151205	1.62707	0.430078	5.991475	7.077595	0.395232
'SIN7'	2	4.13738	8.509805	5.235795	71.06695	15.61234	1.242015
'SIN8'	2	9.1491	0.904076	5.953345	0.934805	5.04324	0.843876
'SIN9'	2	32.10965	0.084774	1.236315	23.9187	16.7327	0.162597
'SIN10'	2	79.7046	7.056975	2.48936	35.04565	36.66045	4.07806

1. 1. 1.	Other fatigue stress concentration factors
4675.	Inner wall limit pressure, p_i
6.0	Elbow bend radius, R_B
.112	Weld distance from the elbow tangency line, W_D
4.	Inside diameter, D_i
0.1115	Minimum wall thickness, outer diameter, tw_1
0.1378	Wall thickness at bend, inner diameter, tw_2
3.01E+07	Young's modulus of elasticity, E
1	Critical duct location
20.	Angular position about the duct circumference, ϕ
1.0	Reference time history period, T
0.00	Noise filter
20001	Number of points in reference time history

Figure 6-1 Format for File DCTHCD (Cont'd)

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

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

Figure 6-1 Format for File DCTHCD (Cont'd)

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}
86000.	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 6-1 Format for File DCTHCD (Cont'd)

1	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

201700.	215300.	2	10

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

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
6	0.10 2	Number of points in division 2, stress ratio, region
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}

Figure 6-2 Format for File RELATD

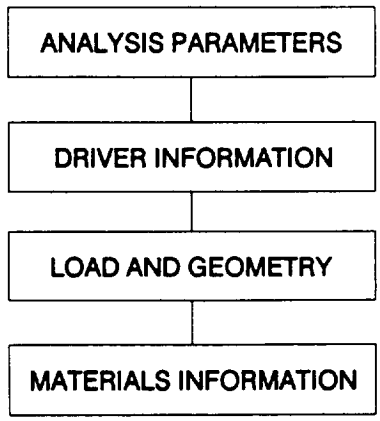

Figure 6-3 Data Blocks for Input File

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.

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[1]
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 **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

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.

---

[2] 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

WEOFA	**WEOFB**	**WEOFR1**	**WEOFR2**	**WEOFT1**	**WEOFT2**
[RE]	[RE]	[RE]	[RE]	[RE]	[RE]
WEOFC	**WEOFD**	**WEOFR3**	**WEOFR4**	**WEOFT3**	**WEOFT4**
[RE]	[RE]	[RE]	[RE]	[RE]	[RE]
WEOFE					
[RE]					

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 ρ. 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.

WEOFA	W_{OFF} lower bound of Beta distribution 1
WEOFB	W_{OFF} upper bound of Beta distribution 1
WEOFR1	ρ Uniform distribution lower bound of Beta distribution 1 of W_{OFF}
WEOFR2	ρ Uniform distribution upper bound of Beta distribution 1 of W_{OFF}
WEOFT1	θ Uniform distribution lower bound of Beta distribution 1 of W_{OFF}
WEOFT2	θ Uniform distribution upper bound of Beta distribution 1 of W_{OFF}
WEOFC	W_{OFF} lower bound of Beta distribution 2
WEOFD	W_{OFF} upper bound of Beta distribution 2
WEOFR3	ρ Uniform distribution lower bound of Beta distribution 2 of W_{OFF}

WEOFR4	ρ Uniform distribution upper bound of Beta distribution 2 of W_{OFF}
WEOFT3	θ Uniform distribution lower bound of Beta distribution 2 of W_{OFF}
WEOFT4	θ Uniform distribution upper bound of Beta distribution 2 of W_{OFF}
WEOFE	decimal equivalent percentage weight occurring in Beta distribution 1 of the weld offset, W_{OFF}

KWODA	**KWODB**	**KWODR1**	**KWODR2**	**KWODT1**	**KWODT2**
[RE]	[RE]	[RE]	[RE]	[RE]	[RE]

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 ρ. Similarly, the last two parameters describe the Uniform distribution on θ. 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	ρ Uniform distribution lower bound of Beta distribution of outer diameter weld axial stress concentration factor
KWODR2	ρ Uniform distribution upper bound of Beta distribution of outer diameter weld axial stress concentration factor
KWODT1	θ Uniform distribution lower bound of Beta distribution of outer diameter weld axial stress concentration factor
KWODT2	θ Uniform distribution upper bound of Beta distribution of outer diameter weld axial stress concentration factor

KWIDA	**KWIDB**	**KWIDR1**	**KWIDR2**	**KWIDT1**	**KWIDT2**
[RE]	[RE]	[RE]	[RE]	[RE]	[RE]

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 ρ. Similarly, the last two parameters describe the Uniform distribution on θ. 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	ρ Uniform distribution lower bound of Beta distribution of inner diameter weld axial stress concentration factor
KWIDR2	ρ Uniform distribution upper bound of Beta distribution of inner diameter weld axial stress concentration factor
KWIDT1	θ Uniform distribution lower bound of Beta distribution of inner diameter weld axial stress concentration factor
KWIDT2	θ Uniform distribution upper bound of Beta distribution of inner diameter weld axial stress concentration factor

KGODA	**KGODB**	**KGODR1**	**KGODR2**	**KGODT1**	**KGODT2**
[RE]	[RE]	[RE]	[RE]	[RE]	[RE]

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 ρ. Similarly, the last two parameters describe the Uniform distribution on θ. 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	ρ Uniform distribution lower bound of Beta distribution of outer diameter geometric axial stress concentration factor
KGODR2	ρ Uniform distribution upper bound of Beta distribution of outer diameter geometric axial stress concentration factor
KGODT1	θ Uniform distribution lower bound of Beta distribution of outer diameter geometric axial stress concentration factor

KGODT2	θ Uniform distribution upper bound of Beta distribution of outer diameter geometric axial stress concentration factor

LAMNA	**LAMNB**	**LAMNC**	**LAMND**
[RE]	[RE]	[RE]	[RE]

Narrow-band random load scale factor distribution information

This line contains the parameters to define the narrow-band random load scale factor $\lambda_{D_{RANDOM}}$ 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

LAMSA	**LAMSB**	**LAMSC**	**LAMSD**
[RE]	[RE]	[RE]	[RE]

Sinusoidal load scale factor distribution information

This line contains the parameters to define the sinusoidal load scale factor $\lambda_{D_{SINUSOIDAL}}$ 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

LAMSTA	**LAMSTB**
[RE]	[RE]

Static load scale factor distribution information

λ_{ST} in *Equation 2-81.* This is the static load scale factor and it is characterized by a Uniform distribution.

LAMSTA	static load scale factor Uniform distribution lower bound
LAMSTB	static load scale factor Uniform distribution upper bound

DSTRA **DSTRB**
[RE] [RE]

Dynamic stress analysis accuracy factor Uniform distribution information
$\lambda_{DYN_{str}}$ 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

SSTRA **SSTRB**
[RE] [RE]

Static stress analysis accuracy factor Uniform distribution information
$\lambda_{ST_{str}}$ 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

CLZA	**CLZB**	**CLYA**	**CLYB**
[RE]	[RE]	[RE]	[RE]
CCZA	**CCZB**	**CCYA**	**CCYB**
[RE]	[RE]	[RE]	[RE]

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	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
λ_{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	λ_{oval} Uniform distribution lower bound
OVALB	λ_{oval} Uniform distribution upper bound

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

Weld offset accuracy factor Uniform distribution information
λ_{OFF} in *Equation 2-73*. This is the weld offset eccentricity stress concentration accuracy factor and it is characterized by a Uniform distribution.

LAMWA	λ_{OFF} Uniform distribution lower bound
LAMWB	λ_{OFF} Uniform distribution upper bound

GAMA **GAMB**
[RE] [RE]

Damage accumulation model accuracy factor distribution information
This line contains the Uniform distribution bounds in $\log_e$ space for the damage accumulation model accuracy factor λ_{dam} 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.

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 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

LDNAME(I)	TYPE(I)	P(I)	T(I)	M(1,I)	M(2,I)	V(1,I)	V(2,I)
[CHR]	[INT]	[RE]	[RE]	[RE]	[RE]	[RE]	[RE]

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
P(I)	P (lbs) in *Equation 2-68,* the dynamic axial load magnitude for load I
T(I)	M_x (in.-lbs) in *Equation 2-72,* the dynamic torsional load magnitude for load I
M(1,I)	M_y (in.-lbs) in *Equation 2-68,* the dynamic moment load magnitude about the y axis for load I
M(2,I)	M_z (in.-lbs) in *Equation 2-68,* the dynamic moment load magnitude about the z axis for load I
V(1,I)	V_y (lbs) in *Equation 2-72,* the dynamic shear load magnitude along the y axis for load I
V(2,I)	V_z (lbs) in *Equation 2-72,* the dynamic shear load magnitude along the z axis for load I

KGID	**KT(2,1)**	**KT(2,2)**
[RE]	[RE]	[RE]

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 **KGOD** and **KGID**, and the weld factors **KWOD** and **KWID**, specified above.

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*

LIMPR
[RE]

Limit pressure

p_i (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
tw_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
tw_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.

LOCAT = 1	outer wall
LOCAT = 2	inner wall

ANGLE

Critical angle
ϕ (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.

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

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(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[3]

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**
[INT]	[INT]

Data regions[4]

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[5]

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[6]

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[7]

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[8]

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 δ 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) σ^2, the known variance of ln (*fatigue life*), $V(\ln N \mid \ln S)$. 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 λ_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(*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,[9] 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*.

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. **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

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

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

RAWSTR(I,J)	RAWNF(I,J)
[RE]	[RE]

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 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**.

6.1.4 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 HPOTP 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 σ, or coefficient of variation C, is set at zero and the mean μ 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.[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 **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 (**NLIFE** = 1 times **NHYPER** = 1000) by using Uniform shape parameter variation **VARY** = 2 and **NMED** = 0; and no materials process variation, **MPROC** = 0. The B-lives[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 (**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 2.2.1.5* 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 ⚠. The bend radius for the elbow **BNRD** is 6.0 inches, and the weld distance from the elbow tangency line **WEDS** is 0.112 inches. The minimum wall

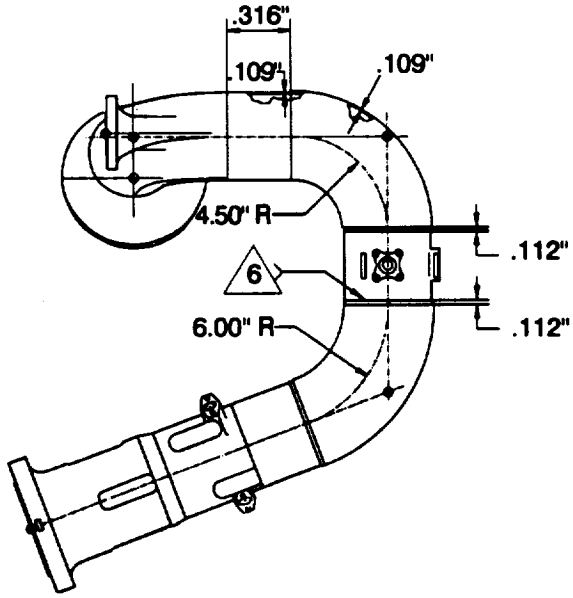

Figure 6-4 Detail of the HPOTP Main Discharge Duct, Near Weld 6

---

[10] The truncated Normal distribution for the materials model shape parameter *m* is discussed on *Page 2-14*.

[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:

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

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 **WEOFA** = **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 1.8×10^6 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.[12]

Input File - DCTHCD

```
675
0
1
1000
2
0
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
```

[12] The information aggregation calculations are discussed on *Pages 2-6* through *2-14*.

```
0.40       0.60
0.40       0.60
0.40       0.60
0.40       0.60
0.85       1.15
0.80       1.20
-1.38629  0.95166
3
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
3.01E+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.
```

```
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
   0.596733661621406
  -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
```

Output File - DCTHCO

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INPUT DATA

DRIVERS		PARAMETER DISTRIBUTIONS	
		RHO	THETA
WELD OFFSET (%)	Be(0.13, 0.13)	U(0.00000, 0.00000)	U(0.0, 0.0)
	Be(0.00, 0.00)	U(0.00000, 0.00000)	U(0.0, 0.0)
	TEST = 1.00		
K WELD (OD)	Be(1.20, 3.50)	U(0.08696, 0.34780)	U(10.0, 10.0)
K WELD (ID)	Be(1.04, 1.43)	U(0.30000, 0.70000)	U(0.5, 10.0)
K GEOM (OD)	Be(1.20, 1.34)	U(0.30000, 0.70000)	U(0.5, 10.0)

LAMBDA RANDOM
k: U(2.00000, 2.00000)
COEFFICIENT OF VARIATION: 0.150
STRAIN GAGE FACTOR: 0.8666670

LAMBDA SINE
k: U(2.00000, 2.00000)
COEFFICIENT OF VARIATION: 0.200
STRAIN GAGE FACTOR: 0.9333330

LAMBDA STATIC	U(0.90000, 1.10000)
DYNAMIC STRESS ANALYSIS	U(0.80000, 1.20000)
STATIC STRESS ANALYSIS	U(0.90000, 1.10000)
STRESS CARRYOVER FACTORS	
IN-PLANE AXIAL	U(0.40000, 0.60000)
OUT-OF-PLANE AXIAL	U(0.40000, 0.60000)
IN-PLANE CIRCUMFERENTIAL	U(0.40000, 0.60000)
OUT-OF-PLANE CIRCUMFERENTIAL	U(0.40000, 0.60000)
OVALITY ANALYSIS FACTOR	U(0.85000, 1.15000)
LAMBDA KOFF	U(0.80000, 1.20000)

DAMAGE MODEL ACCURACY U(ln 0.25000, ln 2.59001)

LOADS INPUT

	P LOADS (LBS)	T LOADS (IN.-LBS)	M2 LOADS (IN.-LBS)	M3 LOADS (IN.-LBS)	V2 LOADS (LBS)	V3 LOADS (LBS)
STATIC	8130.0000	20900.0000	42010.0000	42010.0000	3805.0000	3805.0000
NBP	237.6750	0.0000	0.0000	0.0000	0.0000	0.0000
NBM3	0.0000	0.0000	0.0000	626.1750	0.0000	0.0000
SIN10	79.7046	7.0570	2.4894	35.0457	36.6604	4.0781

GEOMETRIC AND OTHER INPUT

K GEOM (ID)	1.00
K HOOP (OD)	1.00
K HOOP (ID)	1.00
LIMIT PRESSURE, PSI	4675.
BEND RADIUS, IN.	6.00
WELD DISTANCE FROM ELBOW TANGENCY LINE, IN.	0.112
DUCT INSIDE DIAMETER, IN.	4.00
MINIMUM WALL THICKNESS, IN.	0.1115
WALL THICKNESS AT BEND (ID), IN.	0.1378
ELASTIC MODULUS, PSI	0.301E+08
ANALYSIS LOCATION	1
ANGLE PHI (DEG)	20.0

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

MATERIAL INPUT

DESCRIPTION: -320 HOURGLASS + STRAIGHT

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

ORIGINAL S/N STRESS	ORIGINAL S/N LIFE	STRESS RATIO	REGION	TRANSFORMED S/N STRESS	TRANSFORMED S/N LIFE
0.15000E+06	65000.	0.05	1	0.11086E+06	65000.
0.14000E+06	261000.	0.05	1	0.99773E+05	261000.
0.12000E+06	265000.	0.05	1	0.79814E+05	265000.
0.16000E+06	377000.	0.05	1	0.12280E+06	377000.
0.13000E+06	694000.	0.05	1	0.89449E+05	694000.
0.11000E+06	2175000.	0.05	1	0.70802E+05	2175000.
0.10000E+06	4198000.	0.05	1	0.62353E+05	4198000.
0.10500E+06	5053000.	0.05	1	0.66510E+05	5053000.
0.92000E+05	9210000.	0.05	1	0.55964E+05	9210000.
0.95000E+05	9667000.	0.05	1	0.58323E+05	9667000.
0.15000E+06	418000.	0.05	1	0.11086E+06	418000.
0.14000E+06	732000.	0.05	1	0.99773E+05	732000.
0.13000E+06	740000.	0.05	1	0.89449E+05	740000.
0.12000E+06	859000.	0.05	1	0.79814E+05	859000.
0.11000E+06	1181000.	0.05	1	0.70802E+05	1181000.
0.10000E+06	4020000.	0.05	1	0.62353E+05	4020000.
0.92000E+05	5917000.	0.05	1	0.55964E+05	5917000.
0.94000E+05	6522000.	0.05	1	0.57532E+05	6522000.
0.90000E+05	6891000.	0.05	1	0.54416E+05	6891000.
0.86000E+05	4460000.	0.05	1	0.51374E+05	4460000.

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:

REGION	# OF POINTS	LOWER BOUND	UPPER BOUND
1	0	0.0000	0.0000

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

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```
RESULTS OF INFORMATION AGGREGATION CALCULATIONS

95% CONFIDENCE INTERVALS ON C AND m FOR EACH REGION

     REGION:  1        Io = ( 0.092758540, 0.181539600)
                       Jo = ( 3.596348000, 5.874000000)

POINT ESTIMATES OF C AND m FOR EACH REGION

     REGION        E(C)            E(m)

       1        0.122759400      4.735174


POSTERIOR CREDIBILITY RANGE ON m FOR EACH REGION

REGION      LOWER BOUND      UPPER BOUND

    1          3.5963           5.8740




PARAMETER VALUES FOR MEDIAN S/N CURVE

NUMBER OF REGIONS:   1     E(BETAo) =  9.6555     E(k) = 14.2292

REGION        m                K          LIFE BOUND        STRESS BOUND

   1        4.73517       0.15458E+07     0.100E+37          0.00000E+00
```

Output File - IOUTPR

```
                          RANDOM NUMBER SEED =    675.000000000000
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

```
 1   0.100000E-02   0.178612E+07
 2   0.200000E-02   0.454616E+07
 3   0.300000E-02   0.490656E+07
 4   0.400000E-02   0.495901E+07
 5   0.500000E-02   0.508289E+07
 6   0.600000E-02   0.583508E+07
 7   0.700000E-02   0.645511E+07
 8   0.800000E-02   0.701038E+07
 9   0.900000E-02   0.716342E+07
10   0.100000E-01   0.757381E+07
```

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 δ may be negative. Second, a value of δ 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 χ^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
ERROR: NO INTERSECTION BETWEEN 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 λ, *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

DCTHCO

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.[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%.

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 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 α, β, and θ, 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 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 6.1.13*. 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 <u>underlined</u> 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

675	Random number seed
0	Output dump controller
1	Inner loop size
20000	Outer loop size
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

0.0001	0.0005	0.001	0.005	0.01

Weld offset two Beta distribution information

0.06	0.06	0.00	0.00	0.0	0.0
0.00	0.00	0.00	0.00	0.0	0.0
1.00					

Outer diameter weld axial stress concentration factor Beta distribution information

1.00	1.00	0.00	0.00	0.0	0.0

Inner diameter weld axial stress concentration factor Beta distribution information

1.20	3.50	0.1304	0.5652	10.	10.

Duct inside diameter Beta distribution information

0.1885	0.1915	0.50	0.50	0.5	20.

Wall thickness Beta distribution information

0.0113	0.0157	0.27273	0.27273	0.5	20.

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.	666.	29.	56.5	Inner wall temperature Normal distribution information
799.	908.	49.5	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
3		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	0.0

1.0	1.0	1.0	1.0	Other fatigue stress concentration factors
3640.				External pressure, p_o
2				Critical duct location
180.				Angular position about the duct circumference, ϕ
1.0				Reference time history period, T
0.0				Noise filter
20001				Number of points in reference time histories
29000000.	8.8E-06	0.30		E, α, ν
0.615		2.00		The 10 points of the
0.693		4.80		piecewise linear
0.753		7.20		F_k vs. R/t curve
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				Number of segments in $\sigma\varepsilon$ vs. ε curve
21.95		0.001		σ_1 ε_1, ε_1
55.77		0.002		σ_2 ε_2, ε_2
144.85		0.005		σ_3 ε_3, ε_3
322.73		0.010		σ_4 ε_4, ε_4
1945.90		0.050		σ_5 ε_5, ε_5
50688.0		0.660		σ_6 ε_6, ε_6

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

13	-1.0	1

40000.	1000.	S_1, N_1
40000.	2000.	S_2, N_2
40000.	3000.	S_3, N_3
40000.	4000.	S_4, N_4
40000.	5000.	S_5, N_5
40000.	6000.	S_6, N_6
30000.	23000.	S_7, N_7
30000.	66000.	S_8, N_8
25000.	72000.	S_9, N_9
25000.	190000	S_{10}, N_{10}
20000.	789000.	S_{11}, N_{11}
20000.	1070000.	S_{12}, N_{12}
20000.	1450000.	S_{13}, N_{13}
0.00		Stress tensile point
1	0	Number of life regions with and without data
1.0E+36		Life boundary
0.00		*C* constraint
0	0.000	0.000	Prior information *m*

- -

0.00	0.00	0.00	Bayesian prior distribution information

- -

0.00	0.00	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.

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.

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[14]

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]

Request for truncated Normal median S/N curve[15]

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

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.

---

[14] A discussion of the possible stochastic specifications of the materials model shape parameter *m* is given in *Pages 2-13* through *2-14*.

[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 **BLFPER** = 0.001. A total of **NBLIFE** percentages must be provided. The percentage cannot exceed 50% (**BLFPER** ≤ 0.50).

Driver Information Block

WOFFA	**WOFFB**	**WOFFR1**	**WOFFR2**	**WOFFT1**	**WOFFT2**
[RE]	[RE]	[RE]	[RE]	[RE]	[RE]
WOFFC	**WOFFD**	**WOFFR3**	**WOFFR4**	**WOFFT3**	**WOFFT4**
[RE]	[RE]	[RE]	[RE]	[RE]	[RE]
WOFFE					
[RE]					

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 ρ. 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.

WOFFA	W_{OFF} lower bound of Beta distribution 1
WOFFB	W_{OFF} upper bound of Beta distribution 1
WOFFR1	ρ Uniform distribution lower bound of Beta distribution 1 of W_{OFF}
WOFFR2	ρ Uniform distribution upper bound of Beta distribution 1 of W_{OFF}
WOFFT1	θ Uniform distribution lower bound of Beta distribution 1 of W_{OFF}
WOFFT2	θ Uniform distribution upper bound of Beta distribution 1 of W_{OFF}
WOFFC	W_{OFF} lower bound of Beta distribution 2
WOFFD	W_{OFF} upper bound of Beta distribution 2

WOFFR3	ρ Uniform distribution lower bound of Beta distribution 2 of W_{OFF}
WOFFR4	ρ Uniform distribution upper bound of Beta distribution 2 of W_{OFF}
WOFFT3	θ Uniform distribution lower bound of Beta distribution 2 of W_{OFF}
WOFFT4	θ Uniform distribution upper bound of Beta distribution 2 of W_{OFF}
WOFFE	decimal equivalent percentage weight occurring in Beta distribution 1 of the weld offset, W_{OFF}

KWODA	**KWODB**	**KWODR1**	**KWODR2**	**KWODT1**	**KWODT2**
[RE]	[RE]	[RE]	[RE]	[RE]	[RE]

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 ρ. Similarly, the last two parameters describe the Uniform distribution on θ. 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	ρ Uniform distribution lower bound of Beta distribution of outer diameter weld axial stress concentration factor
KWODR2	ρ Uniform distribution upper bound of Beta distribution of outer diameter weld axial stress concentration factor
KWODT1	θ Uniform distribution lower bound of Beta distribution of outer diameter weld axial stress concentration factor
KWODT2	θ Uniform distribution upper bound of Beta distribution of outer diameter weld axial stress concentration factor

KWIDA	**KWIDB**	**KWIDR1**	**KWIDR2**	**KWIDT1**	**KWIDT2**
[RE]	[RE]	[RE]	[RE]	[RE]	[RE]

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 ρ. Similarly, the last two parameters describe the Uniform distribution on θ. 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	ρ Uniform distribution lower bound of Beta distribution of inner diameter weld axial stress concentration factor
KWIDR2	ρ Uniform distribution upper bound of Beta distribution of inner diameter weld axial stress concentration factor
KWIDT1	θ Uniform distribution lower bound of Beta distribution of inner diameter weld axial stress concentration factor
KWIDT2	θ Uniform distribution upper bound of Beta distribution of inner diameter weld axial stress concentration factor

DIA	**DIB**	**DIR1**	**DIR2**	**DIT1**	**DIT2**
[RE]	[RE]	[RE]	[RE]	[RE]	[RE]

Duct inside diameter Beta distribution information

D_i (in.) the duct inside diameter is used to calculate R_i 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 duct inside diameter. The next two parameters are the lower and upper bounds for the Uniform distribution on ρ. Similarly, the last two parameters describe the Uniform distribution on θ.

DIA	D_i lower bound of Beta distribution
DIB	D_i upper bound of Beta distribution
DIR1	ρ Uniform distribution lower bound of Beta distribution of D_i
DIR2	ρ Uniform distribution upper bound of Beta distribution of D_i
DIT1	θ Uniform distribution lower bound of Beta distribution of D_i
DIT2	θ Uniform distribution upper bound of Beta distribution of D_i

THICA	THICB	THICR1	THICR2	THICT1	THICT2
[RE]	[RE]	[RE]	[RE]	[RE]	[RE]

Wall thickness Beta distribution information

t (in.) 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 ρ. Similarly, the last two parameters describe the Uniform distribution on θ.

THICA	t lower bound of Beta distribution
THICB	t upper bound of Beta distribution
THICR1	ρ Uniform distribution lower bound of Beta distribution of t
THICR2	ρ Uniform distribution upper bound of Beta distribution of t
THICT1	θ Uniform distribution lower bound of Beta distribution of t
THICT2	θ Uniform distribution upper bound of Beta distribution of t

LAMNA	LAMNB	LAMNC	LAMND
[RE]	[RE]	[RE]	[RE]

Narrow-band random load scale factor distribution information

This line contains the parameters to define the narrow-band random load scale factor $\lambda_{D_{RANDOM}}$ 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

LAMSA	LAMSB	LAMSC	LAMSD
[RE]	[RE]	[RE]	[RE]

Sinusoidal load scale factor distribution information

This line contains the parameters to define the sinusoidal load scale factor $\lambda_{D_{SINUSOIDAL}}$ 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, ΔT (°R) in *Equation 2-70*, and is characterized by a Normal distribution.

TIMUA	μ Uniform distribution lower bound of Normal distribution of T_i
TIMUB	μ Uniform distribution upper bound of Normal distribution of T_i
TISIGA	σ Uniform distribution lower bound of Normal distribution of T_i
TISIGB	σ 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, ΔT (°R) in *Equation 2-70*, and is characterized by a Normal distribution.

TOMUA	μ Uniform distribution lower bound of Normal distribution of T_o
TOMUB	μ Uniform distribution upper bound of Normal distribution of T_o
TOSIGA	σ Uniform distribution lower bound of Normal distribution of T_o
TOSIGB	σ Uniform distribution upper bound of Normal distribution of T_o

PCMUA	PCMUB	PCSIGA	PCSIGB
[RE]	[RE]	[RE]	[RE]

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	μ Uniform distribution lower bound of Normal distribution of p_i
PCMUB	μ Uniform distribution upper bound of Normal distribution of p_i
PCSIGA	σ Uniform distribution lower bound of Normal distribution of p_i
PCSIGB	σ Uniform distribution upper bound of Normal distribution of p_i

AERDA	AERDB
[RE]	[RE]

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
[RE]	[RE]

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
[RE]	[RE]

The dynamic stress analysis accuracy factor Uniform distribution information $\lambda_{DYN_{str}}$ 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

ASTRA **ASTRB**
[RE] [RE]

Aerodynamic stress analysis accuracy factor Uniform distribution information $\lambda_{AERO_{str}}$ 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

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

Weld offset accuracy factor Uniform distribution information λ_{OFF} in *Equation 2-73.* This is the weld offset eccentricity stress concentration accuracy factor and it is characterized by a Uniform distribution.

LAMWA	λ_{OFF} Uniform distribution lower bound
LAMWB	λ_{OFF} Uniform distribution upper bound

NEUBA **NEUBB**
[RE] [RE]

Neuber's Rule accuracy factor Uniform distribution information λ_{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

GAMA	GAMB
[RE]	[RE]

Damage accumulation model accuracy factor distribution information
This line contains the Uniform distribution bounds in $\log_e$ space for the damage accumulation model accuracy factor λ_{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

LDNAME(I)	TYPE(I)	P(I)	T(I)	M(1,I)	M(2,I)	V(1,I)	V(2,I)
[CHR]	[INT]	[RE]	[RE]	[RE]	[RE]	[RE]	[RE]

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 (lbs) in *Equation 2-68*, the dynamic axial load magnitude for load **I**

T(I) M_x (in.-lbs) in *Equation 2-72*, the dynamic torsional load magnitude for load **I**

M(1,I) M_y (in.-lbs) in *Equation 2-68*, the dynamic moment load magnitude about the y axis for load **I**

M(2,I) M_z (in.-lbs) in *Equation 2-68*, the dynamic moment load magnitude about the z axis for load **I**

V(1,I) V_y (lbs) in *Equation 2-72*, the dynamic shear load magnitude along the y axis for load **I**

V(2,I) V_z (lbs) in *Equation 2-72*, the dynamic shear load magnitude along the z axis for load **I**

KGOD	KGID	KT(2,1)	KT(2,2)
[RE]	[RE]	[RE]	[RE]

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.

LOCAT = 1	outer wall
LOCAT = 2	inner wall

ANGLE
[RE]

Critical angle
ϕ (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	α (/°R) in *Equation 2-70*, the coefficient of thermal expansion
NU	ν 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
$\sigma\varepsilon$ versus ε points for each segment of the σ vs. ε 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)	value of the product of stress and strain, $\sigma\varepsilon$, at the upper end of the Jth segment of the stress-strain versus strain curve
E(J)	value of the strain ε at the upper end of the Jth 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.

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[16]
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**
[INT] [INT]

Data regions[17]
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[18]
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 cuve 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 ∞.

CZERO
[RE]

Prior information on coefficient of variation of fatigue strength[19]

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*[20]

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[21]

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 δ 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)	σ^2, the known variance of ln(*fatigue life*), $V(\ln N \mid \ln S)$. Must be non-negative.

KRATIO **LAMN**
[RE] [RE]

Materials process variation information
If **MPROC** = 1, then specfication of **KRATIO** and **LAMN** is required. **KRATIO** is λ_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(*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,[22] 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.

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 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

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

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

RAWSTR(I,J)	**RAWNF(I,J)**
[RE]	[RE]

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)

6.1.10.3 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 σ, or coefficient of variation C, is set at zero and the mean μ 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

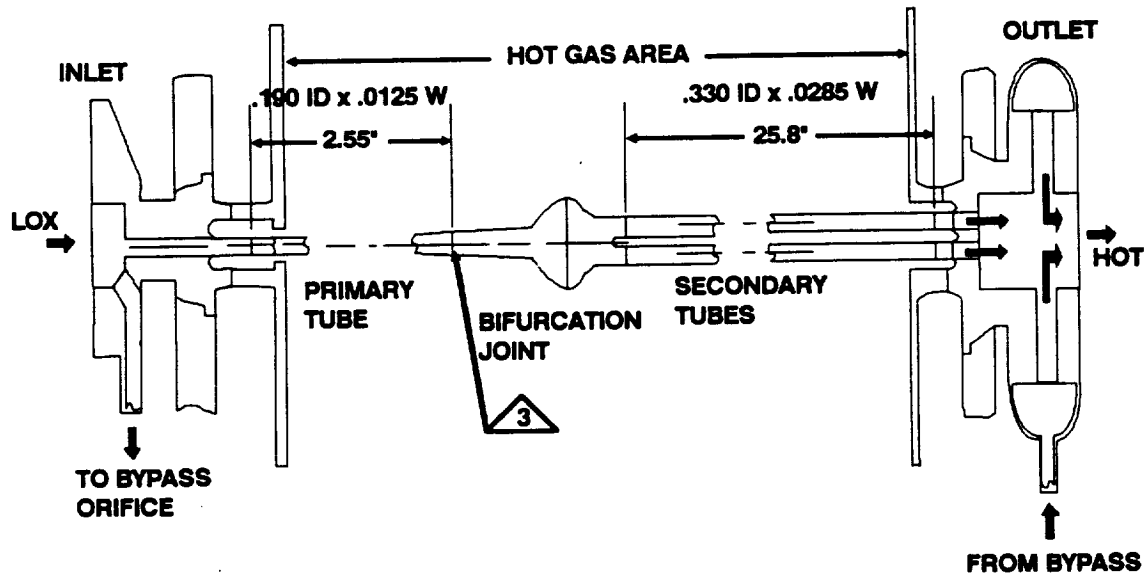

Figure 6-6 Detail of the HPOTP Heat Exchanger Coil Small Tube Outlet Near Weld 3

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.[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 (**NLIFE** = 1 times **NHYPER** = 1000) by using Uniform shape parameter variation, **VARY** = 2 and **NMED** = 0; and no materials process variation, **MPROC** = 0. The B-lives[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 (**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 2.2.1.5* 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 3. The external pressure **PCO** is 3640 psi. All geometric axial and

[23] The truncated Normal distribution for the materials model shape parameter *m* is discussed on *Page 2-14*.

[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 2.9×10^7, the coefficient of thermal expansion **COEXP** is 8.8×10^{-6}, and Poisson's ratio **NU** is 0.30 for the material.

The drivers for the HCF failure of weld 3 are as follows:

DRIVER	DISTRIBUTION
1. Weld Offset	Beta
2. K_T Weld Factors	Beta
3. Inner Diameter	Beta
4. Wall Thickness	Beta
5. Random & Sine Load Scale Factors	Normal
6. Flow Conditions	Normal
7. K_T Weld Offset Eccentricity Accuracy	Uniform
8. Neuber's Rule Accuracy	Uniform
9. Dynamic Aerodynamic Load Scale Factor	Uniform
10. Static Aerodynamic Load Scale Factor	Uniform
11. Dynamic Stress Analysis Accuracy Factor	Uniform
12. Aerodynamic Stress Analysis Accuracy Factor	Uniform
13. Damage Accumulation Model Accuracy	Uniform

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 **ANGLE** = 85°.

Thirteen S/N data points, **NUM** = 13 with a stress ratio of −1.0 (**RATIO** = −1.0) 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 thirteen, **NPTS(0)** = 13. 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 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 4.5×10^9 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.[25]

Input File - HEXHCD

```
675
0
1
1000
2
0
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.
```

[25] 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.      2000.
40000.      3000.
40000.      4000.
40000.      5000.
```

```
40000.      6000.
30000.     23000.
30000.     66000.
25000.     72000.
25000.    190000.
20000.    789000.
20000.   1070000.
20000.   1450000.
0.00
1     0
1.0E+36
0.00
0     0.000      0.000
```

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
-2.176997589958
-2.250379923423
-1.314959553996
-0.5704567649678
```

Output File - HEXHCO

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INPUT DATA

DRIVERS		PARAMETER DISTRIBUTIONS	
		RHO	THETA
WELD OFFSET (%)	Be(0.06, 0.06)	U(0.00000, 0.00000)	U(0.0, 0.0)
	Be(0.00, 0.00)	U(0.00000, 0.00000)	U(0.0, 0.0)
	TEST = 1.00		
K WELD (OD)	Be(1.00, 1.00)	U(0.00000, 0.00000)	U(0.0, 0.0)
K WELD (ID)	Be(1.20, 3.50)	U(0.13040, 0.56520)	U(10.0, 10.0)
INNER DIAMETER	Be(0.1885, 0.1915)	U(0.50000, 0.50000)	U(0.5, 20.0)
WALL THICKNESS	Be(0.0113, 0.0157)	U(0.27273, 0.27273)	U(0.5, 20.0)

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

		MU	SIGMA
INNER TEMPERATURE	NORMAL:	U(486.0, 666.0)	U(29.0, 56.5)
OUTER TEMPERATURE	NORMAL:	U(799.0, 908.0)	U(49.5, 48.0)
INNER PRESSURE	NORMAL:	U(3808.0, 4177.0)	U(69.0, 69.0)

DYNAMIC AERO LOAD FACTOR	U(0.50000, 1.50000)
STATIC AERO LOAD FACTOR	U(0.80000, 1.20000)
DYNAMIC STRESS ANALYSIS	U(0.80000, 1.20000)

AERO STRESS ANALYSIS	U(0.90000, 1.10000)
LAMBDA KOFF	U(0.80000, 1.20000)
NEUBERS RULE	U(0.60000, 1.40000)
DAMAGE MODEL ACCURACY	U(ln 0.25000, ln 2.59001)

LOADS INPUT

P LOADS (LBS)	T LOADS (IN.-LBS)	M2 LOADS (IN.-LBS)	M3 LOADS (IN.-LBS)	V2 LOADS (LBS)	V3 LOADS (LBS)
STATIC AERO					
0.000000	0.000000	-0.072140	0.000000	0.000000	0.000000
NBM3					
0.000000	0.000000	0.000000	0.355475	0.000000	0.000000
SIN1					
0.027374	0.000451	0.001621	0.082116	0.205288	0.005789
AERO1					
0.000000	0.000000	0.000000	0.071790	0.000000	0.000000

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

STRESS-STRAIN PRODUCT	STRAIN VALUES
21.95	0.00100
55.77	0.00200
144.85	0.00500
322.73	0.01000
1945.90	0.05000
50688.00	0.66000

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

STRESS	LIFE	RATIO	REGION	STRESS	LIFE
0.40000E+05	1000.	-1.00	1	0.40000E+05	1000.
0.40000E+05	2000.	-1.00	1	0.40000E+05	2000.
0.40000E+05	3000.	-1.00	1	0.40000E+05	3000.
0.40000E+05	4000.	-1.00	1	0.40000E+05	4000.
0.40000E+05	5000.	-1.00	1	0.40000E+05	5000.
0.40000E+05	6000.	-1.00	1	0.40000E+05	6000.
0.30000E+05	23000.	-1.00	1	0.30000E+05	23000.
0.30000E+05	66000.	-1.00	1	0.30000E+05	66000.
0.25000E+05	72000.	-1.00	1	0.25000E+05	72000.
0.25000E+05	190000.	-1.00	1	0.25000E+05	190000.
0.20000E+05	789000.	-1.00	1	0.20000E+05	789000.
0.20000E+05	1070000.	-1.00	1	0.20000E+05	1070000.
0.20000E+05	1450000.	-1.00	1	0.20000E+05	1450000.

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:

REGION	# OF POINTS	LOWER BOUND	UPPER BOUND
1	0	0.0000	0.0000

B LIVES:	EMPIRICAL
0.00100	0.447327E+10
0.00200	0.104092E+11
0.00300	0.191086E+11
0.00400	0.208025E+11
0.00500	0.398571E+11
0.00600	0.662463E+11
0.00700	0.824330E+11
0.00800	0.959502E+11

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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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        Io = ( 0.047421050, 0.113658400)
                       Jo = ( 7.136659000, 9.595363000)


POINT ESTIMATES OF C AND m FOR EACH REGION

     REGION        E(C)            E(m)

       1        0.066941450      8.366011


POSTERIOR CREDIBILITY RANGE ON m FOR EACH REGION


REGION      LOWER BOUND      UPPER BOUND

    1          7.1367           9.5954



PARAMETER VALUES FOR MEDIAN S/N CURVE
```

```
NUMBER OF REGIONS:   1     E(BETAo) = 19.5380     E(k) = 11.5536

REGION        m                K          LIFE BOUND        STRESS BOUND

   1        8.36601       0.10528E+06     0.100E+37          0.00000E+00
```

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 δ may be negative. Second, a value of δ was specified, but the value for m_o 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 χ^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
ERROR: NO INTERSECTION BETWEEN 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: 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.

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 α, β, and θ, 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 appliction 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 <u>underlined</u> 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

0.0001	0.0005	0.001	0.005	0.01

ΔT_f two Beta distribution information

-200.	200.	0.50	0.50	0.0	0.0
200.	500.	0.00	0.00	10.	10.
0.95					

37592.		507.		Rotational speed Normal distribution information
0.80000		1.20000		Uniform distribution bounds for λ_{K_d}
0.95000		1.05000		Uniform distribution bounds for λ_{K_t}
1.41	2.18	159807.	38600.	K_d, K_t, S_{M_o} (psi), ω_o (rpm)
1915.	0.91325		4.4435	S_{m_o} (psi), C_{mf}, C_m (psi/°F)
14749.	0.04	0.07	101.72	S_{G_o} (psi), C_{G1}, C_{G2}, C_G (psi/°F)

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

9 -1.0 1	
160000. 600.	S_1, N_1
160000. 700.	S_2, N_2
160000. 1000.	S_3, N_3
140000. 4800.	S_4, N_4
130000. 3700.	S_5, N_5
130000. 4300.	S_6, N_6
120000. 3800.	S_7, N_7
120000. 11000.	S_8, N_8
110000. 40000.	S_9, N_9
198000.	Stress tensile point
1 0	Number of life regions with and without data
500.	Life boundary of region 0
1.0E+36	Life boundary of region 1
0.00	C constraint
0 0.00 0.000	Prior information on m

- -

0.00 0.00 0.00	Bayesian prior distribution information

- -

0.00 0.00	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[27]

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]

Request for truncated Normal median S/N curve[28]

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

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

DELTA	DELTB	DELTR1	DELTR2	DELTT1	DELTT2
[RE]	[RE]	[RE]	[RE]	[RE]	[RE]

DELTC	DELTD	DELTR3	DELTR4	DELTT3	DELTT4
[RE]	[RE]	[RE]	[RE]	[RE]	[RE]

DELTE
[RE]

ΔT_f two Beta distribution information

ΔT_f (°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 ΔT_f. The next two parameters are the lower and upper bounds for the Uniform distribution on ρ. 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.

DELTA	ΔT_f lower bound of Beta distribution 1
DELTB	ΔT_f upper bound of Beta distribution 1
DELTR1	ρ Uniform distribution lower bound of Beta distribution 1 of ΔT_f
DELTR2	ρ Uniform distribution upper bound of Beta distribution 1 of ΔT_f
DELTT1	θ Uniform distribution lower bound of Beta distribution 1 of ΔT_f
DELTT2	θ Uniform distribution upper bound of Beta distribution 1 of ΔT_f
DELTC	ΔT_f lower bound of Beta distribution 2

DELTD	ΔT_f upper bound of Beta distribution 2
DELTR3	ρ Uniform distribution lower bound of Beta distribution 2 of ΔT_f
DELTR4	ρ Uniform distribution upper bound of Beta distribution 2 of ΔT_f
DELTT3	θ Uniform distribution lower bound of Beta distribution 2 of ΔT_f
DELTT4	θ Uniform distribution upper bound of Beta distribution 2 of ΔT_f
DELTE	decimal equivalent percentage weight occurring in Beta distribution 1 of the deviation from nominal coolant fluid temperature, ΔT_f

SPDMU **SPDSIG**
[RE] [RE]

Rotational speed Normal distribution information

The rotational speed variation is characterized by a Normal(μ, σ^2) distribution. The mean μ is equal to the expected operating speed of the turbopump, and the standard deviation σ is obtained from the engine performance balance. Both the mean and standard deviation are in rpm.

SPDMU	mean μ of Normally distributed speed
SPDSIG	standard deviation σ of Normally distributed speed

LAMKDA **LAMKDB**
[RE] [RE]

K_d accuracy factor Uniform distribution information

λ_{K_d} in *Equation 2-103*. This is the K_d accuracy factor, and it is characterized by a Uniform distribution.

LAMKDA	K_d accuracy factor Uniform distribution lower bound
LAMKDB	K_d accuracy factor Uniform distribution upper bound

LAMKTA **LAMKTB**
[RE] [RE]

K_t accuracy factor Uniform distribution information

λ_{K_t} in *Equation 2-103*. This is the K_t 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

KD	**KT**	**SMM**	**REFSPD**
[RE]	[RE]	[RE]	[RE]

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 ω_o is the nominal or reference speed (rpm) corresponding to all nominal stress values.

STM	**CMF**	**CM**
[RE]	[RE]	[RE]

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 ΔT_m in *Equation 2-95* due to deviation from nominal coolant fluid temperature.

SG	**CG1**	**CG2**	**CG**
[RE]	[RE]	[RE]	[RE]

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

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. 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.

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[29]

Stress tensile point S_o (psi). Must be non-negative. A value of zero indicates no tensile point.

NUMREG	**NNODAT**
[INT]	[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 ∞.

---

[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[32]

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[33]

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[34]

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 δ 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 **DELTA(L)** is non-zero.

SIGMA2(L) σ^2, the known variance of ln(*fatigure 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 λ^*_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(*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,[35] 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.

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.

---

[35] Related S/N data is discussed on *Page 2-7.*

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 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

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

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

RAWSTR(I,J)	RAWNF(I,J)
[RE]	[RE]

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)

6.2.4 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 σ is set at zero, and the mean μ 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.[36] 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*.

---

[36] The truncated Normal distribution for the materials model shape parameter *m* is discussed on *Page 2-14*.

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[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:

DRIVER	DISTRIBUTION
1. ΔT_f	Two Betas
2. ω	Normal
3. λ_{K_d}	Uniform
4. λ_{K_t}	Uniform

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;

---

[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.[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.
```

[38] The information aggregation calculations are discussed on *Pages 2-6* through *2-14*.

```
0.
1    0
1.0E+36
0.00
0    0.000     0.000
```

Input File - RELATD

```
0
```

Output File - TRBPWO

```
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                              INPUT DATA

            DRIVERS                          PARAMETER DISTRIBUTIONS

                                                 RHO                THETA

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

ORIGINAL S/N STRESS	ORIGINAL S/N LIFE	STRESS RATIO	REGION	TRANSFORMED S/N STRESS	TRANSFORMED S/N LIFE
0.16000E+06	636.	-1.00	1	0.16000E+06	636.
0.16000E+06	677.	-1.00	1	0.16000E+06	677.
0.16000E+06	1019.	-1.00	1	0.16000E+06	1019.
0.14000E+06	4743.	-1.00	1	0.14000E+06	4743.
0.13000E+06	3824.	-1.00	1	0.13000E+06	3824.
0.13000E+06	4163.	-1.00	1	0.13000E+06	4163.
0.12000E+06	3749.	-1.00	1	0.12000E+06	3749.
0.12000E+06	11349.	-1.00	1	0.12000E+06	11349.
0.11000E+06	39600.	-1.00	1	0.11000E+06	39600.

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:

REGION	# OF POINTS	LOWER BOUND	UPPER BOUND
1	0	0.0000	0.0000

B LIVES:	EMPIRICAL
0.00100	0.121108E+03
0.00200	0.155309E+03
0.00300	0.180471E+03
0.00400	0.200357E+03
0.00500	0.214710E+03
0.00600	0.230961E+03
0.00700	0.251356E+03
0.00800	0.263503E+03
0.00900	0.281120E+03
0.01000	0.288462E+03
0.50000	0.411175E+04

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        Io = ( 0.036692030, 0.112948100)
                       Jo = ( 5.734418000,11.972310000)

POINT ESTIMATES OF C AND m FOR EACH REGION

     REGION        E(C)            E(m)

       1        0.055495330      8.853366


POSTERIOR CREDIBILITY RANGE ON m FOR EACH REGION

REGION      LOWER BOUND      UPPER BOUND

    1          5.7344          11.9723


PARAMETER VALUES FOR MEDIAN S/N CURVE

NUMBER OF REGIONS:   1     E(BETAo) = 22.9860     E(k) = 12.7338

REGION        m                K          LIFE BOUND       STRESS BOUND

   1        8.85337       0.34214E+06     0.100E+37         0.00000E+00
```

Output File - IOUTPR

```
                    RANDOM NUMBER SEED =     675.000000000000
      IOUT (MATCHR = 10, TRBPWA = 15) =            0
                       INNER LOOP SIZE =           1
                       OUTER LOOP SIZE =       20000
                       SYMMETRY NUMBER =          50
        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	0.500000E-04	15.2292
2	0.100000E-03	30.8418
3	0.150000E-03	34.1021
4	0.200000E-03	39.0600
5	0.250000E-03	51.4226
6	0.300000E-03	53.2745
7	0.350000E-03	58.0043
8	0.400000E-03	65.5637
9	0.450000E-03	71.9857
10	0.500000E-03	75.1110
11	0.550000E-03	75.8070
12	0.600000E-03	89.4144
13	0.650000E-03	103.456
14	0.700000E-03	104.278
15	0.750000E-03	105.559
16	0.800000E-03	107.647
17	0.850000E-03	107.784
18	0.900000E-03	114.712
19	0.950000E-03	116.542
20	0.100000E-02	121.108
21	0.105000E-02	124.069
22	0.110000E-02	124.429
23	0.115000E-02	124.546
24	0.120000E-02	129.185
25	0.125000E-02	131.056
26	0.130000E-02	132.799
27	0.135000E-02	133.245
28	0.140000E-02	133.803
29	0.145000E-02	134.375
30	0.150000E-02	136.029
31	0.155000E-02	136.142
32	0.160000E-02	146.670
33	0.165000E-02	149.321
34	0.170000E-02	149.350
35	0.175000E-02	149.919
36	0.180000E-02	152.232
37	0.185000E-02	152.349
38	0.190000E-02	152.559
39	0.195000E-02	152.949
40	0.200000E-02	155.309
41	0.205000E-02	155.585
42	0.210000E-02	156.888
43	0.215000E-02	157.319
44	0.220000E-02	158.105
45	0.225000E-02	158.928

46	0.230000E-02	159.245
47	0.235000E-02	160.929
48	0.240000E-02	161.168
49	0.245000E-02	163.429
50	0.250000E-02	164.862
51	0.255000E-02	166.070
52	0.260000E-02	168.230
53	0.265000E-02	169.043
54	0.270000E-02	169.055
55	0.275000E-02	174.029
56	0.280000E-02	175.739
57	0.285000E-02	176.429
58	0.290000E-02	176.966
59	0.295000E-02	178.398
60	0.300000E-02	180.471
61	0.305000E-02	180.738
62	0.310000E-02	181.203
63	0.315000E-02	181.368
64	0.320000E-02	182.887
65	0.325000E-02	184.505
66	0.330000E-02	184.510
67	0.335000E-02	184.919
68	0.340000E-02	185.591
69	0.345000E-02	185.607
70	0.350000E-02	186.154
71	0.355000E-02	191.204
72	0.360000E-02	191.649
73	0.365000E-02	193.389
74	0.370000E-02	195.028
75	0.375000E-02	195.336
76	0.380000E-02	197.925
77	0.385000E-02	198.473
78	0.390000E-02	199.333
79	0.395000E-02	199.871
80	0.400000E-02	200.357
81	0.405000E-02	203.074
82	0.410000E-02	206.303
83	0.415000E-02	207.010
84	0.420000E-02	207.449
85	0.425000E-02	207.492
86	0.430000E-02	207.952
87	0.435000E-02	208.420
88	0.440000E-02	209.027
89	0.445000E-02	209.282
90	0.450000E-02	209.696
91	0.455000E-02	210.907
92	0.460000E-02	211.559
93	0.465000E-02	211.829
94	0.470000E-02	212.364
95	0.475000E-02	212.551

96	0.480000E-02	213.054
97	0.485000E-02	213.175
98	0.490000E-02	214.526
99	0.495000E-02	214.554
100	0.500000E-02	214.710
101	0.505000E-02	215.661
102	0.510000E-02	215.751
103	0.515000E-02	216.391
104	0.520000E-02	216.600
105	0.525000E-02	217.116
106	0.530000E-02	217.569
107	0.535000E-02	217.849
108	0.540000E-02	219.640
109	0.545000E-02	219.643
110	0.550000E-02	220.485
111	0.555000E-02	221.658
112	0.560000E-02	222.904
113	0.565000E-02	223.053
114	0.570000E-02	224.775
115	0.575000E-02	225.854
116	0.580000E-02	227.973
117	0.585000E-02	228.482
118	0.590000E-02	228.934
119	0.595000E-02	230.314
120	0.600000E-02	230.961
121	0.605000E-02	231.353
122	0.610000E-02	232.023
123	0.615000E-02	232.187
124	0.620000E-02	234.333
125	0.625000E-02	234.820
126	0.630000E-02	236.077
127	0.635000E-02	236.604
128	0.640000E-02	237.671
129	0.645000E-02	238.349
130	0.650000E-02	239.269
131	0.655000E-02	239.967
132	0.660000E-02	240.050
133	0.665000E-02	242.428
134	0.670000E-02	244.809
135	0.675000E-02	245.703
136	0.680000E-02	248.848
137	0.685000E-02	250.122
138	0.690000E-02	250.135
139	0.695000E-02	251.327
140	0.700000E-02	251.356
141	0.705000E-02	251.544
142	0.710000E-02	252.696
143	0.715000E-02	252.731
144	0.720000E-02	252.826
145	0.725000E-02	254.045

146	0.730000E-02	255.588
147	0.735000E-02	255.936
148	0.740000E-02	258.845
149	0.745000E-02	259.559
150	0.750000E-02	259.613
151	0.755000E-02	260.046
152	0.760000E-02	260.628
153	0.765000E-02	261.008
154	0.770000E-02	261.185
155	0.775000E-02	261.531
156	0.780000E-02	262.128
157	0.785000E-02	262.237
158	0.790000E-02	262.727
159	0.795000E-02	263.178
160	0.800000E-02	263.503
161	0.805000E-02	264.066
162	0.810000E-02	264.301
163	0.815000E-02	264.491
164	0.820000E-02	264.728
165	0.825000E-02	265.586
166	0.830000E-02	269.652
167	0.835000E-02	271.928
168	0.840000E-02	272.150
169	0.845000E-02	273.784
170	0.850000E-02	274.667
171	0.855000E-02	274.995
172	0.860000E-02	275.158
173	0.865000E-02	278.007
174	0.870000E-02	279.032
175	0.875000E-02	280.049
176	0.880000E-02	280.089
177	0.885000E-02	280.380
178	0.890000E-02	280.779
179	0.895000E-02	280.885
180	0.900000E-02	281.120
181	0.905000E-02	281.155
182	0.910000E-02	281.284
183	0.915000E-02	281.394
184	0.920000E-02	281.707
185	0.925000E-02	283.283
186	0.930000E-02	283.324
187	0.935000E-02	283.371
188	0.940000E-02	283.556
189	0.945000E-02	284.575
190	0.950000E-02	284.579
191	0.955000E-02	284.692
192	0.960000E-02	284.880
193	0.965000E-02	285.136
194	0.970000E-02	285.480
195	0.975000E-02	285.854

```
196    0.980000E-02    285.907
197    0.985000E-02    286.616
198    0.990000E-02    287.837
199    0.995000E-02    288.408
200    0.100000E-01    288.462
```

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 m_o 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 χ^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 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
ERROR: NO INTERSECTION BETWEEN 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 > = 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 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 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 α, β, and θ, 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*.

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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 <u>underlined</u> 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]

<u>Random number seed</u>
Needed by MATCHR's built-in random number generator.

675	Random number seed
0	Output dump controller
1	Stress formulation is to be used
2	Type of S/N variation
0	Request for truncated Normal median S/N curve
0	Controls materials process variation
75000.	Value of stress used in life calculation

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
```

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}
86000.	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)

1	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

201700.	215300.	2	10

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

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
6	0.10	2 Number of points in division 2, stress ratio, region
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}

Figure 6-9 Format for File RELATD

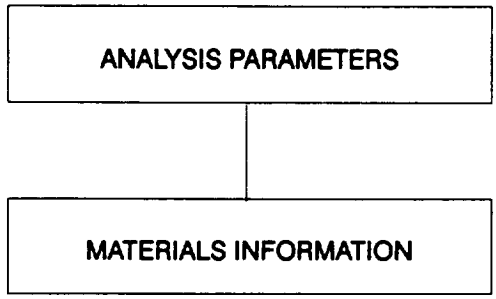

Figure 6-10 Data Blocks for Input File

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[40]
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[41]

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

STRESS
[RE]

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 **RAND** provided. **STRESS** 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.

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

[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[42]

Stress tensile point S_o (psi). Must be non-negative. A value of zero indicates no tensile point.

NUMREG **NNODAT**
[INT] [INT]

Data regions[43]

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[44]

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 ∞.

CZERO
[RE]

Prior information on coefficient of variation of fatigue strength[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 **CZERO** is not in use.

---

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

[43] Extension of the S/N curve to the right is discussed on *Page 2-17*.

[44] Life region boundaries are discussed on *Page 2-15*.

[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*.

MPNT(L)	MZERO(1,L)	MZERO(2,L)
[INT]	[RE]	[RE]

Prior information on the materials shape parameter m[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[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 δ 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_o of the Bayesian prior distribution of the shape parameter m. Must be positive. Required when **DELTA(L)** is non-zero.

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

KRATIO	LAMN
[RE]	[RE]

---

[46] The explicit constraint on the materials shape parameter provided by prior information on the materials shape parameter is discussed on *Page 2-12*.

[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 λ_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(*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,[48] 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

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

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

RAWSTR(I,J)	**RAWNF(I,J)**
[RE]	[RE]

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.[49] 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*.

6.3.5 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.[50] 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*.

```
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

```
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            MATERIAL INPUT


DESCRIPTION:  -320 HOURGLASS + STRAIGHT

YIELD STRENGTH                    0.17860E+06

ULTIMATE STRENGTH                 0.22040E+06

NUMBER OF POINTS                  20
```

ORIGINAL S/N STRESS	LIFE	STRESS RATIO	REGION	TRANSFORMED S/N STRESS	LIFE
0.15000E+06	65000.	0.05	1	0.11086E+06	65000.
0.14000E+06	261000.	0.05	1	0.99773E+05	261000.
0.12000E+06	265000.	0.05	1	0.79814E+05	265000.
0.16000E+06	377000.	0.05	1	0.12280E+06	377000.
0.13000E+06	694000.	0.05	1	0.89449E+05	694000.
0.11000E+06	2175000.	0.05	1	0.70802E+05	2175000.
0.10000E+06	4198000.	0.05	1	0.62353E+05	4198000.
0.10500E+06	5053000.	0.05	1	0.66510E+05	5053000.
0.92000E+05	9210000.	0.05	1	0.55964E+05	9210000.
0.95000E+05	9667000.	0.05	1	0.58323E+05	9667000.
0.15000E+06	418000.	0.05	1	0.11086E+06	418000.
0.14000E+06	732000.	0.05	1	0.99773E+05	732000.
0.13000E+06	740000.	0.05	1	0.89449E+05	740000.
0.12000E+06	859000.	0.05	1	0.79814E+05	859000.
0.11000E+06	1181000.	0.05	1	0.70802E+05	1181000.
0.10000E+06	4020000.	0.05	1	0.62353E+05	4020000.
0.92000E+05	5917000.	0.05	1	0.55964E+05	5917000.
0.94000E+05	6522000.	0.05	1	0.57532E+05	6522000.
0.90000E+05	6891000.	0.05	1	0.54416E+05	6891000.
0.86000E+05	4460000.	0.05	1	0.51374E+05	4460000.

```
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:

REGION      # OF POINTS     LOWER BOUND     UPPER BOUND

    1           2             3.0000          5.0000
```

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 Io = (0.092758540, 0.181539600)
Jo = (3.596348000, 5.874000000)

POINT ESTIMATES OF C AND m FOR EACH REGION

REGION	E(C)	E(m)
1	0.122759400	4.735174

POSTERIOR CREDIBILITY RANGE ON m FOR EACH REGION

REGION	LOWER BOUND	UPPER BOUND
1	3.5963	5.0000

PARAMETER VALUES FOR MEDIAN S/N CURVE

NUMBER OF REGIONS: 1 E(BETAo) = 8.6103 E(k) = 14.5351

REGION	m	K	LIFE BOUND	STRESS BOUND

```
    1        4.29817       0.21044E+07      0.100E+37          0.00000E+00


  SELECTED VALUES OF S/N CURVE PARAMETERS

  NUMBER OF REGIONS:     1      BETAo =    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:     675.000000000000
                      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:            lPHI:   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 <u>underlined</u> 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.

675	Random number seed
0	Output dump controller
2	Strain formulation is to be used
2	Type of S/N variation
0	Request for truncated Normal median S/N curve
0	Controls materials process variation
1.5	Value of strain used in life calculation

Description of specific material S/N data set

'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

4	7	1

1.8	105	0.475	1.325	S_1, N_1, S_{P1}, S_{E1}
1.5	260	0.27	1.23	S_2, N_2, S_{P2}, S_{E2}
1.3	600	0.18	1.12	S_3, N_3, S_{P3}, S_{E3}
1.0	1950	0.115	0.885	S_4, N_4, S_{P4}, S_{E4}
1.49	186			S_5, N_5
1.47	190			S_6, N_6
2.02	55			S_7, N_7
4.17				Tensile point
0	0.00	0.00		Prior information on m_P
0	0.00	0.00		Prior information on m_E

- -

0.00	0.00	0.00	Bayesian prior distribution information on m_P
0.00	0.00	0.00	Bayesian prior distribution information on m_E

- -

0.0	0.0	Materials process variation information

Figure 6-11 Format for File SPECFD

1	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

2	12	2

1.8	202	0.35	1.45	S_1, N_1, S_{P1}, S_{E1}
1.2	980	0.135	1.045	S_2, N_2, S_{P2}, S_{E2}
0.8	4000			S_3, N_3
1.476	340			S_4, N_4
2.25	185			S_5, N_5
0.78	5000			S_6, N_6
1.47	350			S_7, N_7
2.0	240			S_8, N_8
1.05	1870			S_9, N_9
2.05	296			S_{10}, N_{10}
1.48	700			S_{11}, N_{11}
1.05	2000			S_{12}, N_{12}
13.07				Tensile point 1
8.72				Tensile point 2

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[51]
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)**
[RE]	[RE]	[RE]	[RE]

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)**
[RE]	[RE]

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)
[RE]

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.*

MPNTP(1) [INT]	**MZEROP(1,1)** [RE]	**MZEROP(2,1)** RE]
MPNTE(1) [INT]	**MZEROE(1,1)** [RE]	**MZEROE(2,1)** [RE]

Prior information on the materials shape parameters m_p and m_E[53]

The number of **MZEROP** values for the plastic component, the lower and upper bound for the range of m_P, the number of **MZEROE** values for the elastic component, and the lower and upper bound for the range of m_E. If **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.

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 **MZEROP( )** for the plastic strain component.

MZEROP(1,1) The lower bound on the range of m_P or the value of the point prior for m_P.

MZEROP(2,1) The upper bound on the range of m_P. Program requires that the value be zero if a point prior for m_P is specified.

MPNTE(1) The number of points, 0, 1, or 2 (no prior on m_E, a point prior on m_E, or a prior over a range of m_E, respectively), in **MZEROE( )** for the elastic strain component.

MZEROE(1,1) The lower bound on the range of m_E or the value of the point prior for m_E.

MZEROE(2,1) 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.

DELTAP(1) [RE]	**MOP(1)** [RE]	**SIG2P(1)** [RE]
DELTAE(1) [RE]	**MOE(1)** [RE]	**SIG2E(1)** [RE]

[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[54]

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 both plastic and elastic strain components.

DELTAP(1)	The shape parameter δ_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 **DELTAP(1)** is non-zero.
SIG2P(1)	${\sigma_P}^2$, the known variance of ln(*fatigue life*), V (ln N | ln S_P), for the plastic strain components. Must be non-negative.
DELTAE(1)	The shape parameter δ_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 **DELTAE(1)** is non-zero.
SIG2E(1)	${\sigma_E}^2$, the known variance of ln(*fatigue life*), V (ln N | ln S_E), for the elastic strain components. 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 λ_K^*, the ratio *MED* K^*/*MED* K where *MED* K^* is the median value over all heats for the strain (%) at a life of one cycle, and *MED* K is the median value for the specific S/N data for the strain (%) at a life of one cycle. **LAMN** is the ratio of the variance of ln(*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,[55] 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.

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 *Secion 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.[56] In this case, the median S/N curve is based on the empirical median

[56] The truncated Normal distribution for the materials model shape parameters m_P and m_E is discussed on *Page 2-14.*

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, **VARY** = 2, and no process variation **MPROC** = 0. The data set consists of four data points with given plastic and elastic strain components, **NDC(0)** = 4, the total number of strain/life points is seven, **NPTS(0)** = 7, and the number of tensile points, **NTENS(0)**, is one. No explicit ranges on m_P and m_E are provided (**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 **NSETS** = 0. If further explanation of files SPECFD and 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 SPECFO. The DUMP file contains the results of the plastic/elastic strain decomposition and the materials characterization model information aggregation calculations.[57] Finally, the IOUTPR file gives an echo of the analysis parameters, the randomly selected S/N curve, and the resulting life at **STRAIN** = 1.5%. The dump parameter **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
```

[57] The information aggregation calculations are discussed on *Pages 2-6* through *2-14.*

```
0    0.00    0.00
0    0.00    0.00
```

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:  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

     TOTAL STRAIN     LIFE     PLASTIC STRAIN     ELASTIC STRAIN

         1.8000       105.       0.47500           1.32500
         1.5000       260.       0.27000           1.23000
         1.3000       600.       0.18000           1.12000
         1.0000      1950.       0.11500           0.88500
         1.4900       186.
         1.4700       190.
         2.0200        55.


TENSILE DATA

         4.17000


EXOGENOUS INFORMATION
```

```
EXPLICIT CONSTRAINT ON mp
      NUMBER OF POINTS IN RANGE:  0

            LOWER BOUND      UPPER BOUND

              0.0000           0.0000


EXPLICIT CONSTRAINT ON me
      NUMBER OF POINTS IN RANGE:  0

            LOWER BOUND      UPPER BOUND

              0.0000           0.0000
```

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

     Jop = (  1.300915000,  2.791690000)     mp =  2.046302


RESULTS FOR GIVEN PLASTIC COMPONENT DATA


PARAMETER VALUES FOR MEDIAN S/N CURVE

          m              K              E(k)

      2.04630       0.44105E+01       1.4721
```

95% CONFIDENCE INTERVAL AND POINT ESTIMATE OF me
FOR GIVEN ELASTIC COMPONENTS

Joe = (2.411092000, 11.447510000) me = 6.929300

RESULTS FOR GIVEN ELASTIC COMPONENT DATA

PARAMETER VALUES FOR MEDIAN S/N CURVE

m	K	E(k)
6.92930	0.27148E+01	0.9925

ESTIMATED STRAIN DECOMPOSITION

SPECIFIC MATERIAL

DESCRIPTION: H2/HIGH PRESSURE/HIGH TEMPERATURE
NUMBER OF DATA POINTS: 8

LIFE	TOTAL STRAIN	PLASTIC STRAIN	ELASTIC STRAIN
105.	1.8000	0.47500	1.32500
260.	1.5000	0.27000	1.23000
600.	1.3000	0.18000	1.12000
1950.	1.0000	0.11500	0.88500
186.	1.4900	0.31553	1.17447
190.	1.4700	0.30950	1.16050
55.	2.0200	0.58607	1.43393
1.	6.7367	4.17000	2.56673

RELATED MATERIALS

NUMBER OF DATA SETS: 0

RESULTS OF INFORMATION AGGREGATION

95% CONFIDENCE INTERVAL AND POINT ESTIMATE OF mp
FOR ESTIMATED PLASTIC COMPONENTS

Jop = (1.958583000, 2.176915000) mp = 2.067749

POSTERIOR CREDIBILITY RANGE ON mp FOR ESTIMATED PLASTIC COMPONENTS

mp = (1.9586, 2.1769)

RESULTS FOR ESTIMATED PLASTIC COMPONENT DATA

PARAMETER VALUES FOR MEDIAN S/N CURVE

m	K	E(k)
2.06775	0.41636E+01	1.4170

95% CONFIDENCE INTERVAL AND POINT ESTIMATE OF me
FOR ESTIMATED ELASTIC COMPONENTS

Joe = (6.173140000, 8.136055000) me = 7.154597

POSTERIOR CREDIBILITY RANGE ON me FOR ESTIMATED ELASTIC COMPONENTS

me = (6.1731, 8.1361)

RESULTS FOR ESTIMATED ELASTIC COMPONENT DATA

PARAMETER VALUES FOR MEDIAN S/N CURVE

m	K	E(k)
7.15460	0.25704E+01	0.9371

```
TOTAL STRAIN E(BETAo) = 25.5248


SELECTED VALUES OF S/N CURVE PARAMETERS

NUMBER OF REGIONS:    1     BETAo =  21.1961

REGION        m                K          LIFE BOUND     STRESS BOUND

   1        2.11391       0.39587E+01     0.100E+37      0.00000E+00




SELECTED VALUES OF S/N CURVE PARAMETERS

NUMBER OF REGIONS:    1     BETAo =  23.5854

REGION        m                K          LIFE BOUND     STRESS BOUND

   1        6.55215       0.27405E+01     0.100E+37      0.00000E+00


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
Kp:      3.95868     Mp:      2.11391
Ke:      2.74054     Me:      6.55215
PHI =    0.957870     Z:      1.00000
STRAIN:      1.50000     LIFE:      187.393
```

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 δ may be negative. Second, a value of δ was specified, but the value for m_o 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 δ_E may be negative. Second, a value of δ_E was specified, but the value for m_{oE} 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 δ_P may be negative. Second, a value of δ_P was specified, but the value for m_{oP} is not positive. Check file SPECFD.

ERROR: Co TOO LOW

Fatal, Stress Formulation 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 χ^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
ERROR: NO INTERSECTION BETWEEN 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 m_P and m_E. The number of points for the prior range on m_P or m_E 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 > = 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 GTLIF2 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_o and J_o; 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 β 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 β 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 β. 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 β. 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.

PRECEDING PAGE BLANK NOT FILMED

0	Output dump controller
20 100 200	Indices for first and last life for linear regression and number of lives in LOWLIF

Figure 6-13 Format for File BFITD

1	5.E-5	2531849.474236	1, $F(N_1)$, N_1
2	1.E-4	3245429.147959	2, $F(N_2)$, N_2
3	1.5E-4	3491943.38476	3, $F(N_3)$, N_3
4	2.E-4	3807060.913539	4, $F(N_4)$, N_4
5	2.5E-4	3903086.793213	5, $F(N_5)$, N_5
.	.	.	. .
.	.	.	. .
.	.	.	. .
196	9.8E-3	56611082.90833	196, $F(N_{196})$, N_{196}
197	9.85E-3	56827320.11307	197, $F(N_{197})$, N_{197}
198	9.9E-3	57986738.95375	198, $F(N_{198})$, N_{198}
199	9.95E-3	59037352.04528	199, $F(N_{199})$, N_{199}
200	1.E-2	59300005.83862	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 <u>underlined</u> and followed by a description and a list of options, when appropriate; the program and file names are indicated by UPPERCASE letters.

IOUT
[INT]

<u>Output dump controller</u>
BFIT has the ability to write intermediate calculations to file IOUTPR. The following integer values control the "dump" of BFIT's calculations.

IOUT = 0 regression parameters only

IOUT = 10 regression and parameter estimation calculations

START	**END**	**M**
[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 linear regression to estimate β. **END** is the index of the last element of **LIFE(I)** to be used in the linear regression to estimate β. **M** is the total number of lives provided in file LOWLIF. $1 \leq$ **START** $<$ **END** $\leq$ **M**

6.4.3.2 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, ..., **M**, where **FOFN** and **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 β 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 β. 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 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 LOWLIF. The linear regression to obtain β was performed by using failure times 20 through 200, **START** = 20 and **END** = 200. The dump parameter **IOUT** is zero, hence only important regression information is in file 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 β = 1.85889.

Input File - BFITD

```
0
20    200    200
```

Input File - LOWLIF

```
1,  5.E-5,  12128.88138813
2,  1.E-4,  13234.06413769
3,  1.5E-4,  13777.54886666
4,  2.E-4,  18290.37461814
5,  2.5E-4,  18688.80786339
6,  3.E-4,  35612.77878656
7,  3.5E-4,  47497.8018622
8,  4.E-4,  51934.74438263
9,  4.5E-4,  52518.78716911
10,  5.E-4,  53559.43637382
11,  5.5E-4,  53645.49702172
12,  6.E-4,  54851.2225929
13,  6.5E-4,  57513.3189619
14,  7.E-4,  68077.77118247
15,  7.5E-4,  68827.25275096
16,  8.E-4,  72556.30877838
17,  8.5E-4,  72749.52158307
18,  9.E-4,  75602.449978
19,  9.5E-4,  76079.32580619
20,  1.E-3,  78598.59366489
21,  1.05E-3,  79316.56449927
22,  1.1E-3,  82143.75077125
23,  1.15E-3,  82459.303944
24,  1.2E-3,  84409.93934894
25,  1.25E-3,  86330.18444186
26,  1.3E-3,  86743.17312626
27,  1.35E-3,  90236.36829336
28,  1.4E-3,  93683.69936791
29,  1.45E-3,  94648.94058573
30,  1.5E-3,  101180.6660291
31,  1.55E-3,  101450.4345774
32,  1.6E-3,  101805.4813387
33,  1.65E-3,  104639.8405719
34,  1.7E-3,  105079.5788451
35,  1.75E-3,  105698.9303809
36,  1.8E-3,  106926.2200427
37,  1.85E-3,  107110.0748629
```

```
38,  1.9E-3,  108928.2182923
39,  1.95E-3,  110807.9962046
40,  2.E-3,  111315.1131887
41,  2.05E-3,  112452.429632
42,  2.1E-3,  112522.1441635
43,  2.15E-3,  112566.1271853
44,  2.2E-3,  114118.8313652
45,  2.25E-3,  118605.4464924
46,  2.3E-3,  123988.2200704
47,  2.35E-3,  125049.3278475
48,  2.4E-3,  125198.1377061
49,  2.45E-3,  127014.5169407
50,  2.5E-3,  127189.082832
51,  2.55E-3,  127449.4762093
52,  2.6E-3,  127965.2958514
53,  2.65E-3,  131569.2337822
54,  2.7E-3,  132797.2842955
55,  2.75E-3,  136704.5445851
56,  2.8E-3,  137844.3304032
57,  2.85E-3,  141256.2032728
58,  2.9E-3,  144686.6792343
59,  2.95E-3,  148943.931824
60,  3.E-3,  151889.7604185
61,  3.05E-3,  152443.9680104
62,  3.1E-3,  152765.4826451
63,  3.15E-3,  153737.6240023
64,  3.2E-3,  154504.6006673
65,  3.25E-3,  154893.5260934
66,  3.3E-3,  155058.0613059
67,  3.35E-3,  155438.4523919
68,  3.4E-3,  155765.0458041
69,  3.45E-3,  157231.8488651
70,  3.5E-3,  157322.0032301
71,  3.55E-3,  157334.6878786
72,  3.6E-3,  159217.4797218
73,  3.65E-3,  159237.7883244
74,  3.7E-3,  160089.2553861
75,  3.75E-3,  162368.3235312
76,  3.8E-3,  162966.4870006
77,  3.85E-3,  165577.9580924
78,  3.9E-3,  167679.8559978
79,  3.95E-3,  169605.2253805
80,  4.E-3,  171396.0255256
81,  4.05E-3,  173056.8659963
82,  4.1E-3,  173264.2555491
83,  4.15E-3,  175317.5358395
84,  4.2E-3,  175759.5842457
85,  4.25E-3,  176485.1745216
86,  4.3E-3,  179077.8791186
87,  4.35E-3,  180140.9776735
```

88,	4.4E-3,	180774.5060422
89,	4.45E-3,	181698.2378063
90,	4.5E-3,	185495.3261302
91,	4.55E-3,	186106.5667858
92,	4.6E-3,	186124.7899641
93,	4.65E-3,	186311.4320637
94,	4.7E-3,	187524.7074411
95,	4.75E-3,	189345.7559455
96,	4.8E-3,	191669.5592815
97,	4.85E-3,	191968.5642588
98,	4.9E-3,	193410.6184889
99,	4.95E-3,	195233.4752379
100,	5.E-3,	196417.5350341
101,	5.05E-3,	196837.5590899
102,	5.1E-3,	197201.7233965
103,	5.15E-3,	197313.5075424
104,	5.2E-3,	197856.3835949
105,	5.25E-3,	198039.3329058
106,	5.3E-3,	198703.016903
107,	5.35E-3,	199455.6751859
108,	5.4E-3,	200800.8736717
109,	5.45E-3,	201363.7000791
110,	5.5E-3,	201974.7490392
111,	5.55E-3,	203514.9107572
112,	5.6E-3,	203591.7954022
113,	5.65E-3,	204767.3596533
114,	5.7E-3,	208227.3979182
115,	5.75E-3,	209245.5653271
116,	5.8E-3,	209552.5166912
117,	5.85E-3,	209789.7418354
118,	5.9E-3,	210264.9017463
119,	5.95E-3,	210742.9422861
120,	6.E-3,	211162.3206324
121,	6.05E-3,	211226.3769278
122,	6.1E-3,	211585.9292961
123,	6.15E-3,	213303.6603755
124,	6.2E-3,	213739.4638384
125,	6.25E-3,	213767.5927345
126,	6.3E-3,	214182.6618133
127,	6.35E-3,	215428.2841933
128,	6.4E-3,	216000.03853
129,	6.45E-3,	216823.8859702
130,	6.5E-3,	218007.4191103
131,	6.55E-3,	218110.4781512
132,	6.6E-3,	219108.985075
133,	6.65E-3,	220507.7721362
134,	6.7E-3,	221886.4454467
135,	6.75E-3,	221973.6356509
136,	6.8E-3,	221984.7199964
137,	6.85E-3,	223075.4707179

138,	6.9E-3,	223499.3480405
139,	6.95E-3,	224020.3497587
140,	7.E-3,	224333.6221698
141,	7.05E-3,	224471.6622662
142,	7.1E-3,	224877.0230508
143,	7.15E-3,	225518.4058553
144,	7.2E-3,	225545.2069757
145,	7.25E-3,	226004.390243
146,	7.3E-3,	226567.1316152
147,	7.35E-3,	227728.1156545
148,	7.4E-3,	229415.1208135
149,	7.45E-3,	233295.4723347
150,	7.5E-3,	233938.9524359
151,	7.55E-3,	233993.51553
152,	7.6E-3,	234762.8256886
153,	7.65E-3,	235095.1047653
154,	7.7E-3,	235458.7336267
155,	7.75E-3,	235552.6222209
156,	7.8E-3,	236536.8532418
157,	7.85E-3,	237723.0244822
158,	7.9E-3,	238018.3933596
159,	7.95E-3,	238720.7945104
160,	8.E-3,	239973.244866
161,	8.05E-3,	240023.6488295
162,	8.1E-3,	240752.0413359
163,	8.15E-3,	241656.369868
164,	8.2E-3,	242247.9964353
165,	8.25E-3,	245561.0195976
166,	8.3E-3,	246197.8431254
167,	8.35E-3,	246764.8000842
168,	8.4E-3,	247077.518534
169,	8.45E-3,	247518.8531417
170,	8.5E-3,	247687.7147611
171,	8.55E-3,	248238.3713404
172,	8.6E-3,	248619.9877746
173,	8.65E-3,	248625.3856967
174,	8.7E-3,	249933.4362827
175,	8.75E-3,	250021.4723994
176,	8.8E-3,	250120.5415177
177,	8.85E-3,	250951.611891
178,	8.9E-3,	251170.1497572
179,	8.95E-3,	251829.1388452
180,	9.E-3,	252075.203504
181,	9.05E-3,	253434.9835603
182,	9.1E-3,	253949.9140215
183,	9.15E-3,	254855.9036281
184,	9.2E-3,	254872.2306311
185,	9.25E-3,	255055.0616528
186,	9.3E-3,	255161.0192462
187,	9.35E-3,	255291.4438788

```
188,  9.4E-3,  257137.0946024
189,  9.45E-3,  257501.2014016
190,  9.5E-3,  258966.2579515
191,  9.55E-3,  259012.6451334
192,  9.6E-3,  259100.0649377
193,  9.65E-3,  259289.3837005
194,  9.7E-3,  259768.1414826
195,  9.75E-3,  259810.4523777
196,  9.8E-3,  260177.6916228
197,  9.85E-3,  260620.4330979
198,  9.9E-3,  261403.8795405
199,  9.95E-3,  262929.5666654
200,  1.E-2,  263349.9495276
```

Output File - BFITO

```
Copyright (C) 1990, California Institute of Technology.  U.S. Government
Sponsorship under NASA Contract NAS7-918 is acknowledged.


The solution is
   Beta:  .1858893E+01
```

Output File - IOUTPR

```
MEANX =      12.1168219315321      MEANY =   -5.34883972165613
SX2 =    0.102189088449329      SXY =    0.189958590979769
B =     1.85889309575318      LNC =    -27.8727163526519
```

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 α and θ, given β 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*.

20			Output dump controller
20	200	200	Indices for first and last life for the regression and the number of lives in LOWLIF
2.75D6	0.0014434	1.80	Initial guesses for θ and α, and the given value of β
1.0	1.0	1.0D-4	Scaling factors for θ, α, and the lives

Figure 6-15 Format for File PARAMS

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 <u>underlined</u> and followed by a description and a list of options when appropriate; the program and file names are indicated by UPPERCASE letters.

IOUT
[INT]

<u>Output dump controller</u>
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]

<u>Analysis Indices</u>
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 α and θ. **END** is the index of the last element of **LIFE(I)** to be used in the regression to estimate α and θ. **MTOT** is the total number of lives provided in file LOWLIF. $1 \leq$ **START** $<$ **END** $\leq$ **MTOT**

XGUESS(1)	XGUESS(2)	B
[DRE]	[DRE]	[DRE]

Initial guesses and β

Initial guesses of the parameters θ and α, and the estimate of β provided by the user. See *Section 2.1.1* for a discussion on obtaining initial guesses for θ and α.

XSCALE(1)	XSCALE(2)	LSCALE
[DRE]	[DRE]	[DRE]

Scaling factors

Scaling factors for the parameters θ and α 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[58] 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, ..., **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 α and θ of the prior failure distribution, given β. 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-

[58] 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%.

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 α and θ 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 θ and α:

$$\theta_o = N^b_{.001} = (16450.6)^{1.8589} = 6.8780 \times 10^7$$

$$\mathbf{XGUESS(1)} = \left(N_{.001} * \mathbf{LSCALE}\right)^b = \left(16450.6 \times 10^{-4}\right)^{1.8589} = 2.522669$$

$$\mathbf{XGUESS(2)} = \alpha_o = -\ln .999/\ln 2 = 0.0014434$$

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 α = 0.014826, β = 1.85889, and θ = 1.14996x10^9. The number of iterations required to estimate α and θ 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 b of β provided by program BFIT.

Input File - LOWLIF

```
1,  5.E-5,  2171.08268607
2,  1.E-4,  2274.610282879
3,  1.5E-4,  5397.61433618
4,  2.E-4,  5436.913987152
5,  2.5E-4,  7590.725113991
6,  3.E-4,  8243.513935069
7,  3.5E-4,  9478.598493334
8,  4.E-4,  9592.334153456
9,  4.5E-4,  10961.29979166
10,  5.E-4,  11248.37224586
11,  5.5E-4,  12006.79530942
12,  6.E-4,  12394.79049961
13,  6.5E-4,  12458.42625798
14,  7.E-4,  12615.58511637
15,  7.5E-4,  13077.76799579
16,  8.E-4,  13245.47144751
17,  8.5E-4,  13298.6206169
18,  9.E-4,  13398.09257794
19,  9.5E-4,  14890.87886404
20,  1.E-3,  16450.60402927
21,  1.05E-3,  17930.50652629
22,  1.1E-3,  18318.76045862
23,  1.15E-3,  18616.07977373
24,  1.2E-3,  18825.78120489
25,  1.25E-3,  19031.35540271
26,  1.3E-3,  19896.02557763
27,  1.35E-3,  19896.45621919
28,  1.4E-3,  20283.58254505
29,  1.45E-3,  20716.21926102
30,  1.5E-3,  21090.96928527
31,  1.55E-3,  21771.34472699
32,  1.6E-3,  22473.12998514
33,  1.65E-3,  22483.11184718
34,  1.7E-3,  23031.93757268
35,  1.75E-3,  23576.6407008
36,  1.8E-3,  23744.0658441
37,  1.85E-3,  24557.7138378
38,  1.9E-3,  24806.64062718
39,  1.95E-3,  24983.14710955
40,  2.E-3,  25618.40563241
41,  2.05E-3,  25653.09540362
42,  2.1E-3,  26190.33441654
43,  2.15E-3,  26337.13572945
44,  2.2E-3,  28353.02541956
45,  2.25E-3,  28834.7318554
```

46,	2.3E-3,	29108.81760869
47,	2.35E-3,	29162.57978578
48,	2.4E-3,	29244.09472359
49,	2.45E-3,	29603.45152701
50,	2.5E-3,	29632.66087405
51,	2.55E-3,	30291.34679017
52,	2.6E-3,	30446.00942229
53,	2.65E-3,	30493.38478737
54,	2.7E-3,	30673.46359312
55,	2.75E-3,	30760.85836022
56,	2.8E-3,	31007.51798871
57,	2.85E-3,	32148.98623899
58,	2.9E-3,	32372.47132738
59,	2.95E-3,	32390.50914646
60,	3.E-3,	32844.36090394
61,	3.05E-3,	33014.88860404
62,	3.1E-3,	33190.12210164
63,	3.15E-3,	33270.0824175
64,	3.2E-3,	34615.02721604
65,	3.25E-3,	34748.27188751
66,	3.3E-3,	34872.98895736
67,	3.35E-3,	35068.65368964
68,	3.4E-3,	35096.39424284
69,	3.45E-3,	35281.89190532
70,	3.5E-3,	35425.55976141
71,	3.55E-3,	35897.72810911
72,	3.6E-3,	36560.07826949
73,	3.65E-3,	36588.46946974
74,	3.7E-3,	37605.65296311
75,	3.75E-3,	37978.29169689
76,	3.8E-3,	39305.80601728
77,	3.85E-3,	39374.22514173
78,	3.9E-3,	39490.47963762
79,	3.95E-3,	39699.64167016
80,	4.E-3,	39709.99000531
81,	4.05E-3,	40508.29704049
82,	4.1E-3,	41214.003737
83,	4.15E-3,	41506.81491461
84,	4.2E-3,	41532.92876058
85,	4.25E-3,	41622.05616043
86,	4.3E-3,	42243.61170326
87,	4.35E-3,	42632.96056193
88,	4.4E-3,	42744.1434916
89,	4.45E-3,	43060.05554056
90,	4.5E-3,	43148.21678663
91,	4.55E-3,	43425.31080851
92,	4.6E-3,	43485.79372142
93,	4.65E-3,	43665.25474881
94,	4.7E-3,	43679.23619109
95,	4.75E-3,	44087.79399035

```
96,  4.8E-3,  44466.30256251
97,  4.85E-3,  44838.15511878
98,  4.9E-3,  44938.80625138
99,  4.95E-3,  45160.62247766
100,  5.E-3,  45420.16962913
101,  5.05E-3,  45470.65979261
102,  5.1E-3,  45652.11464271
103,  5.15E-3,  46127.71679451
104,  5.2E-3,  46251.00996064
105,  5.25E-3,  46372.88535658
106,  5.3E-3,  47119.6325578
107,  5.35E-3,  47137.13100697
108,  5.4E-3,  48171.37806459
109,  5.45E-3,  48207.11856747
110,  5.5E-3,  48318.70721881
111,  5.55E-3,  48931.61143896
112,  5.6E-3,  49703.44909796
113,  5.65E-3,  49956.33191574
114,  5.7E-3,  50234.61968773
115,  5.75E-3,  50398.55301772
116,  5.8E-3,  50644.56677104
117,  5.85E-3,  51204.9658348
118,  5.9E-3,  52501.46119135
119,  5.95E-3,  52904.03713305
120,  6.E-3,  53010.6194896
121,  6.05E-3,  53167.75826465
122,  6.1E-3,  53357.64587097
123,  6.15E-3,  53468.23112726
124,  6.2E-3,  53929.93276736
125,  6.25E-3,  54082.80324984
126,  6.3E-3,  54293.44219992
127,  6.35E-3,  54346.43533946
128,  6.4E-3,  55234.56773908
129,  6.45E-3,  55326.77795268
130,  6.5E-3,  55585.55479447
131,  6.55E-3,  55938.43019878
132,  6.6E-3,  56350.38162224
133,  6.65E-3,  56711.10774186
134,  6.7E-3,  56817.21030027
135,  6.75E-3,  56967.09611928
136,  6.8E-3,  57346.04643495
137,  6.85E-3,  57566.47058465
138,  6.9E-3,  57613.30154789
139,  6.95E-3,  57832.43925853
140,  7.E-3,  58385.56620338
141,  7.05E-3,  58462.89978311
142,  7.1E-3,  58624.28036547
143,  7.15E-3,  58782.60363557
144,  7.2E-3,  58971.56159982
145,  7.25E-3,  59110.23542496
```

146,	7.3E-3,	59122.95734245
147,	7.35E-3,	59272.60177966
148,	7.4E-3,	59324.77926608
149,	7.45E-3,	59465.20911553
150,	7.5E-3,	59763.82855003
151,	7.55E-3,	60154.6430269
152,	7.6E-3,	60396.64734786
153,	7.65E-3,	60406.48823455
154,	7.7E-3,	60515.31715323
155,	7.75E-3,	61252.11016131
156,	7.8E-3,	61363.38086049
157,	7.85E-3,	61453.41837845
158,	7.9E-3,	61578.69974975
159,	7.95E-3,	61600.93010134
160,	8.E-3,	62563.0930965
161,	8.05E-3,	63269.80866235
162,	8.1E-3,	63291.9881826
163,	8.15E-3,	63950.16419736
164,	8.2E-3,	63965.346384
165,	8.25E-3,	64102.87159225
166,	8.3E-3,	64415.36565053
167,	8.35E-3,	64541.8794529
168,	8.4E-3,	65163.69082135
169,	8.45E-3,	65519.40846814
170,	8.5E-3,	66120.52340431
171,	8.55E-3,	66308.5054934
172,	8.6E-3,	66494.47817761
173,	8.65E-3,	66554.46816072
174,	8.7E-3,	66844.66829289
175,	8.75E-3,	67103.77873876
176,	8.8E-3,	67345.80119819
177,	8.85E-3,	67352.66901473
178,	8.9E-3,	67546.08780309
179,	8.95E-3,	67603.05652641
180,	9.E-3,	67734.1771025
181,	9.05E-3,	67883.78039904
182,	9.1E-3,	68326.94572489
183,	9.15E-3,	68594.12670141
184,	9.2E-3,	68746.50091648
185,	9.25E-3,	69099.14523026
186,	9.3E-3,	69250.94593986
187,	9.35E-3,	69337.50660218
188,	9.4E-3,	69548.02239665
189,	9.45E-3,	69554.70766341
190,	9.5E-3,	69635.84059297
191,	9.55E-3,	70031.91794349
192,	9.6E-3,	70150.2009716
193,	9.65E-3,	70318.54906011
194,	9.7E-3,	70342.87926757
195,	9.75E-3,	71264.7486166

```
196,  9.8E-3,  71823.56061707
197,  9.85E-3,  72118.48961609
198,  9.9E-3,  72605.2876764
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

```
      THETA          ALPHA
F   0.252267E+01  0.144340E-02
J   0.252267E+01  0.144340E-02
F   0.603934E+00  0.215062E-02
J   0.603934E+00  0.215062E-02
F   0.106351E+01  0.218638E-02
J   0.106351E+01  0.218638E-02
F   0.162175E+01  0.241767E-02
J   0.162175E+01  0.241767E-02
F   0.246216E+01  0.282142E-02
J   0.246216E+01  0.282142E-02
F   0.421792E+01  0.359085E-02
J   0.421792E+01  0.359085E-02
F   0.806578E+01  0.503005E-02
J   0.806578E+01  0.503005E-02
F   0.188805E+02  0.856260E-02
J   0.188805E+02  0.856260E-02
F   0.311883E+02  0.119779E-01
J   0.311883E+02  0.119779E-01
```

```
F   0.395049E+02  0.141421E-01
J   0.395049E+02  0.141421E-01
F   0.419369E+02  0.147623E-01
J   0.419369E+02  0.147623E-01
F   0.421691E+02  0.148229E-01
J   0.421691E+02  0.148229E-01
F   0.421800E+02  0.148259E-01
J   0.421800E+02  0.148259E-01
F   0.421804E+02  0.148260E-01
J   0.421804E+02  0.148260E-01
```

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 λ_o for a specified assurance level. The resulting value of λ_o 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 β, θ, α

5.70	0.44E+12	0.75E-01

Figure 6-16 Format for File BAYESD

0	Output dump controller
0.95	Desired assurance level, A
1.454742E-11	λ_o lower bound, λ_{lb}
2.0E-11	λ_o upper bound, λ_{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 λ_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 λ_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.

BETA	**THETA**	**ALPHA**
[DRE]	[DRE]	[DRE]

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.

IOUT
[INT]

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.

A
[DRE]

Desired assurance level
The user requested assurance level specified as the decimal equivalent percentage.

LAML
[DRE]

Lower bound on λ_o
Lower bound λ_{lb} on the value of λ_o provided by the user.

LAMU
[DRE]

Upper bound on λ_o
Upper bound λ_{ub} on the value of λ_o provided by the user.

6.4.16 Options and Capabilities

LZERO is used to calculate λ_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 λ_o for a 95% assurance level (**A** = 0.95). As described in *Section 4.2.4*, the λ_o that corresponds to the 95% assurance level is obtained by using Mueller's iteration method. This method requires bounding values for λ_o. The bounding values for λ_o may be obtained by using

$$\lambda = \frac{-\ln(1-F)}{N^{\beta}}$$

which is *Equation 2-1* solved for λ. For the probability level F = .001, the B.1 life N = 1.64506 x 10^4 and β = 1.8588931, the above equation gives a value for λ of 1.454742 x 10^{-11}. Use this value for the lower bound λ_{lb}, and try 2.0 x 10^{-11} for λ_{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 λ_o = 1.581782 x 10^{-11}, the assurance at λ_{lb} = 0.9488418, and the assurance at λ_{ub} = 0.9532446. If λ_o is not bounded by λ_{lb} and λ_{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 λ_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

```
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The Gamma distribution parameters are

     Alpha  .1482598E-01
     Theta  .1149962E+10


Lambda lower bound  .1454742E-10     Assurance  0.9488418

Lambda upper bound  .2000000E-10     Assurance  0.9532446


At an assurance level of  0.9500000
  The value of lambda is  .1581782E-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 λ_o.

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 **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 β, θ, α

5.70	0.44E+12	0.75E-01

Number of failure and suspension times

2	3

123	Failure 1, t_1
75	Failure 2, t_2
30	Suspension 1, t_3
42	Suspension 2, t_4
10	Suspension 3, t_5

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 β, θ, and α. The operating experience block contains the number of failure and suspension data points and the operating times.

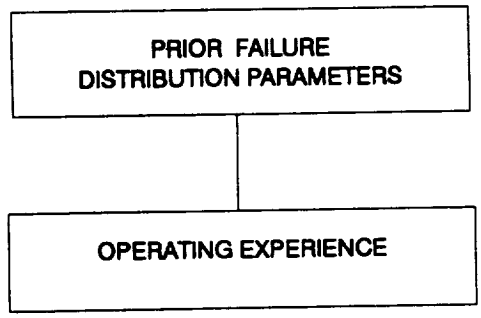

Figure 6-19 Data Blocks for Input File

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

BETA	**THETA**	**ALPHA**
[RE]	[RE]	[RE]

Prior distribution parameters
β, θ, and α of *Equation 2-1.* They are the parameters of the prior failure distribution.

Operating Experience Block

FAIL	**SUSP**
[INT]	[INT]

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.[61] The parameters of the prior failure distribution are **BETA** is 5.7, **THETA** is 4.4×10^{13}, and **ALPHA** is 0.075. The data set consists of no failure times and three suspension times (**FAIL** = 0, and **SUSP** = 3). The posterior failure distribution parameters are contained in file UBAYES and have the values **BETA** is 5.7, **THETUP** is 4.42052×10^{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

```
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                    BAYESIAN UPDATING SUMMARY


                PRIOR DISTRIBUTION          POSTERIOR DISTRIBUTION


PARAMETERS:

      BETA          5.700000                    5.700000

      ALPHA       0.750000E-01                0.750000E-01
```

[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.

```
THETA        0.440000E+12                    0.442052E+12

LAMBDA       0.170455E-12                    0.169663E-12

   ETA       0.173808E+03                    0.173949E+03

BLIVES

  B.01       0.345447E+02                    0.345729E+02

   B.1       0.517963E+02                    0.518386E+02

    B1       0.784758E+02                    0.785399E+02


                    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

1275	Random number seed
0	Value of output dump controller
500	f
0.05	Damping coefficient, ξ
10	N
1.0	T
1.0E+36	Clipping level (no clipping desired)
0.0	Phase angle shift, ψ
6 6 6 1 6	Number of narrow-band and sinusoidal processes

Narrow-band process information

'XP'	1.0	236.	File name 1, σ_{N1}, f_{o1}
'XT'	1.0	634.	File name 2, σ_{N2}, f_{o2}
'XM2'	1.0	424.	File name 3, σ_{N3}, f_{o3}
'XM3'	1.0	386.	File name 4, σ_{N4}, f_{o4}
'XV2'	1.0	740.	File name 5, σ_{N5}, f_{o5}
'XV3'	1.0	358.	File name 6, σ_{N6}, f_{o6}
'YP'	1.0	840.	File name 7, σ_{N7}, f_{o7}
'YT'	1.0	800.	File name 8, σ_{N8}, f_{o8}
'YM2'	1.0	275.	File name 9, σ_{N9}, f_{o9}
'YM3'	1.0	320.	File name 10, σ_{N10}, f_{o10}
'YV2'	1.0	1040.	File name 11, σ_{N11}, f_{o11}
'YV3'	1.0	1011.	File name 12, σ_{N12}, f_{o12}
'ZP'	1.0	1404.	File name 13, σ_{N13}, f_{o13}
'ZT'	1.0	1018.	File name 14, σ_{N14}, f_{o14}
'ZM2'	1.0	1224.	File name 15, σ_{N15}, f_{o15}
'ZM3'	1.0	1336.	File name 16, σ_{N16}, f_{o16}
'ZV2'	1.0	1392.	File name 17, σ_{N17}, f_{o17}
'ZV3'	1.0	1394.	File name 18, σ_{N18}, f_{o18}
'AERO'	1.0	1780.	File name 19, σ_{N19}, f_{o19}

Sinusoidal process information

'SIN1'	1.0	500.	7.4703	File name 1, A_1, f_{c1}, φ_1
'SIN2'	1.0	600.	90.3813	File name 2, A_2, f_{c2}, φ_2
'SIN3'	1.0	1000.	134.2636	File name 3, A_3, f_{c3}, φ_3
'SIN4'	1.0	1500.	176.7569	File name 4, A_4, f_{c4}, φ_4
'SIN5'	1.0	1800.	-69.0515	File name 5, A_5, f_{c5}, φ_5
'SIN6'	1.0	2000.	82.2972	File name 6, A_6, f_{c6}, φ_6

Figure 6-20 Format for File NBSIN

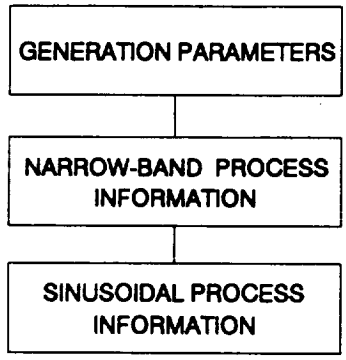

Figure 6-21 Data Blocks for the NBSIN Input File

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 <u>underlined</u> 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]

<u>Random number seed</u>
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
ξ 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

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[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
[DRE]

Sinusoidal phase angle shift, ψ
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 **SHIFT** equal to zero.

NRAND(1)	**NRAND(2)**	**NRAND(3)**	**NRAND(4)**	**NSIN**
[INT]	[INT]	[INT]	[INT]	[INT]

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.

NRAND(1)	the number of narrow-band time histories in load set 1
NRAND(2)	the number of narrow-band time histories in load set 2
NRAND(3)	the number of narrow-band time histories in load set 3
NRAND(4)	the number of narrow-band time histories in load set 4
NSIN	the number of sinusoidal time histories

Narrow-band Process Information Block

HISNAM(K)	**SIGMAN(K)**	**FO(K)**
[CHR]	[DRE]	[DRE]

Narrow-band process generation information
A block of **NRAND(0)** lines must be provided. **K** goes from 1 to **NRAND(0)**.[64] The line contains the time history storage file name, σ_N, and f_o. The file name is a character string up to six characters long enclosed by single quotes. σ_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_o (Hz) of *Equation 2-58* is the frequency of the narrow-band process.

[64] The total number of narrow-band time histories, **NRAND(0) = NRAND(1) + NRAND(2) + NRAND(3) + 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 φ. 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 φ (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 σ_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, **XC** is 0.03333 or 1/30. Ten points per cycle of frequency **F** are specified (**N** = 10) together with a history length **T** of 5×10^{-4} seconds. No clipping or phase angle shifting is desired (**CLIP** = 10^{36} and **SHIFT** = 0).

The three processes simulated for this problem are:

TYPE	NAME	FREQUENCY	PHASE ANGLE
1. Narrow-band	Axial	1306	NA
2. Narrow-band	Moment	498	NA
3. Sinusoid	Sin	2000	-13.1221

Since the three component processes are reference time histories, corresponding σ_N 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 **IOUT** is zero; therefore, no output is in file IOUTPR.

Input File - NBSIN

```
1275
0
2000
0.03333
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 - IOUTPR

```
0
```

Output File - AXIAL

```
-1.02049947079946
-0.981144655736187
-0.684737677520974
-0.366017655522998
 0.158197622376050
```

```
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.

User Specified

These are the time history storage files and are opened in NBSIN. They contain the time histories generated by NBSIN.