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DATING - A COMPUTER CODE FOR DETERMINING ALLOWABLE TEMPERATURES FOR DRY STORAGE OF SPENT FUEL IN INERT AND NITROGEN GASES

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ABSTRACT

The DATING (Determining Allowable Temperatures in Inert and Nitrogen Gases) code can be used to calculate allowable initial temperatures for dry storage of light-water-reactor spent fuel. The calculations are based on the life fraction rule using both measured data and mechanistic equations as reported by Chin et al. (1986). The code is written in FORTRAN and utilizes an efficient numerical integration method for rapid calculations on IBM-compatible personal computers. This report documents the technical basis for the DATING calculations, describes the computational method and code statements, and includes a user's guide with examples. The software for the DATING code is available through the National Energy Software Center operated by Argonne National Laboratory, Argonne, Illinois 60439.

CONTENTS

FIGURES

TABLES

INTRODUCTION

BACKGROUND

Creep rupture has been identified as the principal failure mechanism for spent fuel cladding during dry storage in inert or nitrogen gas. The temperatures and stresses during dry storage must be maintained low enough to prevent significant creep during storage. A maximum temperature limit, based on accumulated strain to fracture, has been recommended (Cunningham 1987) for storage of spent fuel; however, the temperature limit required to ensure that the cladding remain intact is dependent upon characteristics of the fuel and design of the dry storage system.

Chin et al. (1986) developed a technical basis for calculating limits based on specific fuel and dry storage system designs. The technical approach for calculating the temperature limit used a creep-rate- and creep-rupture-map concept in which changes in mechanism with decreasing temperature could be accounted for when calculating creep strain and rupture lifetimes. The creep rupture model has been presented and verified previously (Chin et al. 1986; Levy et al. 1987); however, this numerical computer model required hours of computation time and, hence, was not practical for determining temperature limits for the wide variety of conditions of interest for evaluating dry storage options. Furthermore, the code was written in the Hewlett-Packard language and could be used only on Hewlett-Packard computers.

The DATING Code was developed to provide a method of incorporating the Chin model on IBM-compatible personal computers. DATING is written in the FORTRAN computer language and can be compiled and executed on any computer which is compatible with the FORTRAN language. The code is being made available to the public for evaluation of dry storage options and to ensure compliance with NUREG 10CFR Part 72, Licensing Requirements for the Storage of Spent Fuel in an Independent Spent Fuel Storage Installation (ISFSI).

OVERVIEW OF LIFE FRACTION CONCEPT

The DATING computer code is based on calculating limiting conditions for dry storage of spent fuel based on creep-strain limits for fuel cladding and does not include other failure mechanisms such as those related to hydrogen.

Metallurgical tests for creep-strain limits are typically performed at constant temperature, whereas cladding-creep strain occurs during cooling (governed by radioactive decay) of spent fuel in storage. The constant temperature test data cannot be used directly to accurately predict creep strain and temperature limits. Variable conditions during dry storage, therefore, are accounted for by using a cumulative life-fraction model.

The cumulative life-fraction model assumes that the creep-rupture limit during temperature and stress transients can be estimated by summing damage which occurs in increments of time. The fraction of life consumed at the temperature and stress during each time increment is calculated and summed. The creep-rupture limit is assumed to be achieved when the sum of the incremental life fractions equals unity. The DATING computer code uses the life-fraction model to evaluate cladding integrity during dry storage of spent fuel.

Initial conditions (temperature and stress) are assumed and the fraction of cumulative damage occurring in each time step is integrated to a given time of storage. If the fraction is less than unity for the assumed initial temperature and stress, that condition is considered allowable for the dry-storage time considered. The maximum temperature for a given stress that results in a damage fraction equal-to or less-than unity is defined as the maximum allowable temperature for dry storage. The calculated rupture lifetime in DATING is adjusted to account for the reduced Zircaloy cladding ductility associated with the radiation damage. Radiation is assumed to reduce the rupture lifetime by a factor of ten. Annealing of radiation damage is calculated and the penalty on rupture time is reduced in proportion to the calculated fraction of damage annealed during storage.

The maps of creep-strain and creep-rupture time, which are included in the DATING model, allow the rupture lifetime to be calculated using the appropriate limiting creep mechanism (fastest creep) and limiting rupture mechanism (usually, the least time). The mechanistic equations have been adjusted to fit published creep-rate and rupture-time experimental data. Similarly, the annealing kinetics for radiation damage are based on published annealing kinetics experimentally determined by Steinberg, Weidinger, and Schaa (1984).

Analytical integration of the life fraction cannot be obtained because of the complicated forms of equations for temperature decay, creep rate, rupture life time, and radiation-damage annealing. Therefore, numerical methods are required to integrate the life fraction over time. The numerical computer code developed by Chin et al. (1986) uses a constant time step. The DATING numerical method uses a variable time step selected by the computer package called GEAR (Hindmarsh 1974). The computational efficiency for the variable time-step method greatly exceeds that for a constant time-step method while providing the same accuracy.

The calculation of life fraction during dry storage requires consideration of time-dependent temperature decay, and the time and temperature dependent effects of creep and annealing of radiation damage. These rate effects are described in the next section.

RATE EFFECTS

TEMPERATURE DECAY

The decay of radioisotopes during dry storage results in a decreasing temperature of the fuel cladding and, consequently, decreasing internal pressure and cladding-hoop stress level with increasing storage time. Thus, the rate of temperature decay is required for calculating creep rate and rupture time as a function of fuel storage time; the temperature decay is also dependent on the heat-transfer characteristics of the dry storage system. The temperature-time history of the fuel can be input through equations, such as those used for storage in helium or nitrogen, or in user-specified tabular form provided by the file, HIST.

Storage in Helium

For spent fuel stored in helium gas, DATING assumes a temperature decay function, derived by Levy et al. (1987), which has a two-parameter fit, i.e., the temperature is assumed to be the maximum of two temperatures (T_1 or T_2), where

$$T_1 = T_a \, (t/t_u)^{-0.34} \tag{1}$$

$$T_2 = T_b \, (t/t_u)^{-0.084} \tag{2}$$

$$T_b = T_a \, \frac{7^{0.084}}{7^{0.34}} \tag{3}$$

The constant T_a is determined by the fuel temperature in the storage system. Time, t, is expressed in years after discharge from reactor, t_u is 1 year, and temperature is expressed in K. At times less than 7 years, T_1 is used. Whereas, at times longer than 7 years, T_2 applies. A fuel burnup of 30 MWd/kgM is assumed.

Storage in Nitrogen

For storage in nitrogen gas, the time dependence of temperature is assumed to have the following form for a fuel burnup of 30 MWd/kgM:

$$\ln(T-273) = a_0 + a_1 \bullet \ln(\text{time}) \tag{4}$$

The coefficients a_0 and a_1 depend on burnup, B in MWd/kgU, and time in years. For times from 2 to 5 years,

$$a_0(B) = \exp[1.455 + 0.204 \bullet \ln(B) - 0.2391 \bullet 10^{-1} \bullet \ln(B)^2] \quad (5)$$

$$a_1(B) = -1.0339 + 0.0094 \bullet B \quad (6)$$

For times greater than 5 years,

$$a_0(B) = \exp[1.167 + 0.169 \bullet \ln(B)] \quad (7)$$

$$a_1(B) = -0.51391 \bullet 10^{-1} - 0.98780 \bullet 10^{-2} \bullet B + 0.92362 \bullet 10^{-4} \bullet B^2 \quad (8)$$

As for the helium gas case, the larger of the two temperatures is used by DATING.

CREEP RATE

The dominant creep rate mechanism depends on temperature and stress as seen in Figure 1. The creep rate is calculated for each of the five mechanisms, and the maximum rate is selected as the appropriate dominant rate for calculated cumulative-damage fraction. The temperature at each time is compared to the temperature limit for athermal creep. If the cladding temperature is below the athermal limit, then the creep rate is calculated based on the temperature at the athermal limit, not on the actual cladding temperature which is below the limit.

Creep mechanisms are known to depend on stress and temperature levels. At low stress levels, diffusional creep processes dominate. Whereas, at high-stress and high-temperature levels, dislocation climb is the rate controlling creep process. At high stresses, dislocation climb controls the creep rate. At low stresses, grain boundary sliding is the controlling creep mechanism. At stresses above 100 MPa, the temperature decay associated with dry storage results in conditions at which the creep is controlled initially by dislocation climb and is controlled at later times by grain boundary sliding.

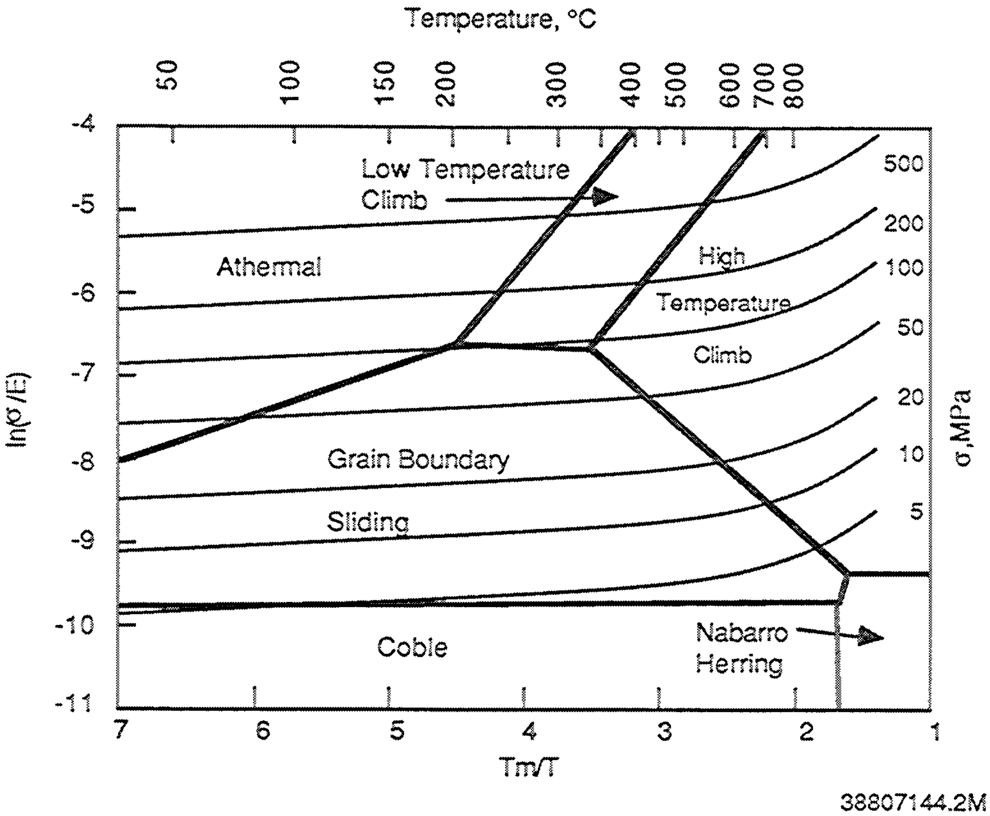


FIGURE 1. Creep-Rate Mechanism Map

The equations for the relevant creep mechanisms are given below for high-temperature climb, low-temperature climb, grain boundary sliding, Nabarro-Herring creep, and Coble creep. The equations are expressed in their reduced form as used in DATING. The corresponding mechanism equations and parameter values are given by Chin et al. (1986) which excludes calculating a creep rate for grain boundary lattice diffusion control. Therefore, DATING outputs a value of zero for that mechanism.

High-Temperature Climb:

$$\ln \dot{\varepsilon}_{HT} = 5 \bullet \ln(\sigma/E) + 55.75 - 14.15\left(\frac{T_M}{T}\right) + \ln\left(\frac{T_M}{T}\right) + \ln\left(\frac{E}{10^4}\right) \tag{9}$$

Low-Temperature Climb:

$$\ln \dot{\varepsilon}_{LT} = 7 \cdot \ln(\sigma/E) + 55.18 - 10.19\left(\frac{T_M}{T}\right) + \ln\left(\frac{T_M}{T}\right) + \ln\left(\frac{E}{10^4}\right) \tag{10}$$

Grain Boundary Sliding:

$$\ln \dot{\varepsilon}_{GBS} = 2 \cdot \ln(\sigma/E) + 20.74 - 9.9200\left(\frac{T_M}{T}\right) + \ln\left(\frac{T_M}{T}\right) + \ln\left(\frac{E}{10^4}\right) \tag{11}$$

Nabarro Herring:

$$\ln \dot{\varepsilon}_{NH} = \ln(\sigma/E) + 18.25 - 14.15\left(\frac{T_M}{T}\right) + \ln\left(\frac{T_M}{T}\right) + \ln\left(\frac{E}{10^4}\right) \tag{12}$$

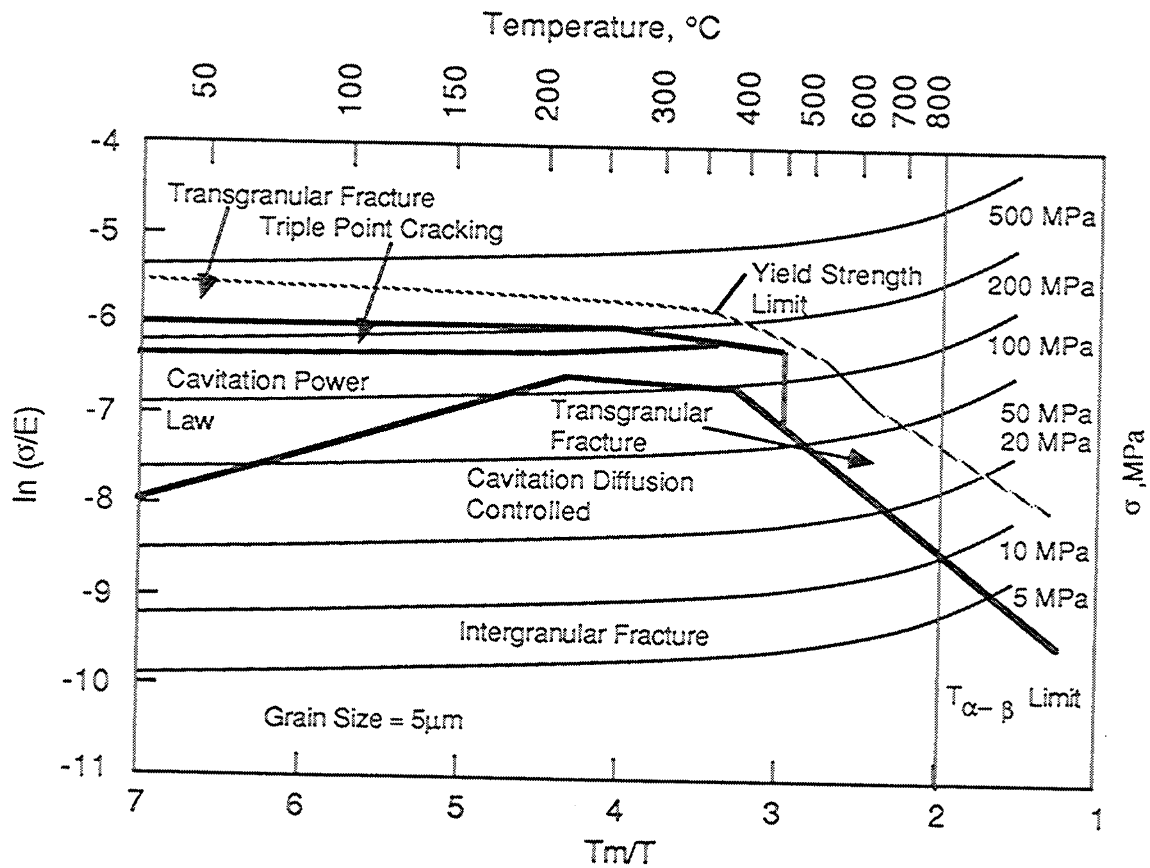
Coble:

$$\ln \dot{\varepsilon}_{CO} = \ln(\sigma/E) + 11.03 - 9.9200\left(\frac{T_M}{T}\right) + \ln\left(\frac{T_M}{T}\right) + \ln\left(\frac{E}{10^4}\right) \tag{13}$$

where $\dot{\varepsilon}$ = creep rate, s^{-1}
σ = stress, MPa
E = elastic modulus, MPa
T_M = melting temperature, K
T = cladding temperature, K

CREEP RUPTURE

The creep-rupture mechanisms also depend on temperature and stress as shown in Figure 2. Cavitation-rupture mechanisms control lifetimes for dry-storage temperatures and stresses. At low stresses (approximately less than 100 MPa), cavitation-diffusion-controlled rupture dominates. At high stresses, cavitation-power-law rupture dominates. A transition from diffusion control to power-law control of the rupture mechanism occurs during dry storage for initial stresses above 100 MPa. Additional creep-rupture



38807144.1M

FIGURE 2. Creep-Rupture Mechanism Map

mechanisms for Zircaloy cladding include transgranular cracking near the yield stress and triple-point-cracking, also at high stresses. These latter two mechanisms are included in DATING for completeness but are not expected to occur for typical dry storage temperatures and stress conditions.

The rupture mechanism equations used in DATING are given below for transgranular cracking, triple-point-cracking, cavitation-power-law, and cavitation-diffusion-controlled rupture. The reduced equations are given and are based on mechanism equations and parameters described by Chin et al. (1986). The rupture time, t_f, is in seconds.

Transgranular:

$$\ln t_f^{TG} = -1.797 - \ln \dot{\epsilon} \qquad (14)$$

Triple Point Cracking:

$$\ln t_f^{TP} = -5.662 - \ln \dot{\varepsilon} - \ln(\sigma/E) - \ln(E/10^4) \tag{15}$$

Cavitation Diffusion:

$$\ln t_f^{CD} = 4.15 - \ln \dot{\varepsilon}_{GBS} + \ln(\sigma/E) \tag{16}$$

where $\dot{\varepsilon}_{GBS}$ is the grain boundary sliding creep rate in s^{-1}.

Cavitation Power Law:

$$\ln t_f^{CP} = -1.587 - \ln \dot{\varepsilon} \tag{17}$$

ANNEALING OF RADIATION DAMAGE

Radiation damage is assumed to reduce the ductility of the cladding and, hence, its rupture lifetime compared to the unirradiated cladding. At elevated temperature, the radiation damage can anneal out and restore the ductility to that of unirradiated cladding. The assumption is made that radiation damage reduces the ductility and, hence, the creep-rupture time to 10% of its unirradiated ductility. With increasing time-at-temperature, more radiation damage is assumed to anneal out until the full unirradiated ductility is restored. The annealing rate is assumed to follow the temperature-dependent equation shown below for the dimensionless recovery factor, r:

$$r = 1 - 0.9 \left[\frac{1}{1 + \sum_{i=1}^{n} \delta t \bullet R \bullet \exp(-4 \bullet 10^4/T_i)} \right] \tag{18}$$

The rate constant, R, is 2.332×10^{17} s^{-1} and T is the absolute temperature in K. The time increment for summation is δt in s.

COMPUTATIONAL METHOD

The cumulative-damage fraction is integrated from the specified initial fuel age to the specified end-of-life age for a given temperature and stress history using the creep rate and rupture-time equations. The time step for the integration is controlled by the GEAR subroutine package (Hindmarsh 1974), and is adjusted to provide a solution with a minimum number of time steps while maintaining control of the numerical error. The allowable temperature/stress limit for storage corresponds to a damage fraction of unity for a specified initial temperature and stress.

CUMULATIVE-DAMAGE FRACTION

For a given initial stress and temperature, DATING calculates the time dependence of cumulative-damage fraction. The temperature and stress at each time step are calculated analytically from the equations for the decay of temperature and stress. The creep rate and annealing rate are calculated to obtain the estimated rate of accumulating damage fraction. The initial time step is 100 s. If that is too large for control of error, then GEAR automatically reduces the initial time step until it is small enough to pass the error-control test. The time step is adjusted by GEAR to be as large as possible while maintaining appropriate control of the error.

The creep rate and rupture mechanisms depend on temperature and stress as seen in Figures 1 and 2. The creep rate is calculated for each of the five mechanisms and the maximum rate is selected as the appropriate dominant rate for calculated cumulative-damage fraction. The temperature at each time is compared to the temperature limit for athermal creep. If the cladding temperature is below the athermal limit, then the creep rate is calculated based on the temperature at the athermal limit, not the actual cladding temperature which is below the limit.

Similarly, the rupture time depends on temperature and stress. The rupture time used in the cumulative-fraction calculation is generally obtained by determining the mechanism exhibiting the minimum rupture time for the temperature and stress of interest. Exceptions to this rule exist for high temperature and/or high stress. Specifically, at temperatures greater than 435°C, the rupture time is assumed to be the minimum of the transgranular rupture time and the cavitation-diffusion-controlled rupture time. Also, triple-point cracking was not allowed to be the controlling mechanism near the yield stress. Therefore, the mechanism boundary between transgranular fracture and triple-point-cracking was adjusted in the temperature range from 258 to 435°C as indicated in Figure 2. At stresses above the indicated boundary, the transgranular-fracture rupture times are assumed to dominate for the calculation of cumulative-damage fraction.

The radiation-damage annealing rate is assumed to be independent of stress and dependent on temperature as indicated in Equation 8. The accumulated annealing fraction is calculated, and used to estimate the reduction in rupture lifetime. The rupture life for cold-worked, irradiated Zircaloy is assumed to be 10% of that of the unirradiated material.

DETERMINATION OF TEMPERATURE LIMIT

The allowable temperature limit is determined by estimating the maximum temperature for which the cumulative fraction does not exceed unity at the specified end-of-life, nominally 40 years. For a given stress, there is a temperature which corresponds to a cumulative fraction of unity as seen in Figure 3. DATING uses a numerical search procedure to determine this temperature.

To establish an initial estimate of allowable temperature, the cumulative fraction is initially calculated at 340°C and 360°C. Based on the cumulative fraction at those two temperatures, a linear relationship is established between reciprocal temperature and cumulative-damage fraction. A new estimate of temperature corresponding to a cumulative fraction of unity is calculated. The correct cumulative fraction is then calculated for that revised temperature. If the correct cumulative fraction is greater than unity, an updated linear relationship is established based on the revised temperature and the revised temperature less 20°C. If the correct cumulative fraction is less than unity, then the relationship is based on the revised temperature and the revised temperature plus 20°C.

With each iteration an improved estimate of the temperature corresponding to a cumulative fraction of unity is obtained. When the newer

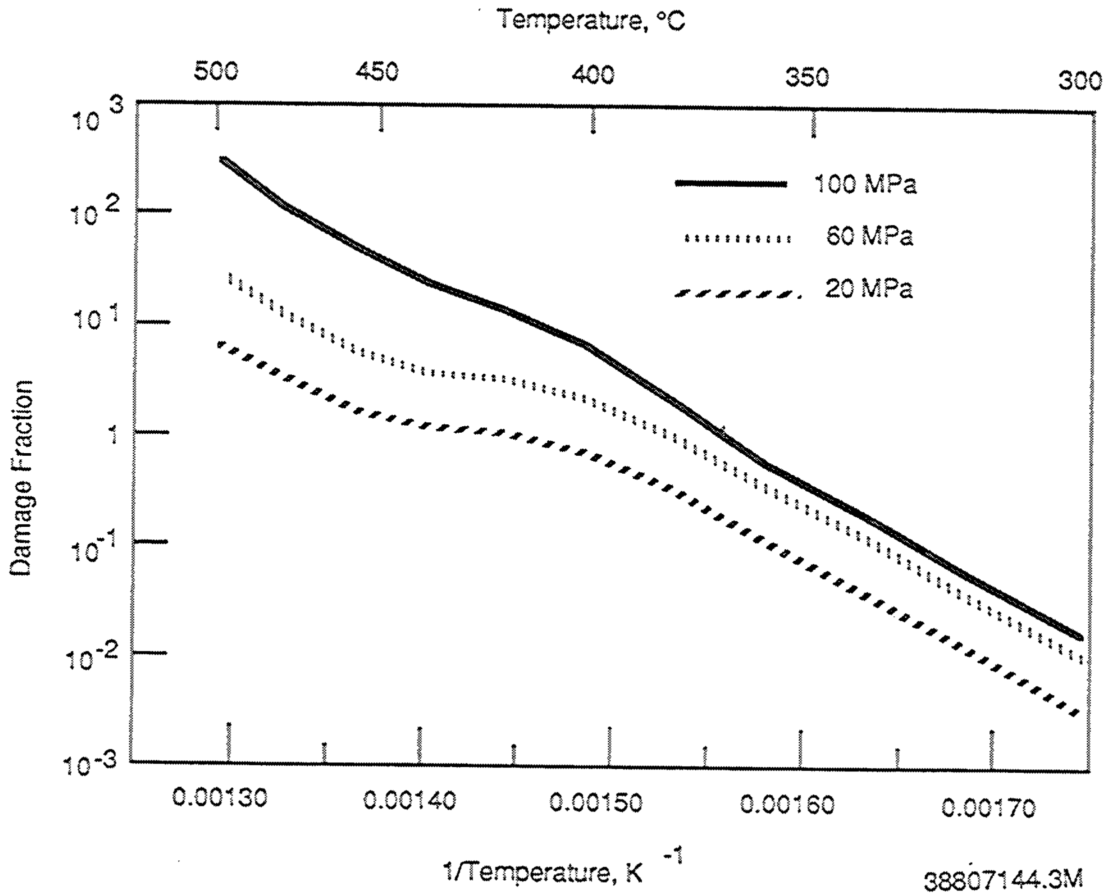


FIGURE 3. Cumulative Damage-Fraction Versus Temperature and Stress

estimate of temperature is less than 1°C different from the previous estimate, the search is concluded, and the temperature is output as the temperature limit for the assumed stress. At low temperatures, where cavitation-diffusion control dominates, the temperature limit is determined with only three calculations of cumulative fraction. At higher temperatures, as many as ten calculations of cumulative-damage fraction may be necessary.

DESCRIPTION OF CODE

The DATING code computes creep behavior of Zircaloy cladding for time-dependent temperature and stress histories. Creep strain, radiation-damage annealing, and cumulative life-fraction are integrated for user-specified temperature and stress histories. The temperature must be below the alpha/beta transition temperature, 800°C, for Zircaloy. The stress must be below the yield stress. Note that Figure 1 indicates that the Nabarro-Herring creep mechanism dominates only for temperatures above 800°C and therefore is not allowed in DATING calculations.

Although the principal purpose of the code is to provide estimates of allowable temperature limits, the code also provides estimates for creep strain, annealing fraction and life fraction as a function of storage time. Equations for the temperature of spent fuel in inert and nitrogen gas storage are included explicitly in the code; however, an option is included for a user-specified cooling history in tabular form. Also, an option is contained in the DATING code for creating tables of the temperature and stress dependencies of creep-strain rate and creep-rupture time for Zircaloy at constant temperature and constant stress or constant ratio of stress/modulus.

The DATING code consists of three components: a) the MAIN program, b) the DIFFUN subroutine, and c) the GEAR package. In addition, the file COMMON.FOR contains common statements used in MAIN and DIFFUN. The MAIN program establishes input parameters, initial conditions, GEAR options, and output of data. The DIFFUN subroutine contains the rate equations which are simultaneously integrated using the GEAR package. The GEAR package is a set of subroutines for the numerical solution of the rate equations specified in DIFFUN. The rate equations include the creep rate, the rate of radiation damage annealing, and the rate of accumulating creep damage. Lastly, the user must supply a data input file, HIST, for the case of the user-specified temperature history or temperature and stress history.

The results of the time-dependent cumulative damage-fraction calculations can be plotted using the BASICA program DPLOT.BAS. This program is written in BASICA language, and plots the time dependence of the calculated cumulative damage fraction, creep strain, radiation damage recovery, and the temperature decay.

MAIN PROGRAM

The MAIN program contains the input options, calls subroutines DIFFUN and DRIVE (in GEAR), and outputs results of calculations. The input data is entered from the keyboard and the output data is written to the file DATING.OUT on the default drive. The user-specified temperature or temperature and stress history is read from the MAIN program. Specific lines and their functions are described in Table 1. Error messages result if the assumed stress is above the yield stress or if the temperature is above the α to β transition temperature.

DIFFUN SUBROUTINE

The DIFFUN subroutine contains the rate equations used for the integration of creep strain, radiation-damage fraction annealed and accumulated creep-damage fraction. The parameters in the DIFFUN subroutine call include the number of rate equations NEQ, the time TT, the array Y and the array YDOT. The arrays Y and YDOT are the integrated values and the rates of change of the values being integrated. The DIFFUN subroutine is called from GEAR to perform the integration. Also, the subroutine is called from the MAIN program when the verification option is selected. Specific lines and their functions are described in Table 2.

COMMON STATEMENTS

COMMON statements used in MAIN and DIFFUN are included in the file named COMMON.FOR. Variables shared in common between the two program units are contained in this file.

GEAR PACKAGE

Details of the GEAR method options are discussed by Hindmarsh (1974). The GEAR package can be obtained from the National Energy Software Center at Argonne National Laboratory.

The DRIVE statement in the MAIN program calls on the GEAR package. The MAIN program also provides input options to run GEAR. These options include the initial time step, HO, the error-control parameter, EPS, and the method

TABLE 1. MAIN Program's Specific Lines and Their Functions

Line Numbers	Function
1 to 6	Define program and compile options.
7 to 11	Define precision, dimension variables, and define COMMON statements.
12 to 19	Open output files.
20 to 26	Define array for yield stress calculation.
27 to 34	Initialize flags for output.
35 to 37	Define alpha-beta phase transition temperature.
38 to 63	Input options for DATING output.
64 to 90	Input options for verifying creep rate and rupture time calculations using DATING (IRUN = 2).
91 to 219	Calculate creep rate/mechanism and rupture time/mechanism for a selected range of temperatures at constant stress or stress/modulus ratio (IOUT = 1 or 2). DIFFUN called at line 152.
220 to 371	Calculate creep rate/mechanism and rupture time/mechanism for a selected range of stresses or ratios of stress/modulus at constant temperatures. DIFFUN called at line 263 (IOUT = 3) of at line 332 (IOUT = 4).
372 to 420	Output creep and rupture mechanism.
421 to 439	Initialize GEAR options (IRUN = 1 or 3).
440 to 571	Select temperature/stress history and options; read HIST.
572 to 756	Integrate CF or determine allowable temperature limit. DRIVE called at line 652; DRIVE calls DIFFUN and GEAR.
757 to 777	Output GEAR run statistics, fuel age, and warning of athermal creep calculations.
778 to 793	Output HIST Table if used.
794 to 798	Stop and end run.

TABLE 2. DIFFUN Subroutine's Specific Lines and Their Functions

Line Numbers	Function
1 to 4	Compile options and definition of subroutine.
5 to 7	Specify precision, dimension variables, and define COMMON statements.
8 to 64	Calculate temperature and stress.
65 to 69	Set NFLAGS if stress exceeds yield stress.
70 to 72	Calculate EM, elastic modulus.
73 to 132	Calculate reduced creep rate.
133 to 157	Calculate rupture time.
158 to 177	Define MFLAG for creep and rupture mechanisms.
178 to 186	Calculate rates of creep, radiation damage annealing, and cumulative creep damage.
187 to 188	Return and end subroutine.

flag, MF. The initial time step is set at 100 s in MAIN. If a smaller time step is required, then GEAR will reduce the time step by an order of magnitude repeatedly until the time step satisfies the error-control criteria.

The EPS parameter is set at 0.0001 in the MAIN program, and has been found to be appropriate for the present applications. Larger values for EPS could result in unstable solutions; whereas, smaller values results in more integration steps without significant improvement in accuracy.

The method flag is set at 22 which causes the solution to be obtained using the backward-differentiation-formula method and the cord method with the Jacobian generated internally for the corrector iteration method.

HIST FILE

The user-specified temperature or temperature and stress history is contained in the file HIST. The first line in the file states the number (integer) of values of time that are in the list. A maximum of 50 values are allowed in the file. Each subsequent line contains the time, temperature and stress written with a decimal point. Numbers must be included in the stress column even when only the temperature history is used for the history option, "TABLE FORM."

USER'S GUIDE

The DATING code is run from keyboard input, and the output is written to a file on disk as well as to the screen. The purpose of this chapter is to describe the input options and to give example runs with output. The disc containing the DATING program may be placed in any drive, but the output will be written to the default drive. If the user wishes to write the output data on the same disc that contains DATING, then the user should place the DATING program disc in the default drive. To write the output on another drive, place the data disc in the desired default drive, and execute DATING with the specification of which drive DATING is on.

RUN OPTIONS

The input options are in two categories: 1) selection of output parameters and 2) selection of assumed values for temperature, stress or temperature-stress history. The first user option is to select whether 1) the allowable temperature limit for dry storage is desired, or 2) the creep rate and rupture magnitudes are to be verified, or 3) the cumulative fraction as a function of time is desired. These options appear on the screen as follows:

1. TEMPERATURE STRESS LIMIT
2. VERIFY CREEP RATE, RUPTURE TIME
3. CUMULATIVE DAMAGE FRACTION VS TIME

Each of these options lead to subsequent options for desired temperatures, stresses, or temperature/stress transients. Note that the above options must be entered as integers. A flow chart of DATING for options one and three is shown in Figure 4 and for option 2 the flow chart is shown in Figure 5.

The output examples in this section are for use in verifying that the program is producing the correct results on the user's computer. One example for each type of output option is given, namely, for the temperature limit, for the verification calculations, and for the cumulative-damage calculations.

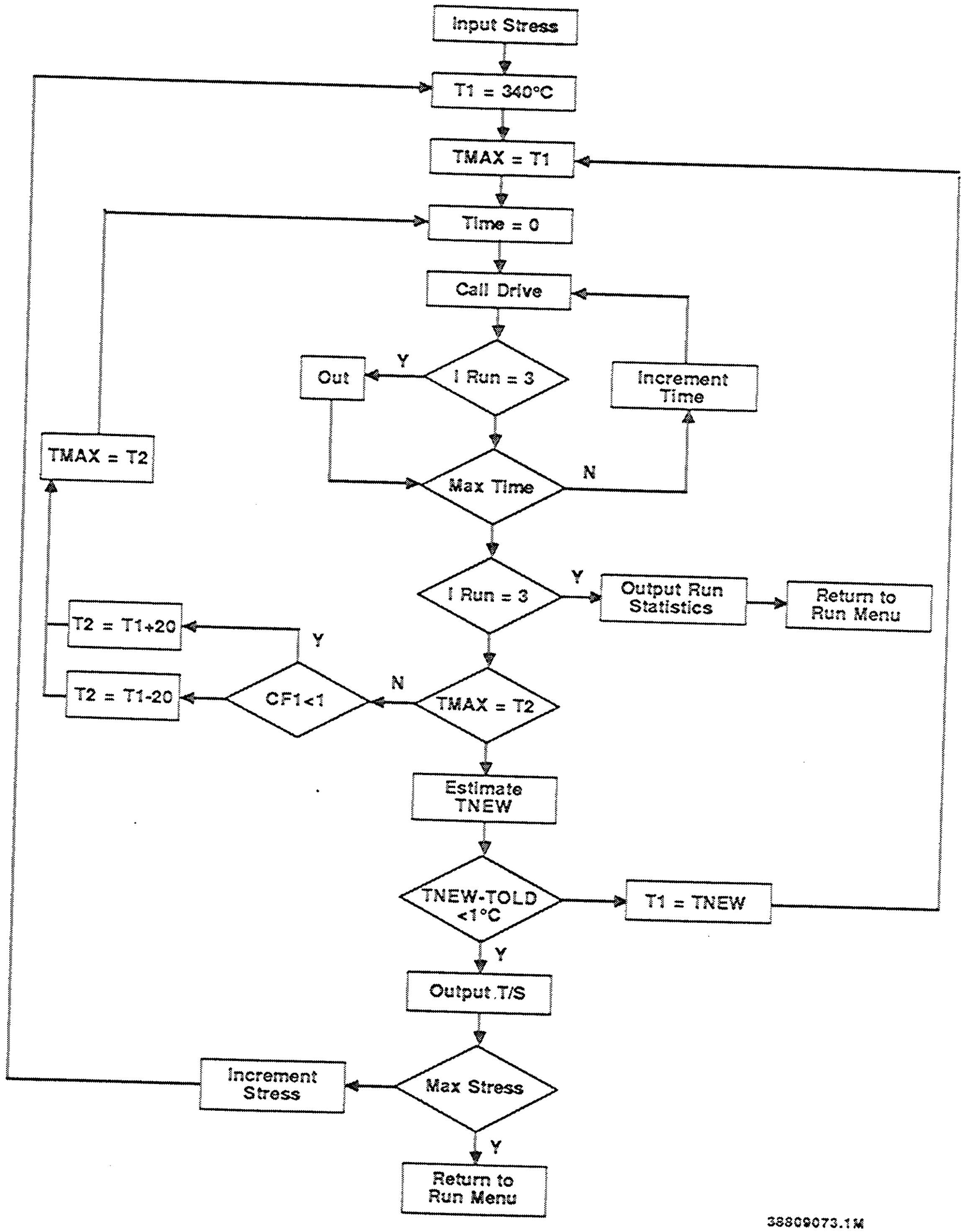


FIGURE 4. Flow Chart for Temperature-Stress Limit and Cumulative Damage Fraction Calculations

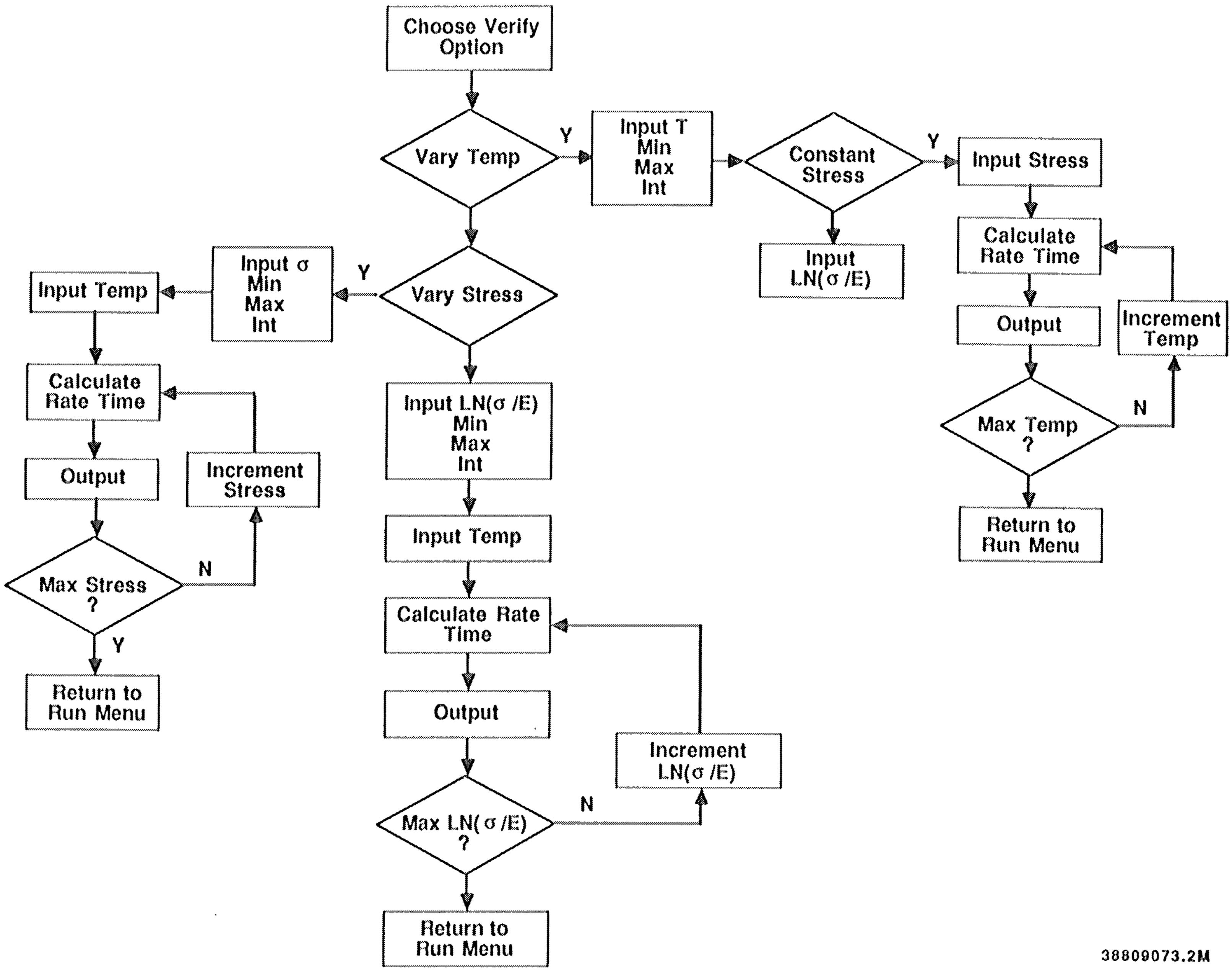


FIGURE 5. Flow Chart for Verification Calculations

Temperature Limit Example

For calculations of the temperature-stress limit, the minimum stress, maximum stress, and stress interval are input as they are prompted on the screen. The stress is in units of MPa. The fuel age in years also has to be entered. Note that each input parameter is entered as an integer. Typically, the run time to determine the allowable temperature for one stress is about 1 min. An example of the input and output format is shown in Table 3; the fuel age is 5 years, the storage is in helium, and the limit is output from 20 to 120 MPa at 20 MPa intervals. The results are plotted in Figure 6 and show excellent agreement with results reported by Chin et al. (1986) shown in Figure 7.

Verification Example

The verification calculations can be made over selected ranges of temperatures or stresses. The purpose of the verification option is to demonstrate that the creep mechanisms are predicted in the same manner reported by Chin. Also, this option can be used to generate tables of expected creep rates and rupture times for uses other than for dry storage. A maximum of 100 values of creep rate and rupture time can be calculated for the table. Options exist to generate tables based on variable temperature or variable stress. Furthermore, the stress range can be displayed as the LOG of stress normalized by the elastic modulus. The verification example in Table 4 is for a constant temperature, and the stress varies from 20 MPa to 200 MPa in intervals of 20 MPa.

Cumulative-Damage Fraction Example

The cumulative-damage fraction option requires entering the number of time steps which should be outputted, the time increment in years between outputted values, the initial temperature in °C, the initial stress in MPa, and the fuel age in years. Each value is entered as an integer except for the time increment which is a floating point variable. The run time for a typical damage-fraction integration to forty years takes as little as 10 s.

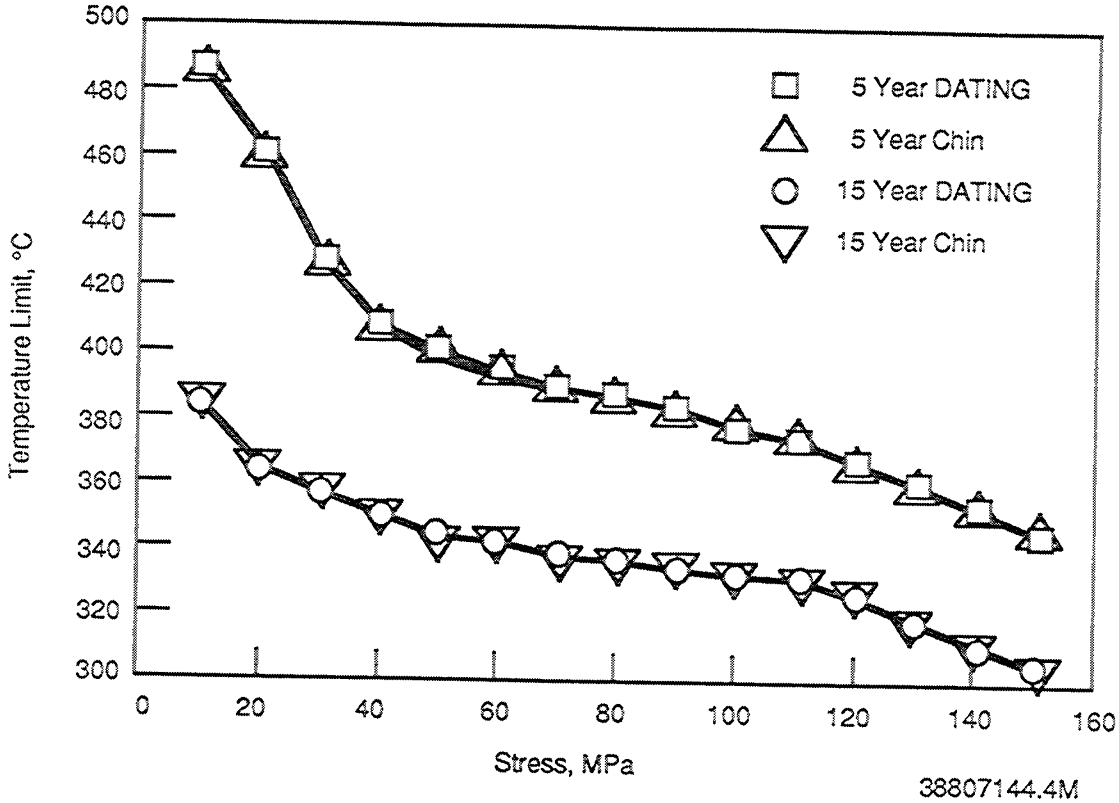


FIGURE 6. Temperature Limit Comparing Results of DATING and Chin et al. (1986)

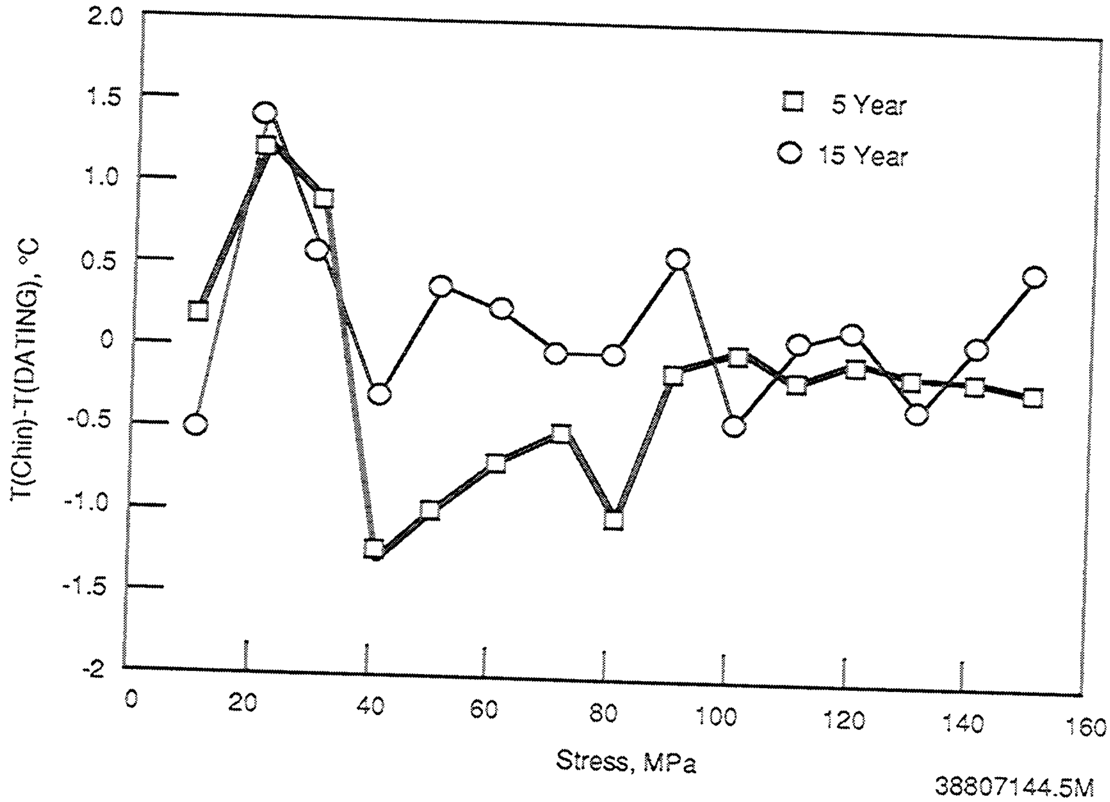


FIGURE 7. Difference in Temperature Limit Between DATING and Chin et al. (1986)

TABLE 3. Example Output of Temperature/Stress Limit

```
*** DATING  1.0 ***
*** Determination of Allowable  Temperature in Inert and Nitrogen Gases ***

 ENTER RUN OPTIONS
   1 - TEMPERATURE/STRESS LIMIT
   2 - VERIFY CREEP RATE, RUPTURE TIME
   3 - CUMULATIVE FRACTION VS TIME
 SELECTED OPTION=?      1

 ENTER TEMP/STRESS HISTORY
       1 - HELIUM
       2 - NITROGEN
       3 - TABLE FORM
       4 - TABLE VALUES
 SELECTED HISTORY=?      1

 ENTER FUEL AGE IN YEARS?       5
 ENTER YEARS OF STORAGE?     40

 ENTER MINIMUM STRESS?     40
 ENTER MAXIMUM STRESS?     70
 ENTER STRESS INTERVAL?     10

 *** PLEASE WAIT - CALCULATING TEMPERATURE LIMIT       ***

     STRESS    TCLIMIT     DAMAGE     STRAIN   RECOVERY
  .4000E+02 .4094E+03 .1015E+01 .4556E-02 .1590E+00
  .5000E+02 .4016E+03 .1038E+01 .5078E-02 .1322E+00
  .6000E+02 .3964E+03 .1021E+01 .5780E-02 .1196E+00
  .7000E+02 .3924E+03 .1012E+01 .7788E-02 .1135E+00

 RUN AGAIN?  ENTER 0 OR 1 FOR NO OR YES      0
```

TABLE 4. Example Output of Verify Creep Rate, Rupture Time

```
*** DATING  1.0 ***
*** Determination of Allowable  Temperature in Inert and Nitrogen Gases ***

 ENTER RUN OPTIONS
   1 - TEMPERATURE/STRESS LIMIT
   2 - VERIFY CREEP RATE, RUPTURE TIME
   3 - CUMULATIVE FRACTION VS TIME
 SELECTED OPTION=?     2

 ENTER TEMPERATURE OR STRESS RANGE
   1 - VARY TEMPERATURE; CONSTANT STRESS
   2 - VARY TEMPERATURE; CONSTANT LOG(STRESS/EM)
   3 - VARY STRESS; CONSTANT TEMPERATURE
   4 - VARY LOG(STRESS/EM); CONSTANT TEMPERATURE
 SELECTED OPTION FOR RANGE=?     1

 ENTER CONSTANT STRESS, MPA?    50
 ENTER MINIMUM TEMPERATURE, C?   300
 ENTER MAXIMUM TEMPERATURE, C?   400
 ENTER TEMPERATURE INTERVAL, C?    25

 CREEP RATES 1/SEC


   TC LOG(ST/E)      HTC       LTC       GBS       GBL        NH        CO
ATHERMAL
   300 -.737E+01 .769E-13 .409E-13 .126E-11 .000E+00 .255E-16 .121E-12
.000E+00
   325 -.735E+01 .707E-12 .211E-12 .569E-11 .000E+00 .219E-15 .540E-12
.000E+00
   350 -.734E+01 .548E-11 .961E-12 .229E-10 .000E+00 .158E-14 .213E-11
.000E+00
   375 -.732E+01 .364E-10 .393E-11 .825E-10 .000E+00 .979E-14 .756E-11
.000E+00
```

TABLE 4. Continued

400 -.730E+01 .211E-09 .146E-10 .271E-09 .000E+00 .528E-13 .244E-10 .000E+00

RUPTURE TIMES

TC	TG	TP	CD	CP
300	.132E+12	.554E+12	.318E+11	.163E+12
325	.291E+11	.122E+12	.712E+10	.359E+11
350	.725E+10	.304E+11	.180E+10	.894E+10
375	.201E+10	.842E+10	.509E+09	.248E+10
400	.612E+09	.257E+10	.158E+09	.755E+09

SUMMARY OF DOMINANT CREEP AND RUPTURE MECHANISMS

TC	CREEP RATE	RUPTURE TIME	MECHANISM
300	.126E-11	.318E+11	33
325	.569E-11	.712E+10	33
350	.229E-10	.180E+10	33
375	.825E-10	.509E+09	33
400	.271E-09	.158E+09	33

MECHANISM CODE = NM

N = CREEP MECHANISM	M = RUPTURE MECHANISM
N=1 - HIGH TEMP CLIMB	M=1 - TRANSGRANULAR
2 - LOW TEMP CLIMB	2 - TRIPLE POINT
3 - GRAIN B. SLIDING	3 - CAV. DIFFUSION
4 - GRAIN B. LATTICE	4 - CAV. POWER LAW
5 - NABARRO HERRING	
6 - COBLE	
7 - ATHERMAL	

RUN AGAIN? ENTER 0 OR 1 FOR NO OR YES 0

The example of cumulative-damage fraction, as a function of storage time in years, is shown in Table 5. The initial fuel age, temperature, and stress are 5 years, 380 °C, and 70 MPa, respectively. The data are output at intervals of two years. An example of calculated cumulative fraction is plotted in Figure 8.

DPLOT BASICA ROUTINE

The output of the cumulative damage-fraction calculation, i.e., run option 3, can be plotted on the screen using the DPLOT.BAS program. The user must have the necessary BASICA files on the disk being used. DPLOT.BAS reads the DATING.OUT file after running option 3 for only one case. If more than one case is run, DPLOT.BAS only reads the output from the first case. Options for plotting are displayed on the screen. The parameter TH defines the thermal history option used for the calculation. Figure 8 is an example plot using DPLOT.BAS.

TABLE 5. Example Output of Cumulative Fraction Versus Time

```
*** DATING  1.0 ***
*** Determination of Allowable  Temperature in Inert and Nitrogen Gases ***

 ENTER RUN OPTIONS
   1 - TEMPERATURE/STRESS LIMIT
   2 - VERIFY CREEP RATE, RUPTURE TIME
   3 - CUMULATIVE FRACTION VS TIME
 SELECTED OPTION=?     3

 ENTER TEMP/STRESS HISTORY
       1 - HELIUM
       2 - NITROGEN
       3 - TABLE FORM
       4 - TABLE VALUES
 SELECTED HISTORY=?     2

 ENTER FUEL AGE IN YEARS?      10
 ENTER YEARS OF STORAGE?    40

 INPUT TOTAL TIME STEPS FOR OUTPUT?    10

 ENTER TMAX C?   390
 ENTER MAX STRESS MPA?    35

      YEARS     DAMAGE     STRAIN   RECOVERY     TEMPC     STRESS
   .100E+02  .000E+00  .000E+00  .100E+00  .390E+03  .350E+02
   .140E+02  .157E+01  .618E-02  .164E+00  .369E+03  .339E+02
   .180E+02  .208E+01  .856E-02  .174E+00  .354E+03  .331E+02
   .220E+02  .232E+01  .973E-02  .177E+00  .343E+03  .325E+02
   .260E+02  .246E+01  .104E-01  .178E+00  .334E+03  .321E+02
   .300E+02  .255E+01  .108E-01  .178E+00  .327E+03  .317E+02
   .340E+02  .261E+01  .111E-01  .179E+00  .321E+03  .314E+02
   .380E+02  .265E+01  .113E-01  .179E+00  .316E+03  .311E+02
```

TABLE 5. Continued

.420E+02	.268E+01	.114E-01	.179E+00	.311E+03	.309E+02
.460E+02	.271E+01	.115E-01	.179E+00	.307E+03	.306E+02
.500E+02	.273E+01	.116E-01	.179E+00	.304E+03	.305E+02

INTEGRATION WAS COMPLETED USING
TIME STEPS= 50 FIRST STEP(SEC)= .100E+03 LAST STEP(SEC)=
.127E+09

RUN AGAIN? ENTER 0 OR 1 FOR NO OR YES 0

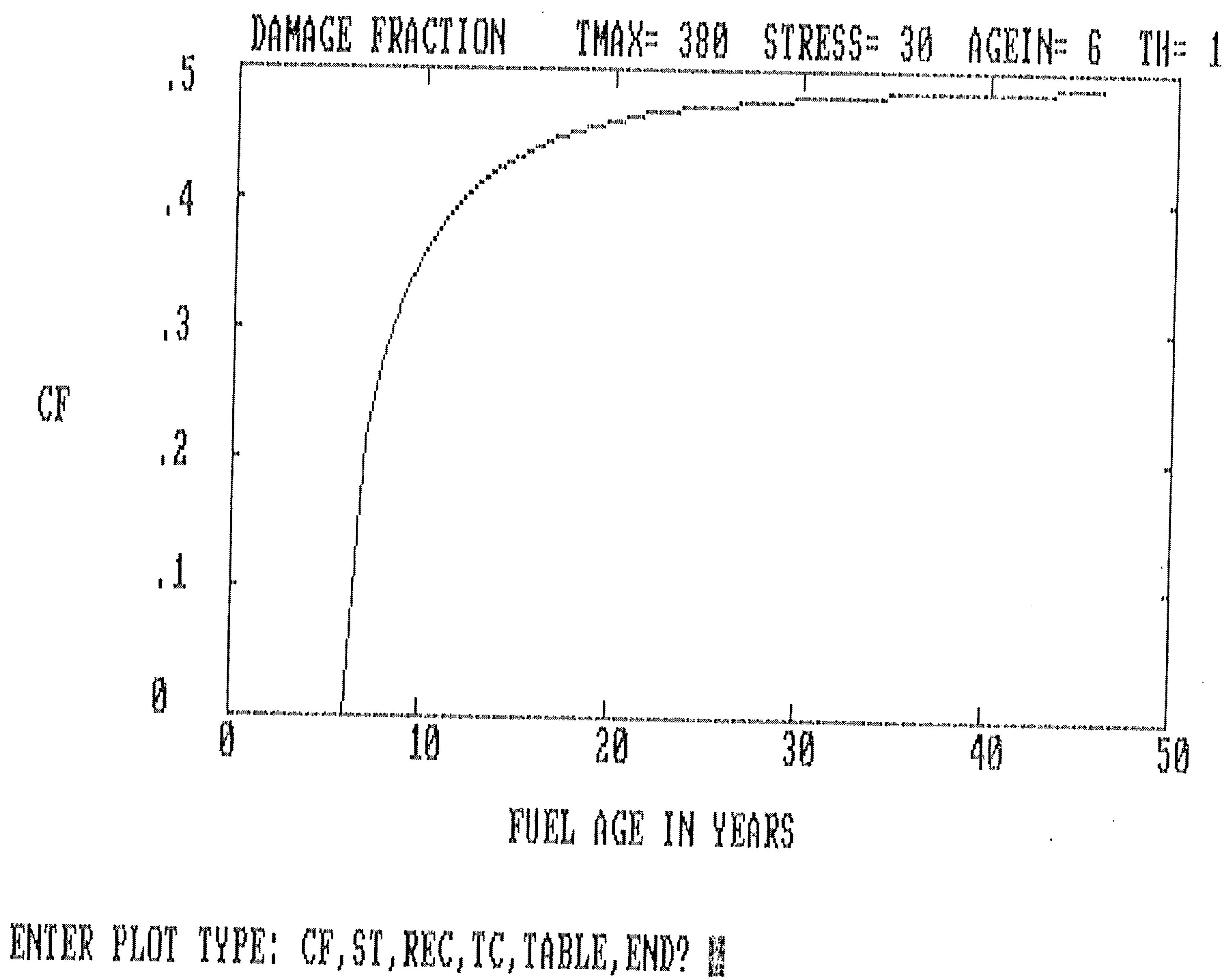


FIGURE 8. Example Plot of Cumulative Damage-Fraction Versus Time

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REFERENCES

Chin, B. A., M. A. Khan, and J. Tarn. 1986. Deformation and Fracture Map Methodology for Predicting Cladding Behavior During Dry Storage. PNL-5998, Pacific Northwest Laboratory, Richland, Washington.

Cunningham, M. E., E. P. Simonen, R. T. Alleman, I. S. Levy, R. F. Hazelton, and E. R. Gilbert. 1987. Control of Degradation of Spent LWR Fuel During Dry Storage in Inert Atmosphere. PNL-6364, Pacific Northwest Laboratory, Richland, Washington.

Hindmarsh, A. C. 1974. GEAR: Ordinary Differential Equation System Solver. Lawrence Livermore Laboratory Report UCID-30001, Rev. 3, Livermore, California.

Levy, I. S., B. A. Chin, E. P. Simonen, C. E. Beyer, E. R. Gilbert, and A. B. Johnson, Jr. 1987. Recommended Temperature Limits for Dry Storage of Spent Light Water Reactor Zircaloy-clad Fuel rods in Inert Gas. PNL-6189, Pacific Northwest Laboratory, Richland, Washington.

Steinberg, E., H. G. Weidinger, and A. Schaa. 1984. "Analytical Approaches and Experimental Verification to Describe the Influence of Cold Work and Heat Treatment on the Mechanical Properties of Zircaloy Cladding Tubes." Zirconium in the Nuclear Industry: Sixth International Symposium, ASTM STP 824, pp. 106-122.

APPENDIX A

LISTING OF MAIN PROGRAM LINES

LISTING OF MAIN PROGRAM LINES

```
*C      DATING DETERMINES MAXIMUM ALLOWABLE TEMPERATURES IN INERT
 C      AND NITROGEN GASES
 C      THIS IS VERSION 1.0
$NOFLOATCALLS
C$STORAGE:2
C$DEBUG
       PROGRAM MAIN
       IMPLICIT REAL*8(A-H,O-Z),INTEGER*4(N)
       DIMENSION Y(3),YDOT(3)
       DIMENSION SAVE1(100,7),NSAV1(100,2)
$INCLUDE: 'COMMON.FOR'
C *******************************************************************
C *** FILE "DATING.OUT" DUPLICATES THE SCREEN FOR POST RUN ANALYSIS ***
C *******************************************************************
       OPEN(5,FILE='DATING.OUT',STATUS='NEW')
C ************************
C *** INITIALIZE VALUES ***
C ************************
       NPTS=0
 2006  YSA(1)=387.1D0
       YSA(2)=313.6D0
       YSA(3)=245.0D0
       YSA(4)=194.0D0
       YSA(5)=96.2D0
       YSA(6)=58.7D0
       YSA(7)=46.1D0
       NFLAG=0
       KFLAG=0
       LFLAG=0
       NFLAGT=0
       NFLAGS=0
       MFLAG=0
       IHIST=0
       TKOLD=0.D0
       TEMPAB=800.D0
C ALPHA BETA TEMP C AND MELTING TEMP K
       TM=2125.28D0
C *********************
C *** SELECT OPTIONS ***
C *********************
       WRITE (*,2046)
       WRITE (5,2046)
 2046  FORMAT (/,'*** DATING  1.0 ***',/,'*** Determination of Allowable
     A Temperature in Inert and Nitrogen Gases ***')
       WRITE (*,1000)
       WRITE (*,1001)
       WRITE (*,1002)
       WRITE (*,1040)
       WRITE (5,1000)
```

```
      WRITE (5,1001)
      WRITE (5,1002)
      WRITE (5,1040)
 1000 FORMAT (/,2X,'ENTER RUN OPTIONS')
 1001 FORMAT (4X,'1 - TEMPERATURE/STRESS LIMIT')
 1002 FORMAT (4X,'2 - VERIFY CREEP RATE, RUPTURE TIME')
 1040 FORMAT (4X,'3 - CUMULATIVE FRACTION VS TIME')
      WRITE (*,2000)
      WRITE(5,2000)
 2000 FORMAT (2X,'SELECTED OPTION=? ',\)
      READ (*,10) IRUN
      WRITE(5,10) IRUN
   10 FORMAT (I5)
      IF (IRUN.NE.2) GO TO 1003
C ***************************
C *** VERIFICATION OPTIONS ***
C ***************************
      IHIST=1
      WRITE (*,1004)
      WRITE (*,1005)
      WRITE (*,1006)
      WRITE (*,1007)
      WRITE (*,1008)
      WRITE (5,1004)
      WRITE (5,1005)
      WRITE (5,1006)
      WRITE (5,1007)
      WRITE (5,1008)
 1004 FORMAT (/,2X,'ENTER TEMPERATURE OR STRESS RANGE')
 1005 FORMAT (4X,'1 - VARY TEMPERATURE; CONSTANT STRESS')
 1006 FORMAT (4X,'2 - VARY TEMPERATURE; CONSTANT LOG(STRESS/EM)')
 1007 FORMAT (4X,'3 - VARY STRESS; CONSTANT TEMPERATURE')
 1008 FORMAT (4X,'4 - VARY LOG(STRESS/EM); CONSTANT TEMPERATURE')
      WRITE(*,2038)
      WRITE(5,2038)
 2038 FORMAT(2X,'SELECTED OPTION FOR RANGE=? ',\)
      READ (*,10) IOUT
      WRITE(5,10) IOUT
      TT=0.D0
      DO 1016 INITIAL=1,3
 1016 Y(INITIAL)=0.D0
      IF (IOUT.GT.2) GO TO 1011
      IF (IOUT.EQ.1) THEN
C ***************************************************
C *** CONSTANT STRESS, VARIABLE TEMPERATURE OPTIONS ***
C ***************************************************
      WRITE (*,2039)
      WRITE(5,2039)
 2039 FORMAT(/,2X,'ENTER CONSTANT STRESS, MPA? ',\)
      READ (*,10) NSTIN
      WRITE(5,10) NSTIN
      STIN=NSTIN
```

```
      ELSE
      WRITE (*,1009)
      WRITE(5,1009)
 1009 FORMAT (/,2X,'ENTER WITH DECIMAL POINT LOG(STRESS/EM)? ',\)
      READ (*,1010) STEMLOG
      WRITE(5,2040) STEMLOG
 2040 FORMAT(F7.2)
 1010 FORMAT (E10.3)
      STEM=DEXP(STEMLOG)
      ENDIF
      WRITE (5,1012)
      WRITE (*,1012)
 1012 FORMAT (2X,'ENTER MINIMUM TEMPERATURE, C? ',\)
      READ (*,10) MINT
      WRITE(5,10) MINT
      WRITE (*,1013)
      WRITE(5,1013)
 1013 FORMAT (2X,'ENTER MAXIMUM TEMPERATURE, C? ',\)
      READ (*,10) MAXT
      WRITE(5,10) MAXT
      WRITE (*,1014)
      WRITE(5,1014)
 1014 FORMAT (2X,'ENTER TEMPERATURE INTERVAL, C? ',\)
      READ (*,10) INTT
      WRITE(5,10) INTT
      NTEMP=0
      WRITE(*,2011)
      WRITE(5,2011)
 2011 FORMAT(/,2X,'CREEP RATES 1/SEC')
      IF(IOUT.EQ.1) THEN
      WRITE(5,2010)
      WRITE(*,2010)
 2010 FORMAT (/,4X,'TC',1X,'LOG(ST/E)',6X,'HTC',6X,'LTC',6X,
     A'GBS',6X,'GBL',7X,'NH',7X,'CO',1X,'ATHERMAL')
      ELSE
      WRITE(*,2013)
      WRITE(5,2013)
 2013 FORMAT (/,4X,'TC',3X,' STRESS',6X,'HTC',6X,'LTC',6X,
     A'GBS',6X,'GBL',7X,'NH',7X,'CO',1X,'ATHERMAL')
      ENDIF
      DO 1015 LTEMP=MINT,MAXT,INTT
      NTEMP=NTEMP+1
      TMAX=LTEMP
      TMTK=TM/(TMAX+273.16D0)
      IF (IOUT.EQ.2) THEN
C CONVERT LOG(STRESS/MODULUS) TO STRESS
      STIN=STEM*(11.09D0-11.67D0/TMTK)*1.D4
      IF (TMTK.GT.4.06D0) STIN=STEM*(11.81D0-14.59D0/TMTK)*1.D4
      ENDIF
C CALCULATE CREEP RATES AND RUPTURE TIMES FROM DIFFUN
      CALL DIFFUN (NEQ,TT,Y,YDOT)
      IF (IOUT.EQ.1) THEN
```

```
      IF (TMTK.GT.4.06D0) THEN
      STEMLOG=LOG(STIN/((11.81D0-14.59D0/TMTK)*1.D4))
      ELSE
      STEMLOG=LOG(STIN/((11.09D0-11.67D0/TMTK)*1.D4))
      ENDIF
C ******************************************************************
C *** NOTE THAT THE GRAIN BOUNDARY LATTICE DIFFUSION CONTROLL     ***
C *** DIFFUSION RATE ER(4) IS NOT CALCULATED IN DIFFUN AND THERFORE ***
C *** IS ZERO IN THE OUTPUT BELOW.  IT HAS BEEN INCLUDED AS        ***
C *** A PARAMETER TO BE CONSISTENT WITH CONVENTIONS ESTABLISHED    ***
C *** BY CHIN ET AL. PNL-5998, 1986.                               ***
C ******************************************************************
C *** THE ATHERMAL CREEP RATE IS NONZERO ONLY IF THE TEMPERATURE AND ***
C *** STRESS HAVE VALUES WHICH CORRESPOND TO THE ATHERMAL REGION OF ***
C *** THE CREEP MECHANISM MAP                                      ***
C ******************************************************************
      WRITE (*,1017) LTEMP,STEMLOG,ER(1),ER(2),ER(3),ER(4),ER(5),
     A ER(6),ER(7)
      WRITE (5,1017) LTEMP,STEMLOG,ER(1),ER(2),ER(3),ER(4),ER(5),
     A ER(6),ER(7)
      ELSE
      WRITE (*,1017) LTEMP,STIN,ER(1),ER(2),ER(3),ER(4),ER(5),
     A ER(6),ER(7)
      WRITE (5,1017) LTEMP,STIN,ER(1),ER(2),ER(3),ER(4),ER(5),
     A ER(6),ER(7)
 1017 FORMAT (1X,I5,E10.3,7E9.3)
      ENDIF
      SAVE1(NTEMP,1)=TF(1)
      SAVE1(NTEMP,2)=TF(2)
      SAVE1(NTEMP,3)=TF(3)
      SAVE1(NTEMP,4)=TF(4)
      SAVE1(NTEMP,5)=EDOTR
      SAVE1(NTEMP,6)=TMINR
      NSAV1(NTEMP,1)=MFLAG
      NSAV1(NTEMP,2)=LTEMP
 1015 CONTINUE
      WRITE(*,2012)
      WRITE(5,2012)
 2012 FORMAT (/,2X,'RUPTURE TIMES')
      WRITE(*,2014)
      WRITE(5,2014)
 2014 FORMAT (/,4X,'TC',7X,'TG',7X,'TP',7X,'CD',7X,'CP')
      DO 1019 LTEMP=1,NTEMP
      WRITE (*,1018) NSAV1(LTEMP,2),
     A  SAVE1(LTEMP,1),SAVE1(LTEMP,2),SAVE1(LTEMP,3)
     B ,SAVE1(LTEMP,4)
      WRITE (5,1018) NSAV1(LTEMP,2),
     A  SAVE1(LTEMP,1),SAVE1(LTEMP,2),SAVE1(LTEMP,3)
     B ,SAVE1(LTEMP,4)
 1018 FORMAT (1X,I5,4E9.3)
 1019 CONTINUE
      WRITE(*,2015)
```

```
      WRITE(5,2015)
 2015 FORMAT(/,3X,'SUMMARY OF DOMINANT CREEP AND RUPTURE MECHANISMS')
      WRITE(*,2016)
      WRITE(5,2016)
 2016 FORMAT(/,4X,'TC',2X,'  CREEP RATE',2X,'RUPTURE TIME',2X,
     A'MECHANISM')
      DO 2017 LTEMP=1,NTEMP
      WRITE(*,2018) NSAV1(LTEMP,2),SAVE1(LTEMP,5),SAVE1(LTEMP,6),
     ANSAV1(LTEMP,1)
      WRITE(5,2018) NSAV1(LTEMP,2),SAVE1(LTEMP,5),SAVE1(LTEMP,6),
     ANSAV1(LTEMP,1)
 2018 FORMAT (2X,I5,E13.3,E14.3,I11)
 2017 CONTINUE
      GO TO 2019
C *****************************************************
C *** CONSTANT STRESS, VARIABLE TEMPERATURE OPTIONS ***
C *****************************************************
 1011 CONTINUE
      WRITE (*,1020)
      WRITE(5,1020)
 1020 FORMAT (/,2X,'ENTER TEMPERATURE,C? '\)
      READ (*,10) KMAX
      WRITE(5,10) KMAX
      TMAX=KMAX
      IF (IOUT.EQ.3) THEN
      WRITE (*,1021)
      WRITE(5,1021)
 1021 FORMAT (2X,'ENTER MINIMUM STRESS, MPA? ',\)
      READ (*,10) MINST
      WRITE(5,10) MINST
      WRITE (*,1022)
      WRITE(5,1022)
 1022 FORMAT (2X,'ENTER MAXIMUM STRESS, MPA? ',\)
      READ (*,10) MAXST
      WRITE(5,10) MAXST
      WRITE (*,1023)
      WRITE(5,1023)
 1023 FORMAT (2X,'ENTER STRESS INTERVAL, MPA? ',\)
      READ (*,10) INTST
      WRITE(5,10) INTST
      NTEMP=0
      WRITE (*,2011)
      WRITE (*,2029)
      WRITE (5,2011)
      WRITE (5,2029)
 2029 FORMAT(/,'  STRESS',' LOG(ST/E)',4X,'HTC',6X,'LTC',
     A6X,'GBS',6X,'GBL',7X,'NH',7X,'CO',1X,'ATHERMAL')
      DO 1024 KSTIN=MINST,MAXST,INTST
      NTEMP=NTEMP+1
      STIN=KSTIN
      TMTK=2125.D0/(TMAX+273.16D0)
      IF (TMTK.GT.4.06D0) THEN
```

```
      STEMLOG=LOG(STIN/((11.81D0-14.59D0/TMTK)*1.D4))
      ELSE
      STEMLOG=LOG(STIN/((11.09D0-11.67D0/TMTK)*1.D4))
      ENDIF
C CALCULATE CREEP RATES AND RUPTURE TIMES FROM DIFFUN
      CALL DIFFUN (NEQ,TT,Y,YDOT)
      WRITE (*,1029) STIN, STEMLOG,ER(1),ER(2),ER(3),ER(4),ER(5),
     A ER(6),ER(7)
      WRITE (5,1029) STIN, STEMLOG,ER(1),ER(2),ER(3),ER(4),ER(5),
     A ER(6),ER(7)
 1029 FORMAT (1X,F6.0,F10.2,7E9.3)
      SAVE1(NTEMP,1)=TF(1)
      SAVE1(NTEMP,2)=TF(2)
      SAVE1(NTEMP,3)=TF(3)
      SAVE1(NTEMP,4)=TF(4)
      SAVE1(NTEMP,5)=EDOTR
      SAVE1(NTEMP,6)=TMINR
      NSAV1(NTEMP,1)=MFLAG
      NSAV1(NTEMP,2)=KSTIN
 1024 CONTINUE
      WRITE (*,2030)
      WRITE(5,2030)
 2030 FORMAT(/,5X,'TC',6X,'TG',7X,'TP',7X,'CD',7X,'CP')
      DO 1031 LTEMP=1,NTEMP
      WRITE (*,1018) NSAV1(LTEMP,2),
     A SAVE1(LTEMP,1),SAVE1(LTEMP,2),SAVE1(LTEMP,3)
     B ,SAVE1(LTEMP,4)
      WRITE (5,1018) NSAV1(LTEMP,2),
     A SAVE1(LTEMP,1),SAVE1(LTEMP,2),SAVE1(LTEMP,3)
     B ,SAVE1(LTEMP,4)
 1031 CONTINUE
      WRITE(*,2015)
      WRITE(*,2033)
      WRITE(5,2015)
      WRITE(5,2033)
 2033 FORMAT(/,4X,'ST',3X,'  CREEP RATE',3X,
     A'RUPTURE TIME',' MECHANISM')
      DO 2031 LTEMP=1,NTEMP
      WRITE(*,2032) NSAV1(LTEMP,2),SAVE1(LTEMP,5),SAVE1(LTEMP,6),
     ANSAV1(LTEMP,1)
      WRITE(5,2032) NSAV1(LTEMP,2),SAVE1(LTEMP,5),SAVE1(LTEMP,6),
     ANSAV1(LTEMP,1)
 2032 FORMAT(1X,I5,E15.3,E15.3,I10)
 2031 CONTINUE
      ELSE
      WRITE (*,1025)
      WRITE(5,1025)
 1025 FORMAT (2X,'ENTER WITH DECIMAL POINT LOG(ST/EM) MINIMUM? '\)
      READ (*,1010) STEMIN
      WRITE(5,2040) STEMIN
      WRITE (*,1026)
      WRITE(5,1026)
```

```
 1026 FORMAT (2X,'ENTER WITH DECIMAL POINT LOG(ST/EM) MAXIMUM? '\)
      READ (*,1010) STEMAX
      WRITE(5,2040) STEMAX
      WRITE (*,1027)
      WRITE(5,1027)
 1027 FORMAT (2X,'ENTER WITH DECIMAL POINT LOG(ST/EM) INTERVAL? '\)
      READ (*,1010) STEINT
      WRITE(5,2040) STEINT
      INTSTE=IDINT((STEMAX-STEMIN)/STEINT)+1
      NTEMP=0
      WRITE(*,2011)
      WRITE(*,2029)
      WRITE(5,2011)
      WRITE(5,2029)
      DO 1028 LSTEM=1,INTSTE
      NTEMP=NTEMP+1
      XSTEM=LSTEM-1
      STEM=STEMIN+XSTEM*STEINT
      TMTK=TM/(TMAX+273.16D0)
      STIN=DEXP(STEM)*(11.09D0-11.67D0/TMTK)*1.D4
      IF (TMTK.GT.4.06D0) STIN=DEXP(STEM)*(11.81D0-14.59D0/TMTK)*1.D4
C CALCULATE CREEP RATES AND RUPTURE TIMES FROM DIFFUN
      CALL DIFFUN(NEQ,TT,Y,YDOT)
      WRITE (*,1029) STIN,STEM,ER(1),ER(2),ER(3),ER(4),ER(5),
     A ER(6),ER(7)
      WRITE (5,1029) STIN,STEM,ER(1),ER(2),ER(3),ER(4),ER(5),
     A ER(6),ER(7)
      SAVE1(NTEMP,1)=TF(1)
      SAVE1(NTEMP,2)=TF(2)
      SAVE1(NTEMP,3)=TF(3)
      SAVE1(NTEMP,4)=TF(4)
      SAVE1(NTEMP,5)=EDOTR
      SAVE1(NTEMP,6)=TMINR
      NSAV1(NTEMP,1)=MFLAG
      SAVE1(NTEMP,7)=STEM
 1028 CONTINUE
      WRITE(*,2034)
      WRITE(5,2034)
 2034 FORMAT(/,5X,'STEM',7X,'TG',7X,'TP',7X,'CD',7X,'CP')
      DO 1035 LTEMP=1,NTEMP
      WRITE (*,1030) SAVE1(LTEMP,7),
     A  SAVE1(LTEMP,1),SAVE1(LTEMP,2),SAVE1(LTEMP,3)
     B ,SAVE1(LTEMP,4)
      WRITE (5,1030) SAVE1(LTEMP,7),
     A  SAVE1(LTEMP,1),SAVE1(LTEMP,2),SAVE1(LTEMP,3)
     B ,SAVE1(LTEMP,4)
 1030 FORMAT (1X,5E9.3)
 1035 CONTINUE
      WRITE(*,2015)
      WRITE(*,2035)
      WRITE(5,2015)
      WRITE(5,2035)
```

```
 2035 FORMAT(/,3X,'STEM',3X,'  CREEP RATE',3X,
     A'RUPTURE TIME',' MECHANISM')
      DO 2036 LTEMP=1,NTEMP
      WRITE (*,2037) SAVE1(LTEMP,7),SAVE1(LTEMP,5),SAVE1(LTEMP,6),
     ANSAV1(LTEMP,1)
      WRITE (5,2037) SAVE1(LTEMP,7),SAVE1(LTEMP,5),SAVE1(LTEMP,6),
     ANSAV1(LTEMP,1)
 2037 FORMAT( 1X,F6.2,2E15.3,I10)
 2036 CONTINUE
      ENDIF
C ********************************************
C *** SUMMARY OF CREEP AND RUPTURE MECHANISMS ***
C ********************************************
 2019 CONTINUE
      WRITE(*,2020)
       WRITE(5,2020)
 2020 FORMAT(/,2X,'MECHANISM CODE = NM')
      WRITE(*,2021)
      WRITE(5,2021)
 2021 FORMAT (2X,'N = CREEP MECHANISM',9X,'M = RUPTURE MECHANISM')
      WRITE(*,2022)
      WRITE(*,2023)
      WRITE(*,2024)
      WRITE(*,2025)
      WRITE(*,2026)
      WRITE(*,2027)
      WRITE(*,2028)
      WRITE(5,2022)
      WRITE(5,2023)
      WRITE(5,2024)
      WRITE(5,2025)
      WRITE(5,2026)
      WRITE(5,2027)
      WRITE(5,2028)
 2022 FORMAT(2X,'N=1 - HIGH TEMP CLIMB        M=1 - TRANSGRANULAR')
 2023 FORMAT(2X,'  2 - LOW TEMP CLIMB           2 - TRIPLE POINT')
 2024 FORMAT(2X,'  3 - GRAIN B. SLIDING         3 - CAV. DIFFUSION')
 2025 FORMAT(2X,'  4 - GRAIN B. LATTICE         4 - CAV. POWER LAW')
 2026 FORMAT(2X,'  5 - NABARRO HERRING')
 2027 FORMAT(2X,'  6 - COBLE')
 2028 FORMAT(2X,'  7 - ATHERMAL')
      IF (TMAX.GT.TEMPAB) THEN
      WRITE (*,311)
      WRITE (5,311)
  311 FORMAT (/,2X,'** ERROR ** TEMPERATURE EXCEEDS ALPHA/BETA
     A TRANSITION')
      ENDIF
      LTMAX=IDINT(TMAX/100.D0)
      TMAXL=LTMAX*100
      YS=YSA(LTMAX)+(TMAX-TMAXL)*(YSA(LTMAX+1)-YSA(LTMAX))/100.D0
      IF (TMAX.LT.100.D0) YS=-0.735D0*TMAX+460.6D0
      IF (TMAX.GT.700.D0) YS=-0.126D0*TMAX+134.3D0
```

```
      IF (STIN.GT.YS) THEN
      WRITE (*,76)
      WRITE (5,76)
   76 FORMAT (/,2X,'** ERROR ** STRESS EXCEEDS THE YIELD',/,
     A14X,'THE STRESS MUST BE LESS THAN THE YIELD')
      ENDIF
      GO TO 77
C ***************************************
C ***************************************
C ***   BEGIN CUMULATIVE FRACTION    ***
C ***              AND               ***
C *** TEMPERATURE LIMIT CALCULATIONS ***
C***************************************
C ***************************************
 1003 CONTINUE
C ***************************************
C *** INITIALIZE PARAMETERS FOR GEAR ***
C***************************************
C HO IS THE INITIAL TIME STEP
C IF NECESSARY GEAR WILL REDUCE THE TIME STEP
      HO=1.D2
C EPS IS THE ERROR CONTROL PARAMETER FOR GEAR
      EPS=1.D-4
C MF IS THE GEAR METHOD PARAMETER
      MF=22
      HOSAVE=HO
C **********************************
C *** SELECT TEMP/STRESS HISTORY ***
C **********************************
      WRITE(*,86)
      WRITE(5,86)
      WRITE (*,87)
      WRITE (*,88)
      WRITE (*,89)
      IF (IRUN.EQ.3) WRITE(*,93)
      WRITE (5,87)
      WRITE (5,88)
      WRITE (5,89)
      IF (IRUN.EQ.3) WRITE(5,93)
   86 FORMAT (/,2X,'ENTER TEMP/STRESS HISTORY')
   87 FORMAT (7X,' 1 - HELIUM')
   88 FORMAT (7X,' 2 - NITROGEN')
   89 FORMAT (7X,' 3 - TABLE FORM')
   93 FORMAT (7X,' 4 - TABLE VALUES')
      WRITE (*,2001)
      WRITE(5,2001)
 2001 FORMAT (2X,'SELECTED HISTORY=? ',\)
      READ (*,10) IHIST
      WRITE(5,10) IHIST
      IF (IHIST.GT.2 .AND. NPTS.EQ.0) OPEN(3,FILE='HIST',STATUS='OLD')
      WRITE (*,84)
      WRITE(5,84)
```

```
   84 FORMAT(/,2X,'ENTER FUEL AGE IN YEARS?  ',\)
      READ(*,10) NAGE
      WRITE(5,10) NAGE
      TIN=NAGE
      WRITE(*,70)
      WRITE(5,70)
   70 FORMAT(2X,'ENTER YEARS OF STORAGE? ' ,\)
      READ (*,10) NYEARS
      WRITE(5,10) NYEARS
      YEARS=NYEARS
      IF (IRUN.EQ.1) THEN
      DTIME=YEARS
      NT=1
      GO TO 321
      ENDIF
      WRITE (*,15)
      WRITE(5,15)
   15 FORMAT (/,2X,'INPUT TOTAL TIME STEPS FOR OUTPUT? ',\)
      READ (*,10) NT
      WRITE(5,10) NT
      DTIME=YEARS/DBLE(NT)
  321 CONTINUE
      IF (IHIST.LT.3) GO TO 90
C *************************************************
C *** READ TEMP STRESS FROM TABLE IN FILE "HIST" ***
C *************************************************
      IF (NPTS.GT.0) GO TO 94
      READ (3,*) NPTS
      NPTSM1=NPTS-1
      DO 91 NTBL=1,NPTS
   91 READ (3,*) HTIME(NTBL),HTC(NTBL),HST(NTBL)
   94 CONTINUE
      DO 3310 IP=1,NPTSM1
 3310 IF (TIN.LE.HTIME(IP+1)) GO TO 3311
      TCC=HTC(NPTS)
      STTBL=HST(NPTS)
      TZTBL=TCC+273.16D0
      GO TO 3312
 3311 SLOPE=(HTC(IP+1)-HTC(IP))/(HTIME(IP+1)-HTIME(IP))
      TCTBL=HTC(IP)+SLOPE*(TIN-HTIME(IP))
      TZTBL=TCTBL+273.16D0
      SLOPES=(HST(IP+1)-HST(IP))/(HTIME(IP+1)-HTIME(IP))
      STTBL=HST(IP)+SLOPES*(TIN-HTIME(IP))
 3312 NSTIN=IDINT(STTBL)
   90 CONTINUE
      IF (IRUN.EQ.1) GO TO 320
      IF (IHIST.EQ.4) GO TO 300
C *******************************************
C *** SELECTE INITIAL TEMPERATURE AND STRESS ***
C ***  FOR CUMULATIVE FRACTION CALCULATION   ***
C *******************************************
      WRITE(*,19)
```

```
      WRITE(5,19)
   19 FORMAT(/,2X,'ENTER TMAX C? ',\)
      READ(*,10) NTMAX
      WRITE(5,10) NTMAX
      WRITE(*,21)
      WRITE(5,21)
   21 FORMAT (2X,'ENTER MAX STRESS MPA? ',\)
      READ (*,10) NSTIN
      WRITE(5,10) NSTIN
C ***********************************
C ***     SELECT STRESS RANGE FOR    ***
C *** TEMPERATURE LIMIT CALCULATION ***
C ***********************************
      GO TO 300
  320 WRITE(*,80)
      WRITE(5,80)
   80 FORMAT(/,2X,'ENTER MINIMUM STRESS? ',\)
      READ(*,10) MINST
      WRITE(5,10) MINST
      WRITE(*,82)
      WRITE(5,82)
   82 FORMAT(2X,'ENTER MAXIMUM STRESS? ',\)
      READ(*,10) MAXST
      WRITE(5,10) MAXST
      IF (MINST.NE.MAXST) THEN
      WRITE(*,83)
      WRITE(5,83)
   83 FORMAT(2X,'ENTER STRESS INTERVAL? ',\)
      READ(*,10) INTST
      WRITE(5,10) INTST
      ELSE
      INTST=1
      LST=(MAXST-MINST)/INTST÷1
      WRITE(5,2045) KST
 2045 FORMAT (2X,'NUMBER OF STRESSES= ',I5)
      ENDIF
  300 CONTINUE
      ITEST2=2
      IF (IRUN.EQ.3) THEN
      MAXST=NSTIN
      MINST=NSTIN
      INTST=NSTIN
      ITEST2=1
      T1=NTMAX
      ELSE
      WRITE(*,2008)
      WRITE(5,2008)
 2008 FORMAT (/,2X,'*** PLEASE WAIT - CALCULATING TEMPERATURE LIMIT
     A ***')
      WRITE(*,2007)
      WRITE(5,2007)
 2007 FORMAT (/,6X,'STRESS',3X,'TCLIMIT',4X,'DAMAGE',4X,'STRAIN',
```

```
     A2X,'RECOVERY')
      ENDIF
C ****************************
C *** LOOP FOR STRESS RANGE ***
C ****************************
C
C ************************************************************
C *** NOTE DO 61 AND DO 62 ARE ONLY PASSED THROUGH ONCE     ***
C *** FOR IRUN = 3 ,I.E., THE CULMULATIVE FRACTION          ***
C *** VS TIME OPTION FOR WHICH ONLY ONE STRESS IS SPECIFIED. ***
C ************************************************************
      DO 61 KSTIN=MINST,MAXST,INTST
      NSTIN=KSTIN
      TMAX=NTMAX
      IF(TMAX.GT.TEMPAB) THEN
      WRITE (*,311)
      WRITE (*,311)
      GO TO 77
      ENDIF
      T1=340.D0
      IF (IRUN.EQ.3) T1=NTMAX
  301 CONTINUE
      DO 62 ITEST=1,ITEST2
      IF (ITEST.EQ.1) TMAX=T1
      IF (ITEST.EQ.2) TMAX=T2
      IF (IHIST.EQ.4) TMAX=TCTBL
      STIN=NSTIN
      IF (IHIST.EQ.4) STIN=STTBL
      LTMAX=IDINT(TMAX/100.D0)
      TMAXL=LTMAX*100
C CHECK IF YIELD STRESS IS EXCEEDED
      YS=YSA(LTMAX)+(TMAX-TMAXL)*(YSA(LTMAX+1)-YSA(LTMAX))/100.D0
      IF (TMAX.LT.100.D0) YS=-0.735D0*TMAX+460.6D0
      IF (TMAX.GT.700.D0) YS=-0.126D0*TMAX+134.3D0
      IF (STIN.GT.YS) THEN
      WRITE (*,76)
      WRITE (5,76)
      GO TO 77
      ELSE
      ENDIF
      T0=0.D0
      NEQ=3
      INDEX=1
      H0=H0SAVE
      Y(1)=0.D0
      Y(2)=0.D0
      Y(3)=0.D0
C CONSTANTS FOR NITROGEN COOLING HISTORY
      BN=30.D0
      A02=DEXP(1.455D0+0.204D0*DLOG(BN)-0.23291D-1*DLOG(BN)**2)
      A06=DEXP(1.167D0+0.169D0*DLOG(BN))
      A12=-1.0339D0+0.0094D0*BN
```

```
      A16=-0.51391D-1-0.98789D-2*BN+0.92362D-4*BN**2
      NTM1=NT-1
      IF (IRUN.EQ.1) GO TO 2009
      WRITE (*,2002)
      WRITE(5,2002)
 2002 FORMAT (/,7X,'YEARS',4X,'DAMAGE',4X,'STRAIN',2X,'RECOVERY',
     A5X,'TEMPC',4X,'STRESS')
      RECO=0.1D0
      IF(IHIST.EQ.4) THEN
      TMAX=TCTBL
      STIN=STTBL
      ENDIF
      WRITE (*,100) TIN,Y(3),Y(1),RECO,TMAX,STIN
      WRITE (5,100) TIN,Y(3),Y(1),RECO,TMAX,STIN
  100 FORMAT (2X,6E10.3)
 2009 CONTINUE
C LOOP FOR CALCULATING CUMULATIVE FRACTION VS TIME
      DO 50 I=1,NT
      TI=I
      TOUT=TI*3.153600D7*DTIME
C ****************************************************************
C *** CALL DRIVE INTERGRATES VALUES TO TIME TOUT USING GEAR    ***
C ***           GEAR USES RATES DEFINED IN DIFFUN              ***
C ****************************************************************
C *** GEAR SELECTS TIME STEPS FOR INTEGRATION BY CALCULATING   ***
C *** RATES OF CHANGE IN THE PARAMETERS STRAIN, RECOV          ***
C *** AND DAM DIFINED IN DIFFUN.  INTEGRATION PROCEEDS UNTIL   ***
C *** THE TIME EXCEEDS TOUT AND THE VALUES ARE THEN            ***
C *** INTERPOLATED TO TOUT FOR OUTPUT.                         ***
C ****************************************************************
      CALL DRIVE (NEQ,TO,HO,Y,TOUT,EPS,MF,INDEX)
      IF (NFLAGS.GT.0) THEN
      WRITE (*,310)
      WRITE (5,310)
  310 FORMAT (2X,'ERROR - STRESS EXCEEDS THE YIELD STRESS')
      ELSE
      ENDIF
      IF (NFLAGT.GT.0) THEN
      WRITE (*,311)
      WRITE (5,311)
      ELSE
      ENDIF
      FLTEST=NFLAGT+NFLAGS
      IF (FLTEST.NE.0) GO TO 77
      STRAIN=Y(1)
      RECOV=1.D0-0.9D0/(1.D0+Y(2))
      DAM=Y(3)
      TY=TOUT/3.153600D7
      IF (IRUN.EQ.1) GO TO 50
C ***************************************************
C ***   CALCULATE TEMP AND STRESS FOR PRINT OUT   ***
C ***************************************************
```

```
C *** THE TEMPERATURE AND STRESS HISTORY            ***
C *** EQUATIONS ARE IDENTICAL TO THOSE IN DIFFUN.   ***
C *** THEY ARE REPRODUCED HERE TO CALCULATE THE     ***
C *** THE TEMPERATURE AND STRESS AT TOUT.           ***
C *** GEAR INTERPOLATES STRAIN, RECOV AND DAM AT    ***
C *** TOUT BUT DOES NOT INTERPOLATE TEMPERATURE     ***
C *** AND STRESS BECAUSE THEY ARE NOT CALCULATED    ***
C *** FROM RATE EQUATIONS IN DIFFUN.                ***
C ***************************************************
      IF (IHIST-2) 5301,5302,5303
 5301 TZ=(TMAX+273.16D0)*(TIN*12.D0)**(0.34D0)
      IF (TIN.GT.7.D0) TZ=(TMAX+273.16D0)*84.D0**.34D0/
     A 84.D0**0.084D0*(TIN*12.D0)**0.084D0
      TB=TZ*84.D0**(-.34D0)/(84.D0**(-0.084D0))
      TCA=TZ*(TIN*12.D0+TY*12.D0)**(-0.34D0)
      TCB=TB*(TIN*12.D0+TY*12.D0)**(-0.084D0)
      TK=DMAX1(TCA,TCB)
      TC=TK-273.16D0
      ST=STIN*TK/(TMAX+273.16D0)
      GO TO 5304
 5302 TZ=DEXP(A02+A12*DLOG(TIN))+273.16D0
      IF(TIN.GT.5.629D0) TZ=DEXP(A06+A16*DLOG(TIN))+273.16D0
      TKA=(DEXP(A02+A12*DLOG(TIN+TY))+273.16D0)/TZ*(TMAX+273.16D0)
      TKB=(DEXP(A06+A16*DLOG(TIN+TY))+273.16D0)/TZ*(TMAX+273.16D0)
      TK=DMAX1(TKA,TKB)
      TC=TK-273.16D0
      ST=STIN*TK/(TMAX+273.16D0)
      GO TO 5304
 5303 NPTSM1=NPTS-1
      DO 5310 IP=1,NPTSM1
      IF(TY+TIN.LE.HTIME(IP+1)) GO TO 5311
 5310 CONTINUE
      TCC=HTC(NPTS)
      ST=HST(NPTS)
      GO TO 5312
 5311 SLOPE=(HTC(IP+1)-HTC(IP))/(HTIME(IP+1)-HTIME(IP))
      TCC=HTC(IP)+SLOPE*(TY+TIN-HTIME(IP))
      SLOPES=(HST(IP+1)-HST(IP))/(HTIME(IP+1)-HTIME(IP))
      ST=HST(IP)+SLOPES*(TY+TIN-HTIME(IP))
 5312 CONTINUE
      IF (IHIST.EQ.4) TZTBL=TMAX+273.16D0
      TK=(TMAX+273.16D0)/TZTBL*(TCC+273.16D0)
      IF (IHIST.EQ.3) ST=STIN*TK/(TMAX+273.16D0)
      TC=TK-273.16D0
 5304 CONTINUE
C *******************************************************
C *** OUTPUT FOR CUMULATIVE DAMAGE FRACTION CALCULATION ***
C *******************************************************
C YEARAGE IS INITIAL FUEL AGE PLUS STORAGE TIME
      YEARAGE=TIN+TY
      WRITE(*,100) YEARAGE,DAM,STRAIN,RECOV,TC,ST
      WRITE(5,100) YEARAGE,DAM,STRAIN,RECOV,TC,ST
```

```
   50 CONTINUE
      IF (IRUN.EQ.3) GO TO 61
C *******************************************************************
C *** TEST FOR CONVERGENCE OF CF TO UNITY FOR TEMP LIMIT CALCULATION ***
C *******************************************************************
      IF (ITEST.EQ.1) THEN
      CF1=DAM
      STRFIN=STRAIN
      RECFIN=RECOV
      ELSE
      CF2=DAM
      ENDIF
      IF (CF1.LT.1) T2=T1+20.D0
      IF (CF1.GT.1) T2=T1-20.D0
      IF (CF1.EQ.1) GOTO 302
   62 CONTINUE
      SLP=(DLOG(CF2)-DLOG(CF1))/(1.D0/(T1+273.16D0)-1.D0/(T2+273.16D0))
      TKNEW=SLP/(DLOG(CF2)+SLP/(T2+273.16D0))
      TKTEST=DABS(TKOLD-TKNEW)
      IF (TKTEST.LT.1.D0) GOTO 302
      T1=TKNEW-273.16D0
      TKOLD=TKNEW
      GOTO 301
  302 TCFINAL=TKNEW-273.16D0
C ***********************************************
C *** OUTPUT FOR TEMPERATURE LIMIT CALCULATION ***
C ***********************************************
      WRITE(5,36) STIN,TCFINAL,CF1,STRFIN,RECFIN
      WRITE(*,36) STIN,TCFINAL,CF1,STRFIN,RECFIN
   36 FORMAT(2X,5E10.4)
   61 CONTINUE
      IF(IRUN.EQ.1) GO TO 77
      WRITE(5,2003)
      WRITE (*,2003)
 2003 FORMAT (/,2X,'INTEGRATION WAS COMPLETED USING')
      WRITE (*,2004) NSTEP,HOSAVE,HUSED
      WRITE (5,2004) NSTEP,HOSAVE,HUSED
 2004 FORMAT (2X,'TIME STEPS=',I5,5X,'FIRST STEP(SEC)=',E10.3,
     A5X,'LAST STEP(SEC)=',E10.3)
   77 CONTINUE
C *********************************************
C *** END OF PROGRAM AND OPTION TO RUN AGAIN ***
C *********************************************
      IF (NFLAG.GT.0) WRITE (*,78)
      IF (NFLAG.GT.0) WRITE (5,78)
   78 FORMAT (2X,'NOTE ATHERMAL CREEP WAS PREDICTED IN CALCULATIONS')
      WRITE(*,2005)
      WRITE(5,2005)
 2005 FORMAT (/,2X,'RUN AGAIN?  ENTER 0 OR 1 FOR NO OR YES ',\)
      READ(*,10) KRUN
      WRITE(5,10) KRUN
      IF (KRUN.EQ.1) GO TO 2006
```

```
C ***********************************
C *** OUTPUT "HIST" TABLE IF USED ***
C ***********************************
      IF(IHIST.GT.2) THEN
      WRITE (*,2041) NPTS
      WRITE(5,2041) NPTS
 2041 FORMAT (2X,'THE FILE "HIST" WAS USED.   NPTS=',I5)
      WRITE(*,2042)
      WRITE(5,2042)
      DO 2043 LPTS=1,NPTS
 2042 FORMAT (2X,5X,'YEARS',4X,'TEMP C',1X,'STRESS MPA')
      WRITE(*,2044) HTIME(LPTS),HTC(LPTS),HST(LPTS)
      WRITE(5,2044) HTIME(LPTS),HTC(LPTS),HST(LPTS)
 2044 FORMAT(2X,3E10.3)
 2043 CONTINUE
      ENDIF
C ************************
C *** TERMINATE PROGRAM ***
C ************************
      STOP
      END
```

APPENDIX B

LISTING OF DIFFUN SUBROUTINE

LISTING OF DIFFUN SUBROUTINE

```
*$NOFLOATCALLS
 C$STORAGE:2
 C$DEBUG
       SUBROUTINE DIFFUN(NEQ,TT,Y,YDOT)
       IMPLICIT REAL*8(A-H,O-Z)
       DIMENSION Y(NEQ),YDOT(NEQ)
 $INCLUDE: 'COMMON.FOR'
 C TT IS TIME IN SECONDS
 C TY IS IS YEARS
       TY=TT/3.153600D7
 C ****************************************
 C *** CALCULATE TEMPERATURE AND STRESS ***
 C ****************************************
       IF (IRUN.EQ.2) THEN
       TC=TMAX
       TK=TMAX+273.16D0
       ST=STIN
       GO TO 304
       ENDIF
       IF (IHIST-2) 301,302,303
 C HELIUM COOLING
   301 TZ=(TMAX+273.16D0)*(TIN*12.D0)**(0.34D0)
       IF (TIN.GT.7.D0) TZ=(TMAX+273.16D0)*84.D0**.34D0/
      A 84.D0**0.084D0*(TIN*12.D0)**0.084D0
       TB=TZ*84.D0**(-.34D0)/(84.D0**(-0.084D0))
       TCA=TZ*(TIN*12.D0+TT/(2.628000D6))**(-0.34D0)
       TCB=TB*(TIN*12.D0+TT/(2.628000D6))**(-0.084D0)
       TK=DMAX1(TCA,TCB)
       TC=TK-273.16D0
       TK=TC+273.16D0
       ST=STIN*TK/(TMAX+273.16D0)
       GO TO 304
 C NITROGEN COOLING
   302 TZ=DEXP(A02+A12*DLOG(TIN))+273.16D0
       IF(TIN.GT.5.629D0) TZ=DEXP(A06+A16*DLOG(TIN))+273.16D0
       TKA=(DEXP(A02+A12*DLOG(TIN+TY))+273.16D0)/TZ*(TMAX+273.16D0)
       TKB=(DEXP(A06+A16*DLOG(TIN+TY))+273.16D0)/TZ*(TMAX+273.16D0)
       TK=DMAX1(TKA,TKB)
       TC=TK-273.16D0
       ST=STIN*TK/(TMAX+273.16D0)
       GO TO 304
 C TABLE TEMPERATURE DEPENDENCE
   303 NPTSM1=NPTS-1
       DO 310 IP=1,NPTSM1
       IF(TY+TIN.LE.HTIME(IP+1)) GO TO 311
   310 CONTINUE
       TCC=HTC(NPTS)
       ST=HST(NPTS)
       GO TO 312
   311 SLOPE=(HTC(IP+1)-HTC(IP))/(HTIME(IP+1)-HTIME(IP))
```

```
      TCC=HTC(IP)+SLOPE*(TY+TIN-HTIME(IP))
      SLOPES=(HST(IP+1)-HST(IP))/(HTIME(IP+1)-HTIME(IP))
      ST=HST(IP)+SLOPES*(TY+TIN-HTIME(IP))
  312 CONTINUE
      IF (IHIST.EQ.4) TZTBL=TMAX+273.16D0
      TK=(TMAX+273.16D0)/TZTBL*(TCC+273.16D0)
C CALCULATE STRESS CHANGE FROM TEMPERATURE COOLING FOR IHIST EQ 3
C IHIST EQ 4 USES STRESS MAGNITUDES PROVIDED BY THE TABLE
      IF (IHIST.EQ.3) ST=STIN*TK/(TMAX+273.16D0)
      TC=TK-273.16D0
  304 CONTINUE
      IF (TC.GT.TEMPAB) NFLAGT=1
      LTMAX=IDINT(TC/100.D0)
      TMAXL=LTMAX*100
C CHECK FOR STRESS GREATER THAN YIELD STRESS
      YS=YSA(LTMAX)+(TC-TMAXL)*(YSA(LTMAX+1)-YSA(LTMAX))/100.D0
      IF (TC.LT.100.D0) YS=-0.735D0*TC+460.6D0
      IF (TC.GT.700.D0) YS=-0.126D0*TC+134.3D0
      IF (ST.GT.YS) NFLAGS=1
      IF (TC.LT.250.D0) EM=(11.81D0-14.59D0*TK/TM)*1.D4
      IF (TC.GE.250.D0) EM=(11.09D0-11.61D0*TK/TM)*1.D4
      EM1=DLOG(EM/1.D4)
C *****************************
C *** CALCULATE CREEP RATES ***
C *****************************
C ER(1) = HIGH TEMPERATURE CLIMB
      ER(1)=DEXP(5.D0*DLOG(ST/EM)+55.75D0-14.15D0*(TM/TK)+DLOG(TM/TK)
     A +EM1)
C ER(2) = LOW TEMPERATURE CLIMB
      ER(2)=DEXP(7.D0*DLOG(ST/EM)+55.18D0-10.19D0*(TM/TK)+DLOG(TM/TK)
     A +EM1)
C ER(3) = GRAIN BOUNDARY SLIDING
      ER(3)=DEXP(2.D0*DLOG(ST/EM)+20.74D0-9.9200D0*(TM/TK)+DLOG(TM/TK)
     A +EM1)
C ER(4) = GRAIN BOUNDARY LATTICE DIFFUSION CONTROL (NOT CALCULATED)
      ER(4)=0.D0
C ER(5) = NABORRO HERRING
      ER(5)=DEXP(DLOG(ST/EM)+18.25D0-14.15D0*(TM/TK)+DLOG(TM/TK)
     A +EM1)
C ER(6) = COBLE
      ER(6)=DEXP(DLOG(ST/EM)+11.03D0-9.9200D0*(TM/TK)+DLOG(TM/TK)
     A +EM1)
C ER(7) = ATHERMAL
      ER(7)=0.D0
C ************************************
C *** DETERMINE DOMINANT CREEP RATE ***
C ************************************
      EDOTR=ER(1)
      JJER=10
      DO 200 JER=2,6
      IF (ER(JER).GT.EDOTR) THEN
      EDOTR=ER(JER)
```

```
      JJER=JER*10
      ENDIF
  200 CONTINUE
      ZZ=ST/EM
      TMTK=TM/TK
      TMTK1=(1.62D0-DLOG(ZZ))/1.827D0
      TMTK2=(-4.171D0-DLOG(ZZ))/0.547D0
      IF (DLOG(ZZ).GT.-6.644D0) THEN
      IF (TMTK.GT.TMTK1) THEN
      EMA=(11.09D0-11.61D0/TMTK1)*1.D4
      IF(TMTK1.GT.4.06D0) EMA=(11.81D0-14.59D0/TMTK1)*1.D4
      ZA=ST/EMA
      EDOTR=DEXP(7.D0*DLOG(ZA)+55.18D0-10.19D0*TMTK1+DLOG(TMTK1)
     A +DLOG(EMA/1.D4))
      NFLAG=1
      ER(7)=EDOTR
      JJER=70
      ENDIF
      ELSE
      IF(TMTK.GT.TMTK2) THEN
      EMA=(11.09D0-11.61D0/TMTK2)*1.D4
      IF(TMTK2.GT.4.06D0) EMA=(11.81D0-14.59D0/TMTK2)*1.D4
      ZA=ST/EMA
      EDOTR=DEXP(7.D0*DLOG(ZA)+55.18D0-10.19D0*TMTK1+DLOG(TMTK1)
     A +DLOG(EMA/1.D4))
      NFLAG=1
      ER(7)=EDOTR
      JJER=70
      ENDIF
      ENDIF
C ********************************
C *** CALCULATE RUPTURE TIMES ***
C ********************************
C TF(1) = TRANSGRANULAR
      TF(1)=DEXP(-1.797D0-DLOG(EDOTR))
C TF(2) = TRIPLE POINT CRACKING
      TF(2)=DEXP(-5.662D0-DLOG(EDOTR)-DLOG(EM/10000.D0)-DLOG(ST/EM))
C TF(3) = CAVITATION DIFFUSION CONTROL
      TF(3)=DEXP(4.15D0-DLOG(ER(3))+DLOG(ST/EM))
C TF(4) = CAVITATION POWER LAW
      TF(4)=DEXP(-1.587D0-DLOG(EDOTR))
      TMTK=TM/TK
      ZZL=DLOG(ZZ)
      TFTGR=TF(1)
      TFTPR=TF(2)
      IF (ZZL.GT.-6.D0) TF(2)=1.D30
      IF (ZZL.LT.-6.D0) THEN
      IF(TMTK.GT.3.D0) THEN
      TMLIM=(ZZL+6.8D0)/0.2D0
      IF (TMTK.GT.TMLIM) TF(1)=1.D30
      IF (TMTK.LE.TMLIM) TF(2)=1.D30
      ELSE
```

```
      ENDIF
      ELSE
      ENDIF
C ********************************************
C *** DETERMINE DOMINANT RUPTURE MECHANISM ***
C ********************************************
      TMINR=1.D0
      TR1=DMIN1(TFTGR,TFTPR)
      TR2=DMIN1(TFCDR,TFCPR)
      TMINR=TR1
      IF(TR2.LT.TR1) TMINR=TR2
      TMINR=TF(1)
      JJTF=1
      DO 210 JTF=2,4
      IF (TF(JTF).LT.TMINR) THEN
      TMINR=TF(JTF)
      JJTF=JTF
      ENDIF
  210 CONTINUE
      TF(1)=TFTGR
      TF(2)=TFTPR
C MFLAG DEFINES THE CREEP AND RUPTURE MECHANISMS
      MFLAG=JJER+JJTF
C ****************************************
C *** CALCULATE RATES REQUESTED BY GEAR ***
C ****************************************
C YDOT(1) IS THE DOMINANT CREEP RATE
      YDOT(1)=EDOTR
C YDOT(2) IS THE RATE OF RADIATION DAMAGE ANNEALING
      YDOT(2)=2.331736D17*DEXP(-4.D4/TK)
C YDOT(3) IS THE RATE OF ACCUMULATION OF CREEP DAMAGE FRACTION
      YDOT(3)=1.D0/(TMINR*(1.D0-9.D-1*(1.D0/(1.D0+Y(2)))))
      RETURN
      END
```

APPENDIX C

LISTING OF COMMON.FOR

LISTING OF COMMON.FOR

```
*C     COMMON BLOCKS
C
C ***********************************************
C *** BLOCKS GEAR9 AND EXIT ARE USED BY GEAR. ***
C *** LOUT IS THE OUTPUT UNIT ASSUMED IN GEAR ***
C *** FOR OUTPUT OF ERROR MESSAGES.           ***
C ***********************************************
      COMMON/GEAR9/HUSED,NQUSED,NSTEP,NFE,NJE
      COMMON/EXIT/LOUT
C *********************************************
C *** DATE BLOCKS COMMUNICATE INPUT, OUTPUT ***
C *** AND CONSTANTS BETWEEN MAIN AND DIFFUN ***
C *********************************************
      COMMON/DATE1/TMAX,ST,STIN,TC,TIN,TOUT,IRUN
      COMMON/DATE2/YSA(7),TEMPAB,TM
      COMMON/DATE3/HTIME(51),HTC(51),HST(51),IHIST,NPTS
      COMMON/DATE4/A02,A06,A12,A16,TZTBL
      COMMON/DATE5/ER(7),TF(4),EDOTR,TMINR
C *************************************************************
C *** FLAG BLOCK COMMUNICATES FLAGGED CONDITIONS BETWEEN    ***
C *** MAIN AND DIFFUN                                       ***
C ***   MFLAG  - CREEP RATE AND RUPTURE MECHANISM           ***
C ***   NFLAG  - ATHERMAL CREEP ASSUMED DURING CALCULATION  ***
C ***   NFLAGT - ALPHA/BETA TRANSITION TEMPERATURE EXCEEDED ***
C ***   NFLAGS - YIELD STRESS EXCEEDED                      ***
C *************************************************************
      COMMON/FLAG/MFLAG,NFLAG,NFLAGT,NFLAGS
      LOUT=5
```

LISTING OF DPLOT.BAS

```
10 REM PLOT DATING.OUT FROM DATING FOR CUMULATIVE FRACTION OPTION
20 CLS
30 KEY OFF
40 DIM TI(100),ST(100),REC(100),CF(100),TC(100),PAR(6,100),ZSTR(100)
50 OPEN "DATING.OUT" FOR INPUT AS #1
60 FOR JLIN=1 TO 18
62 INPUT #1,ZLIN$
64 NEXT JLIN
70 INPUT #1,ZLIN$
80 YLIN$=RIGHT$(ZLIN$,5)
90 HIST=VAL(YLIN$)
100 REM LINE INPUT #1,ZLIN$
110 LINE INPUT #1,ZLIN$
120 LINE INPUT #1,ZLIN$
140 INPUT #1,ZLIN$
150 YLIN$=RIGHT$(ZLIN$,5)
160 AGEIN=VAL(YLIN$)
170 LINE INPUT #1,ZLIN$
180 LINE INPUT #1,ZLIN$
190 LINE INPUT #1,ZLIN$
200 LINE INPUT #1,ZLIN$
205 LINE INPUT #1,ZLIN$
210 YLIN$=RIGHT$(ZLIN$,5)
220 NST=VAL(YLIN$)+1
230 LINE INPUT #1,ZLIN$
232 JJLIN=2
234 IF HIST=4 THEN JJLIN=1
235 IF HIST=4 THEN 310
240 LINE INPUT #1,ZLIN$
250 LINE INPUT #1,ZLIN$
260 YLIN$=RIGHT$(ZLIN$,5)
270 TMAX=VAL(YLIN$)
280 LINE INPUT #1,ZLIN$
285 LINE INPUT #1,ZLIN$
290 YLIN$=RIGHT$(ZLIN$,5)
300 STR=VAL(YLIN$)
310 FOR JLIN=1 TO JJLIN
320 LINE INPUT #1,ZLIN$
330 NEXT JLIN
335 IF NST>100 THEN NST=100
340 FOR LSTEP=1 TO NST
350 INPUT #1,TI(LSTEP),CF(LSTEP),ST(LSTEP),REC(LSTEP),TC(LSTEP),ZSTR(LSTEP)
360 PAR(1,LSTEP)=TI(LSTEP):PAR(2,LSTEP)=ST(LSTEP):PAR(3,LSTEP)=REC(LSTEP)
370 PAR(4,LSTEP)=CF(LSTEP):PAR(5,LSTEP)=TC(LSTEP)
380 NEXT LSTEP
390 REM INPUT #1,TGEAR,I1GEAR,I2GEAR,I3GEAR,I4GEAR
400 REM INPUT #1,AGEIN
410 CLOSE #1
420 A$="CF":LLP=4
```

```
430 REM GOTO 240
440 CLS
442 IF HIST=4 THEN TMAX=TC(1)
444 IF HIST=4 THEN STR=ZSTR(1)
450 PRINT "TMAX=";TMAX;"   STRESS=";STR
460 PRINT "YEAR";TAB(10);"STRAIN";TAB(25);"RECOVERY";TAB(40);"Cum Frac dam";TAB(55);"TEMP,
C";TAB(65);"STRESS, MPA"
470 FOR LSTEP=1 TO NST
480 PRINT TI(LSTEP);TAB(10);ST(LSTEP);TAB(25);REC(LSTEP);TAB(40);CF(LSTEP);TAB(55);TC(LSTEP);T
AB(65);ZSTR(LSTEP)
490 NEXT LSTEP
500 LOCATE 25,1
510 INPUT "ENTER PLOT TYPE: CF,ST,REC,TC,TABLE,END? ",A$
520 IF A$="CF" THEN LLP=4
530 IF A$="ST" THEN LLP=2
540 IF A$="REC" THEN LLP=3
550 IF A$="TC" THEN LLP=5
560 IF A$="END" THEN SYSTEM
570 IF A$="TABLE" THEN 440
580 TIMAX=TI(1):STMAX=ST(1):RECMAX=REC(1):CFMAX=CF(1):TCMAX=TC(1)
590 TIMIN=TI(1):STMIN=ST(1):RECMIN=REC(1):CFMIN=CF(1):TCMIN=TC(1)
600 FOR LSTEP=2 TO NST
610 IF TI(LSTEP)>TIMAX THEN TIMAX=TI(LSTEP)
620 IF TI(LSTEP)<TIMIN THEN TIMIN=TI(LSTEP)
630 IF ST(LSTEP)>STMAX THEN STMAX=ST(LSTEP)
640 IF ST(LSTEP)<STMIN THEN STMIN=ST(LSTEP)
650 IF REC(LSTEP)>RECMAX THEN RECMAX=REC(LSTEP)
660 IF REC(LSTEP)<RECMIN THEN RECMIN=REC(LSTEP)
670 IF CF(LSTEP)>CFMAX THEN CFMAX=CF(LSTEP)
680 IF CF(LSTEP)<CFMIN THEN CFMIN=CF(LSTEP)
690 IF TC(LSTEP)>TCMAX THEN TCMAX=TC(LSTEP)
700 IF TC(LSTEP)<TCMIN THEN TCMIN=TC(LSTEP)
710 NEXT LSTEP
720 REM END
730 KEY OFF
740 REM DETERMINE NUMBER IN FORM X.XXENN
750 FOR LMAX=1 TO 5
760 IF LMAX=1 THEN X1=TIMAX:XMIN=TIMIN
770 IF LMAX=2 THEN X1=STMAX:XMIN=STMIN
780 IF LMAX=3 THEN X1=RECMAX:XMIN=RECMIN
790 IF LMAX=4 THEN X1=CFMAX:XMIN=CFMIN
800 IF LMAX=5 THEN X1=TCMAX:XMIN=TCMIN
810 K=-1
820 IF INT(X1)=0 AND INT(10*X1)<>0 THEN XMAX=X1:GOTO 940
830 IF INT(X1)>0 THEN 890
840 X2=X1
850 X2=X2*10
860 K=K-1
870 IF INT(X2)=0 AND INT(10*X2)<>0 THEN XMAX=X2:GOTO 940
880 GOTO 850
890 X2=X1
900 X2=X2/10
```

```
910 K=K+1
920 IF INT(X2)=0 THEN XMAX=X2:GOTO 940
930 GOTO 900
940 REM END ROUTINE
950 X1MAX=XMAX
960 XMAX=10*XMAX
970 REM PRINT X1,XMAX,K
980 XXM=2
990 IF XMAX=<10 AND XMAX>5 THEN XXM=10
1000 IF XMAX=<5 AND XMAX>2 THEN XXM=5
1010 RMAX(LMAX)=XXM
1020 PMAX(LMAX)=XXM
1030 PMIN(LMAX)=PMAX(LMAX)-RMAX(LMAX)
1040 PKMAX(LMAX)=K
1050 NEXT LMAX
1060 CLS
1070 REM INPUT "LX?",LX
1080 REM INPUT "LY?",LY
1090 CLS
1100 GOTO 1140
1110 SCREEN 0
1120 LOCATE 10,10
1130 PRINT "END"
1140 SCREEN 2
1150 X0=100
1160 Y0=150
1170 DX=440
1180 DY=125
1190 LINE (X0,Y0)-(X0+DX,Y0)
1200 LINE (X0+DX,Y0)-(X0+DX,Y0-DY)
1210 LINE (X0+DX,Y0-DY)-(X0,Y0-DY)
1220 LINE (X0,Y0-DY)-(X0,Y0)
1230 FOR K=X0 TO X0+DX STEP DX/5
1240 LINE (K,Y0)-(K,Y0-3)
1250 LINE (K,Y0-DY)-(K,Y0-DY+3)
1260 NEXT K
1270 FOR K=Y0 TO Y0-DY STEP -DY/5
1280 LINE (X0,K)-(X0+3,K)
1290 LINE (X0+DX-3,K)-(X0+DX,K)
1300 NEXT K
1310 XMIN=0
1320 XMAX=PMAX(1)*10^PKMAX(1)
1330 YMIN=0
1340 YMAX=PMAX(LLP)*10^PKMAX(LLP)
1350 IF LLP=5 THEN YMAX=PMAX(LLP)*100
1360 DMX=XMAX-XMIN
1370 DMY=YMAX-YMIN
1380 REM PSET (X0,Y0)
1390 FOR KP1=1 TO NST
1400 XX=TI(KP1)
1410 YY=PAR(LLP,KP1)
1420 X=XX/DMX*DX+X0
```

```
1430 Y=Y0-YY/DMY*DY
1440 IF KP1=1 THEN PSET(X,Y)
1450 LINE -(X,Y)
1460 REM PRINT XX,YY,XMAX,YMAX
1470 NEXT KP1
1480 LOCATE 3,33:PRINT "TMAX=";TMAX;" STRESS=";STR;" AGEIN=";AGEIN;" TH=";HIST
1490 LOCATE 3,14
1500 IF LLP=2 THEN PRINT "STRAIN FRACTION"
1510 IF LLP=3 THEN PRINT "RECOVERY FACTOR  "
1520 IF LLP=5 THEN PRINT "TEMPERATURE, C"
1530 IF LLP=4 THEN PRINT "DAMAGE FRACTION"
1540 LOCATE 12,2
1550 IF LLP=4 THEN PRINT "CF"
1560 IF LLP=2 THEN PRINT "ST"
1570 IF LLP=3 THEN PRINT "REC"
1580 IF LLP=5 THEN PRINT "TC"
1590 REM FOR K=1 TO 30:PRINT "";:NEXT K
1600 LOCATE 15,55:PRINT ""
1610 FOR L=0 TO 5:LOCATE Y0/200*25+1,12+L*11:PRINT L*PMAX(1)*10^PKMAX(1)/5:NEXT L
1620 IF LLP<>5 THEN FOR L=0 TO 5:LOCATE Y0/200*25-L*3,8:PRINT L*PMAX(1)*10^PKMAX(1)/5:NEXT L
1630 IF LLP=5 THEN FOR L=0 TO 5:LOCATE Y0/200*25-L*3,8:PRINT L*PMAX(LLP)*10^PKMAX(LLP)/5:NEXT
1640 LOCATE 22,30:PRINT "FUEL AGE IN YEARS"
1650 GOTO 500
1660 END
```

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