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A USER'S MANUAL FOR
FINITE-ELEMENT COMPUTER CODE
"CREEP-PLAST"

by

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BASE TECHNOLOGY

January 1978

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I. INTRODUCTION

CREEP-PLAST is a finite element computer code developed by Y. R. Rashid^(1,2) for high temperature structural design of LMFBR vessels, components and core structures. It performs creep and plasticity calculation in two dimensional form under plane stress, plane strain or axisymmetric assumptions.

The original code has been extensively modified to improve its efficiency. The following is a summary of modifications made to CREEP-PLAST to obtain our version of the code:

(1) VARIABLE DIMENSIONING: This means that arrays no longer have some fixed maximum dimensions, but have the size actually required. Hence

(a) All dimensional restrictions are removed; the ultimate restriction is the amount of memory available on a given machine.

(b) Many smaller problems can now be run using modest core (the previous version required, for all problems, 876K on ANL's IBM 360/195).

(2) OPTIMIZATION OF PERIPHERAL DEVICES: Previously, Units 17, 18, 21 and 22 were always used; in our version, their use is invoked depending only on the size of the problem and the amount of the fast memory one wishes to allocate. In addition, the BACKSPACE instruction in subroutine CALC has been eliminated; this reduces WAIT time by a factor of about three. When one considers that for a typical problem WAIT time had been well in excess of CPU time, this development becomes especially attractive.

(3) CLEANUP AND REORGANIZATION: The coding has been so improved that the cost of running a problem has been reduced by a factor ranging from five to twenty-five. In addition, the number of FORTRAN statement cards has been reduced by about 35%.

(4) INCREASED CAPABILITY: Changes to input have increased flexibility (compare new input description with old). In the course of running a problem, the user can now redefine any or all of

- (a) loading increment
- (b) boundary conditions (a new NUMBC, e.g.)
- (c) pressure (a new N4, e.g.)

(5) Changes to input format also allows plotting of meshes via pre-processor developed for SAP4 input.

(6) Certain energy calculations are now performed.

II. PROGRAM DESCRIPTION:

The Creep formulation is based on two alternative approaches;

(1) The equation of state approach with strain hardening assumption, that is, the value of total creep strain together with the current stress determines the amount of additional creep the material will undergo within a specified time increment, and

(2) The memory theory approach based on Boltzman's superposition principle and Voltura's hereditary representation of the material states. In equation of state approach, the creep strain due to reversal situation is taken care of by adjusting the origin of the accumulated creep strain.

The plasticity formulation is based on kinematic hardening and on the Von Mises Yield condition with its associated flow rule. The size of subsequent yield surface or loading surface may change. The loading surface may translate in the stress space if additional loading occurs. This takes account of the Bauschinger effect which some material may exhibit during the plastic loading.

CREEP-PLAST has the capability to iterate on the solution within each time and/or load increment. Each iteration consists of the following steps; (all computation is on an incremental basis)

(1) The thermal strain and creep strain are treated as initial strains together with the existing strain, and the corresponding stress is calculated through the use of elastic matrix $[D]$ or elasto-plastic matrix $[D^*]$ (if plastic flow occurs).

(2) The stiffness matrix which relates the nodal displacements to the nodal forces is assembled. If plastic flow occurs, the additional stress resulting from the non-isothermal kinematic hardening assumption is treated as initial stress. Nodal forces due to initial stress and initial strain from step (1) are computed. The force vector is then assembled. The nodal force vector and stiffness matrix is then used to obtain the nodal displacement vector.

(3) The element strain vector is calculated from the nodal displacement vector.

The above procedure describes one step of the iteration. In terms of program operation, it consists of one cycle of the link sequence STIFF-SOLVE-CREEP.

There are two different types of elements available in the program to model the structural continua.

- (1) Simple plane triangular elements
- (2) Triangular ring (axisymmetric) elements

The elements are defined by their three nodes. The displacement at any point within the element is given by two linear polynomials representing the two degrees of freedom. The plane elements are assumed to have unit thickness. The volume associated with the ring elements is that of one body of revolution and volume integration has to be referred to this.

To save storage and computation time, the bandwidth of the stiffness matrix is to be kept as narrow as possible. This can be achieved by paying attention to the numbering of nodes. Narrow bandwidth can be attained by numbering nodes in sequence across the narrow direction of the body rather than across the long direction of the body. The program contains a mesh generation routine which can be used for regular cylinders, rectangular flat plates or any large rectangular regions in an irregular structure.

CREEP-PLAST permits displacement constraints on nodes. A node may be constrained in one or both orthogonal displacement directions. In the system of equilibrium equations, the displacements of the nodal points are the basic unknown parameters. Rigid body movement can be eliminated and solution can be obtained uniquely by substitution of a number of prescribed displacements. This substitution is performed in the routine STIFF.

The input loading conditions in CREEP-PLAST include a complete description of mechanical and thermal loading history throughout the entire computation period. The temperature should be prescribed on an element by element basis while the mechanical loads are given at both orthogonal directions at each nodal point. The mechanical load and temperature are assumed to be constant for the increment of the load calculation and for the prediction of the creep increment by the equation of state approach. For the memory theory approach, the integration of creep compliance is performed by Simpson integration over six points between each two consecutive time steps. The pressure and temperature are assumed to vary linearly within the increment. The discrete time increments are chosen by user. Under very high temperature, the relaxation time of thermal stress, defined as the length of time it takes to relax the local effective stress to one-half of its initial strength, is relatively short. The time increment is selected such that in the critical elements, i.e., the elements that are under highest temperature or most severely stressed, the increments are in a compatible order with the estimated relaxation time for that particular element. Some methods of estimating the relaxation time have been reported (3). A proper choice of time increments at the beginning will insure a stable calculation and reduce the numerical error in output.

III. SUBROUTINE DESCRIPTION

(1) Routine DFMTOT;

This routine defines MTOT, and gives system load size of blank COMMON.

The latter contains all variably dimensional arrays.

(2) Routine MAIN;

MAIN is the driver routine wherein STIFF, SOLVE and CREEP are called sequentially once for each solution iteration during each time increment.

MAIN reads in the following:

CARD (1)	TITLE CARD	FORMAT (ALPHA NUMERIC)
	Col. 1-72	problem title
CARD (2)	OPTION CARD	FORMAT (12I6, 2I4)
NUMEL	Col. 1-6	the number of elements in the structure
NUMNP	7-12	the number of nodal points
NUMBC	13-18	the maximum number of nodal points to be constrained in the run
N1	19-24	the number of materials
N2	25-30	option to read temperature and load history. = 0 read neither card (6) nor card (7) = 1 read card (6) only = 2 read card (7) only = 3 read card (6) and card (7)
N3	31-36	plotting option, for this version of code, set N3=0
N4	37-42	the maximum number of pressure groups for this run

N5	43-48	the number of time increments
N6	49-54	option to read in temperature input. = 0 card (8) and tape 10 are not used ≠ 0 read either card (8) or tape 10. N6 is the time step after which the element temperature remain constant
N7	55-60	option for initial run or restart = 1 begin from increment 1 >1 restart calculation at time increment N7.
N8	61-66	unused
N9	67-72	option for creep calculation, using either equation of state or memory theory. =0 memory theory =1 equation of state both include plasticity.
MM6	73-76	
MM9	77-80	
N10	1-6	

a node is permitted no more than (MM9-1) other nodes adjacent to it and of these, only (MM6-1) can have higher indices. Defaults: MM6 = 6, MM9 = 9.

time increment number at the end of which run is to be terminated. If we run out of time, program will have terminated at a natural restart point.

N11	7-12	restart option, number of steps which have been completed in all previous runs.
N12	13-18	option for invoking MESH subroutine (automatic mesh generator) = 0 no mesh generation, complete mesh information will be furnished by user. = 1 partial or total mesh generation = 2 restart from tape
N13	19-24	no longer used
N14	25-30	option indicating if problem is plane or axisymmetric = 0 all the elements are axisymmetric = 1 all the elements are plane stress = 2 all the elements are plane strain
N15	31-36	option to read temperature history from card or tape = 0 read the temperature history from card (8) = 1 read the temperature history from tape 10, ignored if N6=0
N16	37-42	unused
N17	43-48	number of iteration to be performed within each time step; 2 is recommended.
NT1	49-54	input tape 14 or 9; if zero, NT1=14
NT2	55-60	temperature tape 10, to be specified only if N6≠0

NT3	61-66	output tape 9 or 14; if zero, NT3=NT1
	67-72	unused
MM100	73-76	maximum value of (NBC (I), I=1,N4) for this run; see description of card (19)
NFT4	77-80	option for stress output; if NFT4=0, program writes stress on unit 4.

From the above data, indices are calculated that locate variably dimensioned arrays in blank COMMON that are to be used in subroutine GEE and elsewhere.

(3) Routine LTRAN (NTAPE, NI, IDIM1, ARRAY 1, ICHECK)

LTRAN	reads or writes peripheral devices
NTAP	the logical unit number of the device.
ARRAY 1	the data array to be transmitted
IDIM1	the dimension of the data array
NI	= 1, the data array is written onto the unit NTAPE = 2, the data array to read from the unit NTAPE
ICHECK	unused

(4) Routine GEE (LODCYC, PCYC, XMATD, LBC, THERM, TEM, IDM3).

This routine reads in the following:

CARD (3)	Material properties card	FORMAT (6E 12.6, E8)
XM (1)	Col. 1-12	EPSI1, yield stress; if zero, uses built-in yield stress
XM (2)	13-24	ESTEEL, modulus of elasticity
XM (3)	25-36	ALFAS, coefficient of thermal expansion
XM (4)	37-48	EPSI2, hardening modulus

XM (5)	49-60	XVC, poisson's ratio
XM (6)	61-72	YRATIO, ratio of initial yield stress to yield stress from a 10-cycle curve.
XM (7)	73-80	DELT*, base temperature at which the structure is stress free.

Next follow J cards, J=1, N1   FORMAT (6E12.6)

XMATD (I,J), I=1,6

These XMATD are then redefined as: XMATD (I,J) = XMATD (I,J) * XM (I), I=1,6

CARD (4)   Redefinition flags and time   FORMAT (5 (I3, F13.5))

increment card

(LBC (I), DTIM (I), I=1, N5)

LBC (I) consists of a three digit number (L1, L2, L3) which controls logical flow during routine STIFF. (Will describe in STIFF)

DTIM (I)   defines the cumulative time at the step I.

CARD (5)   unused

CARD (6)   Pressure loading history   FORMAT (6F 12.3)
card

PCYC (I,J)   pressure and/or load multiplier
I=N5   array. This permits the variation
J=1, Min (N4,3)   of the first three surface pressure groups independently. Surface pressure loads are converted to the corresponding nodal loads in routine STIFF

*If N6=0, all element temperatures are set equal to DELT unless otherwise specified by ALFATE on Card (14).

CARD (7)   Temperature history card   FORMAT (6F12.3)

LODCYC (I)   temperature multiplier array.

I=1, N5   This permits the variation of

all element temperatures equally;

it is a cumulative temperature

change array.

CARD (8)   Element temperature   FORMAT (I6, 6X, 5F 12.3)

card

(NN, TEM (I), I=1, N6)   element temperature at time Step I

If the above TEMPERATURE CARDS were read in (N6>0, N15 = 0), the data would be written on unit NT2, unit 21 would be used for temperature storage.

Additional indices to locate various arrays to be used in subroutine RESTAR and elsewhere are calculated.

(5) Routine MESH (NPI, NPJ, NPK, NPM, XORD, YORD, SCAL, LUMPT, NUMPT, XLOAD, YLOAD, NFIX, NYB, SLOPE, NUMEL, NUMNP, MUNBC, NUMEL1, NUMNP1, NUMBC1).

This routine, called by RESTAR when N12=1, generates meshes automatically.

Cards (9) through (13) are read in:

CARD (9)		FORMAT (3I6)
NN7	Col. 1-6	number of blocks for mesh generation.
NUMEL1	7-12	number of extra element to be read in.
NUMNP1	13-18	number of extra node to be read in.

Cards (10) through (13) define the rectangular region (block) in which the mesh is to be generated and are repeated NN7 times.

CARD (10)		FORMAT (3I6)
NUMR1	1-6	number of rows of elements in block.
NUML	7-12	number of columns of elements in block.
NMAT	13-18	number of elements in block.
CARD (10A)		FORMAT (12I6)

NPM (I)		material index number
I=1, NPMAT		
CARD 11		FORMAT (12I6)
(NUMPT (I), I=1, NUMR1+1)		number of first node in each row.
(LUMPT (J), J=1, NUMR1)		number of first element in each row.
CARD (12)		FORMAT (3E 12.4)
RI	Col. 1-12	inner radius of section.
RA	13-24	outer radius of section.
YREF	25-36	axial coordinate of first node in the section.
CARD (13)		FORMAT (6E 12.4)
(SCAL (I), I=2, NUMR1 + 1)		height of two elements regions in the I th row. The program sets SCAL (1) = 0.

Some physical problems may require a very large number of time increments to fully describe their complicated loading and temperature history and to achieve a stable and accurate solution. Other problems may be such as to require monitoring so as to allow changing parameters in order to achieve correct results. Finally, the user may not have allowed sufficient computer time for the solution of a problem, perhaps quite deliberately. For these and other reasons, the program contains a restart capability. If so instructed, the program reads in a restart dump from a previous run from unit NT1; at the conclusion of a run, it will write a new one on unit NT3.

(6) Routine RESTAR (NPI, NPJ, NPK, NPM, ALFATE, XORD, YORD, XLOAD, YLOAD, CF, XMATD)

This routine reads in a dump from a previous run if computation is to proceed from a restart, in which case go to step (c) below. Otherwise the routine does the following:

If N12=1, routine MESH is called for partial or total mesh generation.

(a) If there remain some elements requiring definition, the following are read in:

CARD (14) Additional elements information card FORMAT (5I6, 2E12.4)

N	Col. 1-6	the element index number
NPI(N)	7-12	nodal index I
NPJ(N)	13-18	nodal index J
NPK(N)	19-24	nodal index K
NPM(N)	25-30	material index number ($1 \leq \text{NPM}(N) \leq \text{N1}$)
CF(N)	31-42	coefficient of thermal expansion.
ALFATE	43-54	element temperature.

If N is negative, $N = -N$, ignore entries for nodal indices, store last three entries. If either of last two is blank, ignore (i.e., use previously defined values)

Note: In routine STRAIN, if $I = \text{NPM}(N)$, then

$$\text{CFTO} = \text{CF}(N) * \text{XMATD}(3, I)$$

If $\text{N14}=2$, then

$$\text{CFTO} = \text{CFTO} * (1 + \text{XMATD}(5, I)),$$

(b) If there remain some nodal points requiring definition, the following are read in:

CARD (15) Additional nodes information card FORMAT (I6, 6X, 4F12.2)

M	Col. 1-6	nodal index
XORD(M)	13-24	X (radial) coordinate.
YORD(M)	25-36	Y (axial) coordinate.
XLOAD(M)	37-48	radial force on the nodal point.
YLOAD(M)	49-60	axial force on the nodal point.

If M is negative, $M = -M$, ignore coordinates, store loads. Note: The reason we have negative N and/or M for the last two cards is to allow the user to modify data generated in some versions of subroutine MESH. The same applies to boundary condition cards CARD (16).

(c) All remaining indices to locate variably dimensioned arrays are now computed. Information indicating optimum choices of MTOT and corresponding REGION (the amount of memory required to run problems) is now printed.

(7) Routine STIFF (PCYC, LBC, NFIX,.....)

At the beginning of each time step the routine interrogates LBQ(NT), a three digit number L1, L2, L3 (see CARD (4)).

(a) If L1 is zero, go to step (b) otherwise, read in the following:

CARD (15A)	Load increment card	FORMAT (I8)
NY	Col. 1-8	the number of nodes whose loads we wish to increment.

CARD (15B)	FORMAT (I6, 30X, 2F12.2,

(M,RXLD(M),ZYLD(M),N=1, NY)	incremental loads; M specifies the node being modified. Later in STIFF, RXLD is added to RLOAD, and ZYLD to ZLOAD at the indicated nodal point M.

(b) If NT=1, set N=NUMBC-NUMBC1+1, go to step (b, ii)

(i) If L2 is zero, go to step (c), otherwise read in the following:

CARD (15C)	FORMAT (2I6)
NUMBC	Col. 1-6 new value for NUMBC
N	7-12

(ii) With L ranging from N through NUMBC, read in the following:

CARD (16)	Boundary condition card	FORMAT (2I6, F12.6, 2E 12.4)
M	1-6	the index of the constrained nodal point NPB (L) = M
NFIX(L)	7-12	type of constraint to be imposed.
		= 3, both U_r and U_z are constrained
		= 2, only U_z is constrained
		= 1, only U_r is constrained
		= 0, no constraint

SLOPE(M)	13-24	the angle between the line of constraint and the horizontal axis. (in degrees)
DSX(M)	25-36	initial radial displacement
DSY(M)	37-48	initial axial displacement

If M is negative, $M=-M$, NFIX and SLOPE are ignored, only DSX and DSY are stored.

(c) If initial $N4=0$, go to step (d). If $NT=1$, go to step (c ii).

(i) If $L3$ is zero go to step (d), otherwise read in the following:

CARD (16A)		FORMAT (I6)
N4	Col. 1-6	New value of $N4$.

(ii) With M varying from 1 through $N4$, read in the following:

CARD (19)		FORMAT (I6, 6X, 5F 12.3)
MBC	1-6	NBC (M)=MBC
PRESS1 (M)	13-24	constant in the pressure formula.
PRESS2 (M)	25-36	constant in the pressure formula.
PRESS3 (M)	37-48	constant in the pressure formula.

$$P = \text{PRESS1} + \text{PRESS2} * (r-RI) + \text{PRESS3} * (z-ZI)$$

RRI (M)	49-60	the radial coordinate of a reference point for the pressure group.
ZZI (M)	61-72	the axial coordinate of a reference point for the pressure group.

CARD (20)	Pressurized nodes description card	FORMAT (12I6)

MPB (L,M), $L=1, \text{MBC}$	the index of the pressurized node.

(d) Note that this version of the code no longer reads in the special yielding cards (17) and (18), since they are no longer necessary.

In conclusion, the existence of the set of numbers ($L1, L2, L3$) allows one (1) to vary the loads at certain nodes, (2) to add extra boundary nodes and (3) to vary the pressure intensity correspondingly during each load increment.

Subroutine STIFF assembles the stiffness matrix of the structure and applies the boundary conditions to the system of governing equations. Initial values of displacement vector and the stiffness matrix are set to zero at the beginning of the routine.

The basic unknown of the system of equations, the displacement vector of the nodal points, is related to the nodal force vector by $[K]$, the stiffness matrix, that is

$$[K] d\{\delta\} = d\{F\}.$$

STIFF assembles the sub-matrices obtained from STCREP and forms the $[K]$ matrix. The mechanical load, equivalent load due to initial strain and stress at each nodal point is gathered and constitutes the $\{F\}$ vector.

If the displacements at certain boundary nodes are specified, both the stiffness matrix and load vector are modified, that is, suppose the K^{th} row of the displacement is set to a value d , the loading vector is modified such that

$$\bar{F}_i = F_i - K_{ki} \quad k = 1, N \quad i \neq k$$

$$\bar{F}_k = d$$

where overhead bar indicates modified value. In the stiffness matrix, the corresponding row and column is set to zero and the diagonal term is set to unity. If $d=0$, then only the stiffness matrix is modified in the manner as described above, leaving the load vector unchanged.

$[K]$ matrix is a large symmetric and banded matrix with only the upper triangular and diagonal elements needed to be stored. The condition of stiffness matrix is examined in STIFF; if ill-conditioned behavior is indicated, program will be terminated. The coefficient of $[K]$ will be used as input to routine SOLVE, which solves the system of equilibrium equation. The block size is the semi-bandwidth.

(8) Routine MATCON (NPAR, T, SIGMA, EI, CON, YIELD, DSIG, N8)

The routine contains all material constants of the uniaxial stress-strain relation for heat 8043813 of type 304 stainless steel. It comprises three blocks. Block 1 is employed to define temperature varying Young's modulus and/or yield stress. Block 2 will return a non-linear stress curve for average properties of 304 stainless steel. The user's formula for calculation of the ratio of tangent modulus to elastic modulus for non-linear curve can be inserted in Block 3.

Input arguments of routine are:

NPAR	option flag to activate either block 1 or block 2.
T	temperature of element under consideration.
SIGMA	effective stress of element under consideration, based on the stress coordinate of translating loading surface if plastic flow takes place.
DSIG	incremental effective stress between two consecutive time steps.

Return arguments of this routine are:

EI	temperature varying Young's modulus.
YIELD	temperature varying yield stress.
CON	ratio of the tangent modulus to the elastic modulus.

(9) Routine SHIFT (T, SIGMA, EX, R, EM, A, D, N8)

SHIFT describes and formulates the thermal creep behavior of the material. Creep strain ϵ^c is assumed to be a function of temperature and stress.

ϵ^c has the following general form:

$$\epsilon^c(\sigma, T, t) = \epsilon_t(\sigma, T) [1 - e^{-r(\sigma, T)t}] + \dot{\epsilon}_m(\sigma, T)t$$

where the first term represents the primary creep strain, the second term represents the steady state creep.

Input arguments are:

T	temperature of element under consideration.
SIGMA	σ , effective stress of element under consideration, based on stress coordinate of translating loading surface if plastic flow occurs.

Return arguments are:

EX	$\epsilon_t(\sigma, T)$
R	$r(\sigma, T)$
EM	$\dot{\epsilon}_m(\sigma, T)$
A	$\epsilon_t(\sigma, T)/\sigma$
D	$\dot{\epsilon}_m(\sigma, T)/\sigma$

(10) Routine STATE (T, EFFSTR, TIJ, SG, AR, DELTM, DTM, ITER, CREEP, N8)

Routine STATE defines the equation of state formulation of creep calculation. The creep law is assumed to have the general form as that in routine SHIFT. It mathematically describes the experimentally observed axial creep strain as a function of constant uniaxial stress, time and temperature. To apply such a creep law to a variable stress condition a certain hardening rule is needed. Strain hardening rule is chosen over time hardening rule, since it is more representative of material behavior. It is assumed that the principal factor governing the creep rate is the strain, regardless of the stress history required to produce the strain. To eliminate too complicated numerical computation, it is assumed that strain-hardening is based on primary creep strain only, hence the time factor in the creep law can then be eliminated analytically. The general

creep law states:

$$\epsilon^c(\sigma, t, T) = \epsilon_t(\sigma, T) [1 - e^{-r(\sigma, T)t}] + \dot{\epsilon}_m(\sigma, T)t$$

By differentiating the primary creep strain w.r.t. t and eliminating e^{-rt} from the creep law, the constitutive equation becomes

$$\epsilon_{ij}^c = \frac{3}{2} \{ r(\sigma, T) [\epsilon_t(\sigma, T) - \epsilon^{-t}] - \dot{\epsilon}_m(\sigma, T) \} \frac{\sigma_{ij}}{\sigma}$$

where ϵ^{-t} is defined as effective primary creep strain to be calculated at the beginning of a time interval. If stress reversal occurs, the creep strain origin is relocated (4).

Input arguments are:

T	temperature of the element under consideration.
EFFSTR	effective strain of the element.
TLJ (I) I=1,4	effective stress of the element.
SG (I) I = 1,4	stress vector of the element.
DELT	time increment.
DTM	accumulated time.
ITER	specified number of iteration.

Return arguments are:

AR (I,J) I = 1,20; J = 1,3	storage matrix; Some variables computed in this routine are stored in part of this matrix, to be transmitted to other routines or used as input for next time step. These variables are:
AR (I + 12,2) I = 1,4	instantaneous strain vector.

AR (I + 16, I) I = 1,2

possible strain origins which exist at any time in the primary creep strain space.

AR (10, I) I = 1,2

a measure, on an effective strain basis, of the distance between an instantaneous strain state and the appropriate strain origin.

CREEP

computed increment creep strain.

(11) Routine INVERT (A) .

This is a matrix inversion subroutine.

(12) Routine MEMORY (GE, DT, AR, RO, N8)

Memory theory is an alternative to the equation-of-state approach in incremental creep computation. It treats the material as a non-linear viscoelastic substance in which the current strain state can be made to depend on the loading history, that is

$$\epsilon(t) = F[\sigma(\tau)], \text{ where } \sigma(\tau) \text{ is the loading history.}$$

In terms of functional approximation,

$$\begin{aligned} \epsilon(t) = & \int_{-\infty}^t J_1(t-\tau_1) \frac{d\sigma(\tau_1)}{d\tau_1} d\tau_1 + \int_{-\infty}^t \int_{-\infty}^t J_2(t-\tau_1; t-\tau_2) \frac{d\sigma(\tau_1)}{d\tau_1} \frac{d\sigma(\tau_2)}{d\tau_2} d\tau_1 d\tau_2 \\ & + \dots \end{aligned}$$

$J_1, J_2, \dots$ are the creep kernel functions.

The above equation can be further approximated by the following non-linear superposition equation:

$$\epsilon(t) = \int_{-\infty}^t \frac{\partial C(\sigma, t-t')}{\partial \sigma(t')} \frac{d\sigma(t')}{dt'} dt'$$

where $C(\sigma, t)$ is the usual single-step creep formula; with new notation, it appears as

$$\epsilon(t) = \int_{-\infty}^t J(\sigma, t-t') \frac{d\sigma(t')}{dt'} dt'$$

where $J(\sigma, t)$ is defined as creep compliance at stress level σ . The physical time t finally is replaced by the equivalent time $\xi(t)$

$$\epsilon(t) = \int_{-\infty}^t J[\xi(t) - \xi(t')] \frac{d\sigma(t')}{dt'} dt'$$

Routine MEMORY uses a single step creep formula to compute the creep compliance. The stress and temperature variations within the increment are assumed to be linear, the primary and secondary creep components in the creep formula are computed accordingly. The numerical integration over time increment is performed by Simpson method over six points.

The creep compliance J defined above can be expressed in the following form in terms of the physical time t

$$J(\sigma, T, t) = \frac{\epsilon_c}{\sigma} A \left[1 - \exp(-R(\sigma, T)t) \right] + Bt,$$

where A and B are defined as $\epsilon_t(\sigma, T)/\sigma$ and $\dot{\epsilon}_m(\sigma, T)/\sigma$ respectively and are computed by routine SHIFT.

Input arguments are:

DT	time increment
RO	coefficient which describes the exponential decay behavior of the primary creep, based on the stress and temperature level at the beginning of the time step.

Output arguments are:

GE (I)	the creep compliance, its dimension being inverse to that of a tangential modulus.
AR (17,2)	Shift factor
AR (18,2)	

(13) Routine STRAIN (AR, LODCYC, EX, EY, EN, EXMATD)

The fundamental type element is the basic triangular element with three nodal points.

The figure above shows the typical triangular element under consideration with its nodes i, j, k ordered in a counterclockwise manner. Each node in this two dimensional element has two components. The displacements within an element are uniquely defined by these six displacement components which defines the displacements at nodes i, j, k.

$$\left\{ \delta \right\}^e = \begin{Bmatrix} \delta_i \\ \delta_j \\ \delta_k \end{Bmatrix} = \begin{Bmatrix} u_i \\ v_i \\ u_j \\ v_j \\ u_k \\ v_k \end{Bmatrix}$$

The displacements within such an element are represented by two linear polynomials.

$$u = \alpha_1 + \alpha_2 x + \alpha_3 y$$

$$v = \alpha_4 + \alpha_5 x + \alpha_6 y$$

The six constants α can be expressed in terms of the position coordinates and displacements at the nodes i, j, k. The displacement, within the element becomes

$$u = \frac{1}{2\Delta} \left\{ (a_i + b_i x + c_i y) u_i + (a_j + b_j x + c_j y) u_j + (a_k + b_k x + c_k y) u_k \right\}$$

$$v = \frac{1}{2\Delta} \left\{ (a_i + b_i x + c_i y) v_i + (a_j + b_j x + c_j y) v_j + (a_k + b_k x + c_k y) v_k \right\}$$

in which

$$a_i = x_j y_k - x_k y_j$$

$$b_i = y_j - y_k$$

$$c_i = x_k - x_j$$

with the other coefficients obtained by cyclic permutation of subscripts in the order i, j, k and where

$$2\Delta = \det \begin{vmatrix} 1 & x_i & y_i \\ 1 & x_j & y_j \\ 1 & x_k & y_k \end{vmatrix} = 2 \times \text{area of the element } i, j, k.$$

Consider two adjacent triangular T_m and T_{m+1} with nodes as shown below:

There are two sets of polynomials describing the displacements within T_m and T_{m+1} . These two sets of polynomials have common values at j and k, namely the displacements at those points. Thus the difference between these polynomials on the edge C_m joining T_m and T_{m+1} is a linear polynomial in the arc lengths that vanishes at the end points j and k. Hence, it is identically zero on C_m . Physically speaking, the choosing of a linear displacement function for a three node triangular element indicates that after the structure deformed under loading there is no gap or overlap between elements. The straight line joining the nodes

remains straight.

The displacements within an element can then be expressed in terms of nodal displacement in matrix form

$$\begin{Bmatrix} u \\ v \end{Bmatrix} = [N] \{\delta\} = [N'_1 \quad N'_j \quad N'_k] \{\delta\}^e,$$

where $\{\delta\}^e$ is the displacement vector at nodal points within the element, and

$$N'_i = (a_i + b_i x + c_i y) / 2\Delta.$$

In linear elasticity the expression for the strain vector is as follows

$$\{\epsilon\} = \begin{Bmatrix} \epsilon_x \\ \epsilon_z \\ \epsilon_y \\ \epsilon_{xy} \end{Bmatrix}.$$

Under plane strain or plane stress assumption, ϵ_z and its associated stress σ_z do not contribute to internal work and are set to zero, that is

$$\{\epsilon\} = \begin{bmatrix} \frac{\partial N'_1}{\partial x} & 0 & \frac{\partial N'_j}{\partial x} & 0 & \frac{\partial N'_k}{\partial x} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{\partial N'_1}{\partial y} & 0 & \frac{\partial N'_j}{\partial y} & 0 & \frac{\partial N'_k}{\partial y} \\ \frac{\partial N'_1}{\partial y} & \frac{\partial N'_1}{\partial x} & \frac{\partial N'_j}{\partial y} & \frac{\partial N'_j}{\partial x} & \frac{\partial N'_k}{\partial y} & \frac{\partial N'_k}{\partial x} \end{bmatrix} \begin{bmatrix} u_i \\ v_i \\ u_j \\ v_j \\ u_k \\ v_k \end{bmatrix}$$

or

$$\{\epsilon\} = \begin{bmatrix} b_i & 0 & b_j & 0 & b_k & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & c_i & 0 & c_j & 0 & c_k \\ c_i & b_i & c_j & b_j & c_k & b_k \end{bmatrix} \begin{Bmatrix} u_i \\ v_i \\ u_j \\ v_j \\ u_k \\ v_k \end{Bmatrix} = [B] \{\delta\}$$

The $[B]$ matrix is implied rather than explicitly formulated in STRAIN.

Under axisymmetrical assumption, the internal work performed by circumferential strain ϵ_θ and its associated stress σ_θ are generally non-zero, the strain vector takes the following form:

$$\{\epsilon\} = \begin{Bmatrix} \epsilon_r \\ \epsilon_\theta \\ \epsilon_z \\ \gamma_{rz} \end{Bmatrix} = \begin{Bmatrix} \frac{\partial u}{\partial r} \\ \frac{u}{r} \\ \frac{\partial v}{\partial z} \\ \frac{\partial u}{\partial z} + \frac{\partial v}{\partial r} \end{Bmatrix}$$

In terms of displacement functions we have

$$\{\epsilon\} = [B] \{\delta\}^e = [B_i \quad B_j \quad B_k] \{\delta\}^e$$

in which

$$[B_i] = \begin{bmatrix} b_i & 0 \\ \frac{a_i}{r} + b_i + \frac{c_i z}{r} & 0 \\ 0 & c_i \\ c_i & b_i \end{bmatrix}$$

Unlike the plane stress and plane strain cases, the $[B]$ matrix or the strains are no longer constant within an element. The variation is due to ϵ_θ term. In routine STRAIN, the implied $[B]$ matrix of the element is approximated by its value evaluated at centroidal point, that is r and z are replaced by $\bar{r}$ and $\bar{z}$,

$$\bar{r} = (r_i + r_j + r_k)/3$$

$$\bar{z} = (z_i + z_j + z_k)/3$$

with this approximation, the strains become constant within the element.

The nodal coordinate information is transmitted to routine STRAIN through common block BCOM, and the $[B]$ matrix for plane stress, plane strain and the axisymmetric case is implied by pre-multiply $[XE]$ to $[FE]$.

Routine STRAIN formulates the incremental stress-strain relation. The derivation of general form of the incremental stress-strain relation is based upon three basic assumptions:

(a) In the plastic range, a material can be considered as incompressible, that is,

$$\epsilon_{kk}^c = 0$$

$$\epsilon_{kk}^p = 0$$

where the repeated index implies summation.

(b) Yield can occur only if the stresses satisfy a given yield function, and plastic increments in relation to the yield surface obey certain constitutive equations. Von Mises yield condition states that initial yield occurs if

$$f = \frac{1}{2} s_{ij} s_{ij} - \kappa^2 = 0$$

and incremental plastic flow relates to the yield surface in the following manner

$$\dot{\epsilon}_{ij}^p = \lambda \frac{\partial f}{\partial \sigma_{ij}},$$

where the deviatoric stress S_{ij} is given by

$$S_{ij} = \sigma_{ij} - \frac{1}{3} \delta_{ij} \sigma_{kk}$$

λ is a scalar function, and κ is a hardening parameter that may depend on temperature.

(c) To take the Bauschinger effect into account, the kinematic hardening rule is assumed, and the deviatoric stress S_{ij} stated above is then replaced by S'_{ij}

$$S'_{ij} = (\sigma_{ij} - \alpha_{ij}) - \frac{1}{3} (\sigma_{kk} - \alpha_{kk}) \delta_{ij}$$

where α_{ij} are the stress coordinates of the origin of the translating loading surface.

Based on the above assumption, the incremental stress-strain relation becomes

$$d\sigma_{ij} = 2\mu (d\epsilon_{ij} + \frac{\nu}{1-2\nu} \delta_{ij} d\epsilon_{kk} - \eta \frac{S'_{ij} S'_{mn}}{R} d\epsilon_{mn}) \\ - 2\eta \frac{S'_{ij} \kappa}{R} \frac{\partial \kappa}{\partial T} dT$$

where μ is shear modulus

$$R = 2\kappa^2 (1 + \frac{E'}{2\mu}), \text{ with } E' \text{ the hardening modulus,}$$

and where values of η are set as follows:

$$\eta = 0 \text{ when } f < 0 \quad (\text{i.e., yield does not occur}),$$

$$\eta = 1 \text{ when } f = 0 \text{ and } \frac{\partial f}{\partial \sigma_{ij}} d\sigma_{ij} + \frac{\partial f}{\partial T} dT < 0$$

(i.e., unloading takes place),

$$\text{and, } \eta = 1 \text{ when } f = 0 \text{ and } \frac{\partial f}{\partial \sigma_{ij}} d\sigma_{ij} + \frac{\partial f}{\partial T} dT > 0$$

(i.e., loading takes place).

The translating of loading surface is given by

$$d\alpha_{ij} = (\sigma_{ij} - \alpha_{ij}) \frac{\partial f}{\partial \sigma_{ij}} d\sigma_{ij} / [(\sigma_{kl} - \alpha_{kl}) \frac{\partial f}{\partial \sigma_{kl}}] .$$

Incremental thermal strain and creep strain are treated as initial strain. The incremental stress-strain relation can be written in matrix form as follows

$$d\{\sigma\} = [D^*] d\{\epsilon + \epsilon_0\} + d\{\sigma_0\}$$

where $[D^*]$ is the elasto-plastic matrix, it will degenerate to elastic matrix if $\eta = 0$.

$d\{\epsilon_0\}$ is the incremental thermal and creep strain.

$d\{\sigma_0\}$ is $\eta \frac{2S'_{ij} \kappa}{R} - \frac{\partial \kappa}{\partial T} dT$, stress component resulting from non-isothermal kinetic hardening assumption and vanishes if η is zero.

The $[D^*]$ matrix is modified once each iteration step. Modification is achieved by pre-multiplying $[D^*]$ with $[I + JD^* H]^{-1}$ where

I is unit matrix 4 by 4 in size,

J is $\frac{d\epsilon^c_e}{\sigma}$ if equation of state is used, or is creep compliance if memory theory is used,

and H is a 4 by 4 matrix which relates the deviatoric stress S_{ij} to the coordinate stress σ_{ij} .

The stress-strain computation and iteration process follows the procedures outlined below:

(a) It is suggested that for the first time step (which has a duration of zero), a load increment be selected such that the most severely stressed element of the structure has a state of stress lying inside of the yield surface. The corresponding elastic strain and stress vectors are computed and will be used as initial values of next time increment. With the computed stress and strain vectors and the length of next time increment, routine STATE or MEMORY predicts one incremental creep strain vector.

(b) At the beginning of the new time increment strain increment due to displacement is calculated;

$$d\{\epsilon\} = [B] d\{\delta\}$$

The state of stress is examined; if $f < 0$, the state of stress lies within the yield surface. Incremental creep strain obtained from step (a) and incremental thermal strain are treated as initial strain; knowing the creep strain or the creep compliance, $[D]$ matrix is modified immediately and incremental stress computed.

$$d\{\sigma\} = [D] [d\{\epsilon\} + d\{\epsilon_0\}]$$

(c) The stiffness matrix $[K]$ defined as

$$[K] = \iint [B]^T [D] [B] dA$$

is assembled, the nodal force $d\{F_0\}$ due to incremental initial strain $d\{\epsilon_0\}$,

$$d\{F_0\} = - \iint [B]^T [D] d\{\epsilon_0\} dA$$

is computed in routine STCREP.

(d) System of equilibrium equations

$$[K]d\{\delta\} = d\{F + F_0\}$$

is solved by Gaussian elimination in Routine SOLVE.

(e) With the incremental displacement vector $d\{\delta\}$ computed from step (d) incremental strain vector $d\{\epsilon\}$

$$d\{\epsilon\} = [B]d\{\delta\}$$

is updated and step (b) is repeated. At the end of this iteration step, the state of stress is examined again. If $f > 0$ and $\frac{\partial f}{\partial \sigma_{ij}} d\sigma_{ij} + \frac{\partial f}{\partial T} dT > 0$, it is an

indication that the incremental stress has caused yield to occur and plastic flow to take place. The proportion of elastic stress and strain increment which has taken place in the range under the yield point is determined by linear interpolation. The incremental translation of stress origin of yield surface is also calculated.

The elastic matrix $[D]$ mentioned in step (b) will then be replaced by the elasto-plastic matrix $[D^*]$ if further iteration or time increment proceeds.

The incremental stress-strain relation becomes

$$d\{\sigma\} = [D^*][d\{\epsilon\} + d\{\epsilon_0\}] + d\{\sigma_0\}$$

when step (d) is encountered again during subsequent computation process, the nodal force due to $d\{\sigma_0\}$ should be added to the system of equations. In each sequence of iteration $d\{\epsilon_0\}$ and $[D^*]$ are adjusted and modified. Each iteration consists of one cycle of the link sequence of STIFF-SOLVE-CREEP.

Most of the input and output arguments of routine STRAIN are transmitted through COMMON block BCOM.

U (I), I=1,6	Incremental displacement vector at nodal point.
TF (I), I=1,4	Incremental stress vector due to plastic flow under non-isothermal kinematic hardening assumption, also generalized to include the incremental stress due to incremental creep strain.
SG (I), I = 1,4	Stress vector calculated from the incremental stress-strain relation. Also used to store principal stress vector later.
CREEP	Estimated incremental creep strain calculated from creep law with the state of stress and temperature level exist at the beginning of the time step.
SIGMA	Effective stress based upon updated stress origin of yield surface if plastic flow has taken place.
STR (I), I =1,4	Creep strain vector.

EP (I) I = 1,4	incremental strain vector due to displacement increment $d \{ \epsilon \} = [B] d \{ \delta \}$.
BF (I), I = 1,4	incremental creep strain vector.
GE (I), I = 1,4	creep compliance, computed by routine MEMORY.
TAU (I), I = 1,4	total accumulated stress vector.
SIJ (I), I = 1,4	deviatoric stress vector, based on updated stress coordinates of the origin of the translating yield surface.
ITJ (I), I = 1,4	deviatoric stress vector, based on the stress coordinate of the origin of the initial yield surface.
H (I,J), I = 1,4 J = 1,4	$\frac{2 \mu}{2K^2(1 + \frac{E'}{3\mu})} S'_{ij} S'_{ij},$ where $K = \sigma_y / \sqrt{3}$ σ_y = uniaxial yield stress μ = shear modulus E' = uniaxial hardening modulus.
XE (I,J), FE(K,L) I = 1,4 J = 1,6 K = 1,6 L = 1,6	a multiplication of [XE] by [FE] gives the [B] matrix.
THERM	temperature in the element.
PH (I,J) I = 1,4 J = 1,4	elastic matrix [D], or elasto-plastic Matrix [D*] if plastic flow takes place.
RI,ZI,RJ,ZJ,RF,ZK	$X_1, Y_1, X_j, Y_j, X_k, Y_k$ coordinates of the nodes of the triangular element.
AK, BJ	$(X_k - X_1), (Y_j - Y_1)$ respectively.
D	$(X_j - X_1)^2 + (Y_j - Y_1)^2$.
AJ2	$(X_j - X_1)^2$.
BJ2	$(Y_j - Y_1)^2$.

AB

2 x area of element.

(14) Routine STCREP

In this routine, sub-matrices of $[K]$ are computed. The nodal force due to initial stress resulting from the plastic flow under non-isothermal kinematic hardening assumption and initial strain resulting from thermal and creep strain are also calculated in this routine.

$[B]$ has never been explicitly coded throughout this routine, but is implied by the result of multiplication of $[XE]$ to $[FE]$, that is

$$[B] = [XE] \times [FE] / 2\Delta$$

the transpose of matrix $[B]$ then becomes

$$[B]^T = ([XE] \times [FE])^T / 2\Delta = [FE]^T [XE]^T / 2\Delta.$$

for constant strain element, the stiffness matrix defined as

$$[K] = [B]^T [D] [B] \Delta$$

can be written as

$$[K] = [FE]^T [XE]^T [D] [XE] [FE] / 4\Delta.$$

Nodal forces due to initial stress and initial strain are

$$d\{F\}_{\epsilon_0} = -\frac{1}{2} [FE]^T [XE]^T [D] d\{\epsilon_0\}$$

$$d\{F\}_{\sigma_0} = \frac{1}{2} [FE]^T [XE]^T d\{\sigma_0\}$$

$[D]$ will be replaced by $[D^*]$ if plastic flow occurs.

THERM

$\alpha \Delta T$, incremental initial strain due to thermal expansion.

α thermal expansion coefficient

ΔT temperature difference between the consecutive loading increment.

TF (I), I = 1,4

stress increment due to plastic flow under non-isothermal kinematic hardening assumption, transmitted from STRAIN through COMMON block BCOM.

H (I,J), I = 1,4
J = 1,4

$[D]$ matrix, replaced by $[D^*]$ if plastic flow occurs. Transmitted from STRAIN through

COMMON block BCOM.

XKBAR (I,J)

results of $[XE]^T D [XE] \times \Delta$.

I = 1,6

J = 1,6

FINV (I,J)

$[FE]$ matrix, transmitted from STRAIN

I = 1,6

through COMMON block BCOM.

J = 1,6

ARR (I), I = 1,6

results of $\{- [XE][D] (THERM) + [XE]^T [TF] \} \Delta$.

P (I) I = 1,6

nodal forces due to initial strain and stress.

S (I,J) I = 1,6

$[FE]^T [XE]^T [D] [XE] [FE] / 4\Delta$,

J = 1,6

submatrix of $[K]$.

(15) Routine CALC (Y, X, LOW, A, UP, TEMP, DIAG, KP1)

CALC is a routine which solves a system of equations, such as

$$[K] \{\delta\} = \{F\}$$

where $[K]$ is an N by N symmetrical banded matrix with half bandwidth M.

Gaussian elimination is the solution method programmed in CALC. The solution procedure can be illustrated as follows:

The first equation is solved for δ_1

$$\delta_1 = K_{11}^{-1} (F_1 - K_{12} \delta_2 - K_{13} \delta_3 - K_{14} \delta_4 \dots K_{1M} \delta_M).$$

After substituting into equation 2 to M of the system, the coefficient in load vector becomes

$$\bar{F}_2 = F_2 - K_{12}^T K_{11}^{-1} F_1$$

.....

$$\bar{F}_M = F_M - K_{1M}^T K_{11}^{-1} F_1,$$

The element of $[K]$ matrix becomes

$$\bar{K}_{ij} = K_{ij} - K_{1i}^T K_{11}^{-1} K_{1j}, \quad 2 \leq i \leq M \\ 2 \leq j \leq M$$

This procedure reduces the $[K]$ matrix to an $N-1$ matrix of the form

$$\{\bar{K}\} \{\delta\} = \{\bar{F}\}.$$

Only one block of coefficient of $[K]$ matrix is operated upon during above procedure, the block has the size of half bandwidth. The procedure can be repeated until finally the system is reduced to a one by one matrix

$$\bar{K}_{NN} \delta_N = \bar{F}_N.$$

Back substitution in reverse order may now be applied to solve for remaining

δ .

Y	incremental force or load vector.
X	incremental displacement vector.
DIAG	diagonal term of the stiffness matrix.
TEMP	array for transpose of the coefficients of $[K]$ matrix.
LOW	TEMP/DIAG
A	array for the coefficient of $[K]$ matrix
UP	array for the coefficient of $[\bar{K}]$ matrix.

(16) Routine SOLVE (F, BUFF, AUP, RLOAD, ZLOAD, DSX, DSY)

SOLVE is the driver routine for solving the system of equations. It formulates the load vector from the loading conditions at each node, and also feeds the stiffness matrix into CALC and obtains the resulting incremental displacement vector from CALC.

F	incremental force or load vector
BUFF	incremental displacement vector
AUP	array for the coefficient of stiffness matrix
RLOAD	incremental radial load vector at nodal point
ZLOAD	incremental axial load vector at nodal point
DSX	total radial displacement vector
DSY	total axial displacement vector

(17) Routine CREEP (LODCYC, ...)

The function of CREEP is to perform the second half of the iteration process. The new updated displacement information is obtained by CREEP through SOLVE and the stress, strain and creep information transmitted from STIFF through the variable array BR. Then CREEP calls routine STRAIN and carries out the iteration step (e). A link sequence of STIFF-SOLVE-CREEP completes one cycle of iteration. All the variables in CREEP have been previously identified.

IV. EXAMPLE PROBLEM

The example problem is a long thick-wall cylinder of axisymmetric geometry subject to internal pressure of 3,650 psi. The base temperature is set at 1200°F. Plane strain condition is the appropriate assumption for the stress computation. The finite element mesh for the problem is shown in Fig. 1.

The material is assumed to follow the built-in creep law and the built-in nonlinear stress strain curve for the average properties of 304 stainless steel [4].

Fig. 1 Finite Element Mesh for Example Problem of Cylinder Under Internal Pressure.

INPUT OF THE EXAMPLE PROBLEM

CARD (1) TITLE CARD FORMAT (ALPHA NUMERIC)

CREEP-PLAST CYLINDER UNDER INTERNAL PRESSURE NEW VERSION

CARD (2) OPTION CARD FORMAT (12I6, 2I4)

24	26	26	2	1	0	1	6	0	1	0	0	0	0
2	0	1	0	0	0	0	1	0	0	0	0	2	0

CARD (3) MATERIAL PROPERTIES CARD FORMAT (6E12.6, E8)

0.0	0.0	0.0	0.0	0.3	1.0	1200.0

CARD (4) REDEFINITION FLAGS AND TIME INCREMENT CARD FORMAT [5 (13, F13.5)]

0	0.0	0	3.00	0	10.00	0	50.00	0	100.00
0	600.00								

CARD (5) UNUSED

CARD (6) PRESSURE LOADING HISTORY CARD FORMAT (6F12.3)

1.00	1.00	1.00	1.00	1.00	1.00	1.00

CARD (7) TEMPERATURE HISTORY CARD FORMAT (6F12.3)

1.00	1.00	1.00	1.00	1.00	1.00	1.00

CARD (8) NOT USED IN THE PRESENT EXAMPLE PROBLEM, SINCE N6 IS SET TO ZERO.

CARD (9) FORMAT (3I6)

1	0	0

CARD (10) FORMAT (3I6)

1	12	24

CARD (10A) FORMAT (12I6)

1	2	1	2	1	2	1	2	1	2	1	2
1	2	1	2	1	2	1	2	1	2	1	2

CARD (11) FORMAT (12I6)

1	14	1

CARD (12)

FORMAT (3E12.4)

0.16

0.25

CARD (13)

FORMAT (16E12.4)

1.00

CARD (14) NOT USED

FORMAT (5I6, 2E12.4)

CARD (15) NOT USED

FORMAT (I6, 6X, 4F12.2)

CARD (15A) NOT USED

FORMAT (I8)

CARD (15B) NOT USED

FORMAT (I6, 30X, 2F12.2)

CARD (15C) NOT USED

FORMAT (2I6)

CARD (16) BOUNDARY CONDITION CARD

FORMAT (2I6, F12.6, 2E12.4)

1	2
2	2
3	2
4	2
5	2
6	2
7	2
8	2
9	2
10	2
11	2
12	2
13	2
14	2
15	2
16	2
17	2
18	2
19	2
20	2
21	2
22	2
23	2
24	2
25	2
26	2

CARD (16A) NOT USED

FORMAT (I6)

CARD (17) NOT USED

CARD (18) NOT USED

CARD (19)

FORMAT (I6, 6X, 5F12.3)

2	-3650.00	0.00	0.00

CARD (20)

FORMAT (12I6)

1 14

OUTPUT OF THE EXAMPLE PROBLEM

CREEP - PLAST CYLINDER UNDER INTERNAL PRESSURE NEW VERSION

EPST1 0.0 ESTEEL 0.0 ALFAS 0.0 EPST2 0.0 XVC 3.000000-01 YRATIO 1.000000 00 DELT 1.200000 03

MAT MULTIPLIERS
1 1.000000 00 1.000000 00 1.000000 00 1.000000 00 1.000000 00 1.000000 00
2 1.000000 00 1.000000 00 1.000000 00 1.000000 00 1.000000 00 1.000000 00

ILBC(IJ,DT(H(I)))=
0 0.0 0 3.000000 0 10.000000 0 50.000000 0 100.000000
0 600.600000

PCVC(I,J)=
1.000 1.000 1.000 1.000 1.000 1.000

OPTIONS (N1-N17): N1 N2 N3 N4 N5 N6 N7 N8 N9 N10 N11 N12 N13 N14 N15 N16 N17
2 1 0 1 6 0 1 0 0 2 0 1 0 0 0 0 1

INPUT TAPE GENERATED IN PREVIOUS RUN 14

OUTPUT TAPE TO BE GENERATED IN THE PRESENT RUN 14

TEMPERATURE HISTORY TAPE 0

NUMBER OF ELEMENTS = 24

NUMBER OF NCCAL POINTS = 26

NUMBER OF BOUNDARY POINTS = 26

MEM ALL OPTS MM6,MM9,MM100 = 4 4 2

1 0 0

***** BLOCK 1 MESH GENERATION DATA *****

1 12 24
1 14 1
0.1600 0.2500 0.0
1.0000

INPUT MTOT= 10000 MTOT USED= 4317

MAX2 MTOT= 4317 REGION= 137

MAX1 MTOT= 4317 REGION= 137

MIN MTOT= 2917 REGION= 179

MAXIM= 13 MAXIN= 52

BOUNDARY CONCITIONS

NOCE CCNSTRANT SLOPE OSK OSY

PRINTED IN U.S.A.

1	2	0.0	0.0	0.0
2	2	0.0	0.0	0.0
3	2	0.0	0.0	0.0
4	2	0.0	0.0	0.0
5	2	0.0	0.0	0.0
6	2	0.0	0.0	0.0
7	2	0.0	0.0	0.0
8	2	0.0	0.0	0.0
9	2	0.0	0.0	0.0
10	2	0.0	0.0	0.0
11	2	0.0	0.0	0.0
12	2	0.0	0.0	0.0
13	2	0.0	0.0	0.0
14	2	0.0	0.0	0.0
15	2	0.0	0.0	0.0
16	2	0.0	0.0	0.0
17	2	0.0	0.0	0.0
18	2	0.0	0.0	0.0
19	2	0.0	0.0	0.0
20	2	0.0	0.0	0.0
21	2	0.0	0.0	0.0
22	2	0.0	0.0	0.0
23	2	0.0	0.0	0.0
24	2	0.0	0.0	0.0
25	2	0.0	0.0	0.0
26	2	0.0	0.0	0.0

EFFECTIVE BANDWIDTH IS 55

MATERIAL PROPERTIES

ELASTIC MODULUS, INITIAL YIELD STRESS AND TEN-CYCLE YIELD STRESS AT BASE TEMPERATURE 1000.0 ARE

1	2.300859D 07	1.006000D 04	1.006000D 04
2	2.300859D 07	1.006000D 04	1.006000D 04

EXPLANATION OF STRESS OUTPUT LIST

ELEMENT STRAINS - MICRO INCHES PER INCH

EPS-R	RR OR XX STRAIN
EPS-T	THETA STRAIN
EPS-Z	ZZ OR YY STRAIN
EPSRZ	RZ OR XY STRAIN
EPS-1	MAX. PRINCIPAL STRAIN
EPS-2	MIN. PRINCIPAL STRAIN
ANGL	MAX. PRINCIPAL DIRECTION - POSITIVE CLOCKWISE

ELEMENT STRESSES - PSI

SIG-R	RR OR XX STRESS
SIG-T	THETA STRESS
SIG-Z	ZZ OR YY STRESS
SIGRZ	RZ OR XY STRESS
SIG-1	MAX. PRINCIPAL STRESS
SIG-2	MIN. PRINCIPAL STRESS

STRESS COORDINATES OF THE CENTER OF THE YIELD SURFACE ALFA THE EFFECTIVE STRESS COORDINATE

EFFECTIVE STRESS AND STRAIN

SICEFF	EFFECTIVE STRESS - PSI
ELAEN	ELASTIC STRAIN ENERGY
EPSEFF	EFFECTIVE INELASTIC STRAIN - MICRO INCHES
ENERG	INT.(ELAEN + INT.(SICEFF*EPSEFF))*ELEMNT VOLUME)

YIELD STATUS

ERR	PERCENT DEVIATION FROM THE YIELD SURFACE
PLA	PLA=0 ELEMENT IS ELASTIC PLA=1 ELEMENT IS PLASTIC

PRINTED IN U.S.A.									
EL	J	K	MAT	COFF TH EXP	TEMP	1	2	3	4
1	1	2	1	1	1.200000	0.0	0.0	0.0	0.0
2	2	15	2	2	1.200000	0.0	0.0	0.0	0.0
3	3	16	3	1	1.200000	0.0	0.0	0.0	0.0
4	3	16	3	2	1.200000	0.0	0.0	0.0	0.0
5	3	16	3	1	1.200000	0.0	0.0	0.0	0.0
6	4	4	1	2	1.200000	0.0	0.0	0.0	0.0
7	4	4	1	1	1.200000	0.0	0.0	0.0	0.0
8	5	5	2	2	1.200000	0.0	0.0	0.0	0.0
9	5	5	1	1	1.200000	0.0	0.0	0.0	0.0
10	6	6	2	2	1.200000	0.0	0.0	0.0	0.0
11	6	6	1	1	1.200000	0.0	0.0	0.0	0.0
12	7	7	2	2	1.200000	0.0	0.0	0.0	0.0
13	7	7	1	1	1.200000	0.0	0.0	0.0	0.0
14	8	8	2	2	1.200000	0.0	0.0	0.0	0.0
15	8	8	1	1	1.200000	0.0	0.0	0.0	0.0
16	9	9	2	2	1.200000	0.0	0.0	0.0	0.0
17	9	9	1	1	1.200000	0.0	0.0	0.0	0.0
18	10	10	2	2	1.200000	0.0	0.0	0.0	0.0
19	10	10	1	1	1.200000	0.0	0.0	0.0	0.0
20	11	11	2	2	1.200000	0.0	0.0	0.0	0.0
21	11	11	1	1	1.200000	0.0	0.0	0.0	0.0
22	12	12	2	2	1.200000	0.0	0.0	0.0	0.0
23	12	12	1	1	1.200000	0.0	0.0	0.0	0.0
24	13	13	2	2	1.200000	0.0	0.0	0.0	0.0
25	13	13	1	1	1.200000	0.0	0.0	0.0	0.0
26	13	13	2	2	1.200000	0.0	0.0	0.0	0.0
FORM 411 B									
NP	R-ORD	Z-ORD	R-LOAD	Z-LOAD					
1	0.160000	0.0	0.0	0.0					
2	0.167500	0.0	0.0	0.0					
3	0.175000	0.0	0.0	0.0					
4	0.182500	0.0	0.0	0.0					
5	0.190000	0.0	0.0	0.0					
6	0.197500	0.0	0.0	0.0					
7	0.205000	0.0	0.0	0.0					
8	0.212500	0.0	0.0	0.0					
9	0.220000	0.0	0.0	0.0					
10	0.227500	0.0	0.0	0.0					
11	0.235000	0.0	0.0	0.0					
12	0.242500	0.0	0.0	0.0					
13	0.250000	0.0	0.0	0.0					
14	0.160000	1.000000	0.0	0.0					
15	0.167500	1.000000	0.0	0.0					
16	0.175000	1.000000	0.0	0.0					
17	0.182500	1.000000	0.0	0.0					
18	0.190000	1.000000	0.0	0.0					
19	0.197500	1.000000	0.0	0.0					
20	0.205000	1.000000	0.0	0.0					
21	0.212500	1.000000	0.0	0.0					
22	0.220000	1.000000	0.0	0.0					
23	0.227500	1.000000	0.0	0.0					
24	0.235000	1.000000	0.0	0.0					
25	0.242500	1.000000	0.0	0.0					
26	0.250000	1.000000	0.0	0.0					
THERE ARE 2 NODES. PRESSURE FORMULA CONSTANTS ARE									
1	14								
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NP	R-ORD	Z-ORD	R-LOAD	Z-LOAD
1	0.1600000	0.0	292.0000000	0.0
14	0.1600000	1.0000000	292.0000000	0.0

TOTAL AREA = 9.0000000-02

ANE,ANS= 4 4

PRINTED IN U.S.A.

FORM 1017

TIME 1 = 0.0 HOURS AT PRESSURE = 1.0000 0.0 AND AT TEMPERATURE = 1.0000

NODAL POINT R-DISPLACEMENT Z-DISPLACEMENT

1	6.54160-05	0.0	2	6.33030-05	0.0	3	6.14100-05	0.0	4	5.97080-05	0.0
5	5.81770-05	0.0	6	5.67950-05	0.0	7	5.55460-05	0.0	8	5.44170-05	0.0
9	5.33950-05	0.0	10	5.24690-05	0.0	11	5.16290-05	0.0	12	5.08690-05	0.0
13	5.01810-05	0.0	14	6.46410-05	0.0	15	6.26090-05	0.0	16	6.07870-05	0.0
17	5.91480-05	0.0	18	5.76710-05	0.0	19	5.63380-05	0.0	20	5.51330-05	0.0
21	5.46420-05	0.0	22	5.30550-05	0.0	23	5.21600-05	0.0	24	5.13500-05	0.0
25	5.06150-05	0.0	26	4.99500-05	0.0						

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FORM 14112

TIME	0.0 HOURS AT PRESSURE = 1.0000 0.0										0.0 AND AT TEMPERATURE = 1.0000									
ELEM/	EPS-R/	EPS-T/	EPS-Z/	EPSKZ/	EPS-1/	EPS-2/	ANGL*	SIG-R/	SIG-T/	SIG-Z/	SIGRZ/	SIG-1/	SIG-2/	* ALFA/	SIGFFF/	ELAEN/	EPSEFF/	ENERG/	ERR/	PLA
1	-281	396	0	0	0	-281	89 *	-3460	8545	1525	-6	1525	-3460 *	0	10447	2	0	2	0	0
2	-270	384	0	0	0	-270	89 *	-3280	8327	1513	-6	1513	-3280 *	0	10103	2	0	2	0	0
3	-252	367	0	0	0	-252	89 *	-2943	8025	1524	-6	1524	-2943 *	0	9553	1	0	1	0	0
4	-243	357	0	0	0	-243	89 *	-2786	7835	1514	-5	1514	-2786 *	0	9253	1	0	1	0	0
5	-226	341	0	0	0	-226	89 *	-2490	7569	1523	-5	1523	-2490 *	0	8771	1	0	1	0	0
6	-218	332	0	0	0	-218	89 *	-2352	7403	1515	-4	1515	-2352 *	0	8508	1	0	1	0	0
7	-204	318	0	0	0	-204	89 *	-2091	7168	1523	-4	1523	-2091 *	0	8083	1	0	1	0	0
8	-196	311	0	0	0	-196	89 *	-1969	7021	1515	-4	1515	-1969 *	0	7852	1	0	1	0	0
9	-184	298	0	0	0	-184	89 *	-1738	6813	1522	-4	1522	-1738 *	0	7475	1	0	1	0	0
10	-177	291	0	0	0	-177	89 *	-1629	6683	1516	-4	1516	-1629 *	0	7270	1	0	1	0	0
11	-166	281	0	0	0	-166	89 *	-1424	6497	1522	-4	1522	-1424 *	0	6935	1	0	1	0	0
12	-160	274	0	0	0	-160	89 *	-1327	6382	1516	-3	1516	-1327 *	0	6752	0	0	0	0	0
13	-150	265	0	0	0	-150	89 *	-1143	6215	1521	-3	1521	-1143 *	0	6453	0	0	0	0	0
14	-145	259	0	0	0	-145	89 *	-1056	6112	1516	-3	1516	-1056 *	0	6290	0	0	0	0	0
15	-136	250	0	0	0	-136	89 *	-891	5962	1521	-3	1521	-891 *	0	6021	0	0	0	0	0
16	-131	245	0	0	0	-131	89 *	-813	5870	1517	-3	1517	-813 *	0	5875	0	0	0	0	0
17	-123	238	0	0	0	-123	89 *	-664	5734	1521	-3	1521	-664 *	0	5633	0	0	0	0	0
18	-119	233	0	0	0	-119	89 *	-593	5651	1517	-2	1517	-593 *	0	5502	0	0	0	0	0
19	-111	226	0	0	0	-111	89 *	-459	5529	1520	-2	1520	-459 *	0	5284	0	0	0	0	0
20	-108	222	0	0	0	-108	89 *	-395	5454	1517	-2	1517	-395 *	0	5166	0	0	0	0	0
21	-101	215	0	0	0	-101	89 *	-273	5342	1520	-2	1520	-273 *	0	4967	0	0	0	0	0
22	-97	212	0	0	0	-97	89 *	-215	5274	1517	-2	1517	-215 *	0	4861	0	0	0	0	0
23	-91	206	0	0	0	-91	89 *	-104	5172	1520	-2	1520	-104 *	0	4661	0	0	0	0	0
24	-88	203	0	0	0	-88	89 *	-51	5111	1517	-2	1517	-51 *	0	4584	0	0	0	0	0

WORK C NE (ASSUME CONSTANT LOAD) (IN. LB.)= 2.38615D-01
 TGTAL ENERGY OF SYSTEM (IN. LB.)= 3.71149D-17
 WORK DCNE - TGTAL ENERGY (IN. LB.)= 2.38615D-01

TYPE 2 = 3.000 HOURS AT PRESSURE = 1.0000 0.0 0.0 AND AT TEMPERATURE= 1.0000

NODAL POINT R-DISPLACEMENT Z-DISPLACEMENT

1	7.33090-05	0.0	2	7.07770-05	0.0	3	6.85250-05	0.0	4	6.65140-05	0.0
5	6.47100-05	0.0	6	6.30880-05	0.0	7	6.16260-05	0.0	8	6.03050-05	0.0
9	5.91110-05	0.0	10	5.80290-05	0.0	11	5.70480-05	0.0	12	5.61600-05	0.0
13	5.53540-05	0.0	14	7.21230-05	0.0	15	6.97000-05	0.0	16	6.75400-05	0.0
17	6.56080-05	0.0	18	6.38740-05	0.0	19	6.23130-05	0.0	20	6.09040-05	0.0
21	5.96320-05	0.0	22	5.84800-05	0.0	23	5.74370-05	0.0	24	5.64910-05	0.0
25	5.56330-05	0.0	26	5.48550-05	0.0						

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FORM 1411 2

TIME		2 =		3.000 HOURS AT PRESSURE = 1.0000 0.0 0.0 AND AT TEMPERATURE= 1.0000																	
ELEM/	EPS-R/	EPS-T/	EPS-Z/	EPSRZ/	EPS-1/	EPS-2/	/ANGL*	SIG-R/	SIG-T/	SIG-Z/	SIGRZ/	SIG-1/	SIG-2/	*	ALFA/	SIGEFF/	ELAEN/	EPSEFF/	ENERG/	ERR/	PLA
1	-337	443	0	-1	0	-337	89 *	-3468	8054	1510	-8	1510	-3468 *	0	10009	1	75	2950	0	0	
2	-323	429	0	-1	0	-323	89 *	-3294	7899	1511	-8	1511	-3294 *	0	9726	1	69	2685	0	0	
3	-300	409	0	-1	0	-300	89 *	-2968	7719	1550	-8	1550	-2968 *	0	9292	1	61	2324	0	0	
4	-287	397	0	0	0	-287	89 *	-2813	7573	1548	-7	1548	-2813 *	0	9033	1	57	2128	0	0	
5	-268	380	0	0	0	-268	89 *	-2524	7399	1578	-7	1578	-2524 *	0	8637	1	51	1859	0	0	
6	-257	369	0	0	0	-257	89 *	-2386	7261	1574	-6	1574	-2386 *	0	8400	1	47	1712	0	0	
7	-240	354	0	0	0	-240	89 *	-2129	7096	1598	-7	1598	-2129 *	0	8039	1	42	1509	0	0	
8	-231	345	0	0	0	-231	89 *	-2006	6969	1593	-6	1593	-2006 *	0	7823	1	40	1396	0	0	
9	-216	331	0	0	0	-216	89 *	-1776	6814	1612	-6	1612	-1776 *	0	7494	1	36	1240	0	0	
10	-208	323	0	0	0	-208	89 *	-1665	6696	1607	-6	1607	-1665 *	0	7298	1	34	1154	0	0	
11	-194	311	0	0	0	-194	89 *	-1459	6552	1623	-6	1623	-1459 *	0	7000	1	31	1032	0	0	
12	-187	304	0	0	0	-187	89 *	-1360	6444	1617	-5	1617	-1360 *	0	6821	1	29	964	0	0	
13	-176	293	0	0	0	-176	89 *	-1174	6310	1630	-5	1630	-1175 *	0	6550	0	27	869	0	0	
14	-169	287	0	0	0	-169	89 *	-1085	6210	1625	-5	1625	-1095 *	0	6388	0	25	815	0	0	
15	-159	277	0	0	0	-159	89 *	-918	6088	1636	-5	1636	-918 *	0	6141	0	23	739	0	0	
16	-153	271	0	0	0	-153	89 *	-837	5996	1630	-5	1630	-837 *	0	5993	0	22	695	0	0	
17	-144	263	0	0	0	-144	89 *	-685	5883	1640	-5	1640	-685 *	0	5769	0	21	634	0	0	
18	-139	257	0	0	0	-139	89 *	-612	5798	1634	-4	1634	-612 *	0	5634	0	20	598	0	0	
19	-130	250	0	0	0	-130	89 *	-474	5694	1643	-4	1643	-474 *	0	5429	0	18	548	0	0	
20	-126	245	0	0	0	-126	89 *	-408	5616	1638	-4	1638	-408 *	0	5306	0	18	519	0	0	
21	-118	238	0	0	0	-118	89 *	-283	5520	1645	-4	1645	-283 *	0	5119	0	16	478	0	0	
22	-114	233	0	0	0	-114	89 *	-222	5449	1640	-4	1640	-222 *	0	5007	0	16	454	0	0	
23	-107	227	0	0	0	-107	89 *	-108	5360	1646	-4	1646	-108 *	0	4836	0	15	419	0	0	
24	-103	223	0	0	0	-103	89 *	-53	5294	1642	-4	1642	-53 *	0	4733	0	14	399	0	0	

WORK DONE (ASSUME CONSTANT LOAD) (IN. LB.)= 2.668230-01
 TOTAL ENERGY OF SYSTEM (IN. LB.)= 2.810460-02
 WORK DONE - TOTAL ENERGY (IN. LB.)= 2.387180-01

OUTPUT TAPE 14 HAS BEEN UPDATED THROUGH TIME STEP 2

RESTART NEXT RUN EITHER FROM TIME STEP 3 USING 14 AS INPUT TAPE, OR FROM TIME STEP 1 USING 14 AS INPUT TAPE
 THE PROBLEM CAN BE REINITIALIZED BY SIMPLY SETTING N7=2 AND REDEFINING THE DTIM(I) ARRAY
 ALL OTHER PARAMETERS HAVE THE SAME MEANING AS IN A NORMAL RESTART RUN

V. REFERENCES

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3. Deitrich, et. al., *Modeling the Response of Fast Reactor Fuel to Hypothetical Accident Transients*, International Meeting Fast Reactor Safety and Related Physics, Chicago, Illinois, U.S.A., (Oct 5-8, 1976).
4. Pugh, C. E., Corum, J. M., Liu, K. C., and Greenstreet, W. L., *Currently Recommended Constitutive Equations for Inelastic Design Analysis of FFTF Components*, ORNL-TM-3602, Oak Ridge National Laboratory (Sep 1972).