COVE-I
A Finite Difference Creep
Collapse Code for Oval
Fuel Pin Cladding Material

**Prepared for the U.S. Nuclear
Regulatory Commission**

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COVE - 1
A FINITE DIFFERENCE CREEP COLLAPSE CODE
FOR OVAL FUEL PIN CLADDING MATERIAL

by
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to

CORE PERFORMANCE BRANCH
NUCLEAR REGULATORY COMMISSION

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On January 19, 1975, research and development programs of the U.S. Atomic Energy Commission (AEC) became part of the newly formed Energy Research and Development Administration (ERDA). In this report, since it refers to work done in 1974, most references are to AEC programs.

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loading and evaluates the new initial ovality including the changes due to creep for the next time step. The influence coefficient for the finite length is applied at the end of each time step to correct the incremental deflection.

This process of calculation is continued until one of the collapse criteria has been reached. At present, two collapse criteria are used: a) maximum ovality limit, and b) maximum tangential stress equal to material yield stress.

The available output includes:

- A. Deflected shape of the tube wall from $\theta = 0$ to $\theta = \pi/2$ at any point in time.
- B. Stress distributions across the wall for any one of the circumferential tangential nodes.
- C. Effective stress distributions for any of the nodal points.

At present the number of tangential mesh points ranges from a minimum of 6 nodes to a maximum of 21 nodes equally spaced from $\theta = 0$ to $\pi/2$. This mesh is used in the finite difference equations and is represented numerically by Numerov's equation for a second order differential equation. The finite difference formulation has an error of $(\Delta\theta)^6$ as compared with second order difference operator with an error of $(\Delta\theta)^2$.

The radial nodes are used as quadrature points for the bending stress and strains. They are restricted to range between a minimum of 6 and a maximum of 46 nodes. At present a fifth order Newton Cotes quadrature formula is used with an error of $(\Delta r)^5$.

From actual practice it appears that it is more important to use the nodal refinement in the tangential rather than radial directions. For most problems a tangential mesh of 11 to 16 nodes with 21 radial nodes will provide a solution within 3% of using the maximum number of nodal points. By using this type of mesh the computation time is reduced by half.

The incremental creep calculation can use either a time hardening or strain hardening procedure. The creep equations used can be either the standard PNL or a user-supplied optional routine.

THEORY

The development of the differential equations describing the deflections of an infinite tube to external pressure loading is based on assumption of the initial displacement profile. This assumption provides the basis for developing the fundamental displacement mode shape solution. It makes it possible to construct an analysis using as a tool the geometries of the distorted and undistorted tubes.⁽³⁾

BASIC DIFFERENTIAL EQUATIONS

Consider the deflected profile of a circular tube segment shown in Figure 1. It is useful at this point to consider that the tube segment has some small initial ovality which will allow the tube to have a radial deflection pattern described by equation (1). It should be noted that there is no restriction on the actual shape; it is not limited to a $\cos 2\theta$ form but could be any general displacement function.

$$U(\theta) = U_0 (\max) \cos 2\theta = U_0 f(\theta) \quad (1)$$

Consider some arc segment dS located an angle θ from the horizontal. The arc segment can be defined as

$$dS = R d\theta$$

where R is the radius of curvature of the tube at that point.

The ultimate goal of this approach is to develop a differential equation for the radial displacement U in terms of the angular position θ around the tube wall. The most obvious solution is to develop the equations as a function of U and surface distance S . This approach would be similar to that used in the development of the differential equation of a beam. The resulting equation which is a function $f(S)$ will then be transformed into an equation as $f(\theta)$. By using this approach the development is in terms of identifiable parameters θ and radial motion or displacement U .

The angle $d\theta$ represents the included incremental angle between the section normals for Sections 1 and 2. After deformation this included

FIGURE 1. Basic Geometry of an Initially Oval Tube Compared With a True Circle

angle is increased to $d\theta + \Delta d\theta$ and the radius of curvature changes magnitude and location. The center of curvature of the oval or deformed tube is of course no longer located in the center of the tube. This can be readily seen by

$$\text{Undeformed Tube: } \frac{1}{R} = \frac{d\theta}{ds} \quad (2)$$

$$\text{Deformed Tube: } \frac{1}{R_1} = \frac{d\theta + \Delta d\theta}{ds + \Delta ds} \quad (3)$$

where the centers of curvature for these two cases for the same tube segment have changed locations.

The development of the governing differential equation depends upon developing expressions for the terms in Equation (3). By using the similarity to the bending of a beam, where for a simple beam the curvature can be described as:

$$\frac{1}{R} = \frac{-M}{EI} \quad (4)$$

and for a curved beam the change in curvature becomes:

$$\frac{\Delta d\theta}{dS} = \frac{1}{\Delta R} = \frac{-M}{EI} \quad (5)$$

for the case of interest then

$$\frac{1}{\Delta R} = \frac{1}{R_1} - \frac{1}{R} = \frac{-M}{EI} \quad (6)$$

Figure 2 shows that the segment 1-2 undergoes a net rotational shift as well as a change in curvature. The change in angular position can be defined as

$$\phi = \tan^{-1} \frac{dU}{dS}$$

whereas the increased curvature becomes:

$$d\theta + \Delta d\theta = d\theta + \left(\phi + \frac{\partial}{\partial S} \left(\frac{\partial U}{\partial S} \right) dS - \phi \right) \quad (7)$$

or for small angles

$$d\theta + \Delta d\theta = d\theta + \frac{d^2 U}{dS^2} dS \quad (8)$$

Additional expressions must be developed for the change in surface length S as is shown in Equation (3). The elemental length of segment 1-2 is $dS = R d\theta$.

The development of the distorted arc length expression is based on the sign convention used and the displacements that are assumed. If the value of the included angle is increased by the distorted motion such that $d\theta + \Delta d\theta > d\theta$, and if U considered as positive for inward motion results in the new radius of curvature such that $R' = R - U$ where $(R - U) < R$, then for small angles and small distortions the change in surface length can be defined as:

$$dS + \Delta dS = (R - U)(d\theta + \Delta d\theta)$$

or
$$dS + \Delta dS = R d\theta - U d\theta \text{ (neglecting the product of small terms)}$$

or
$$dS + \Delta dS = dS \left(1 - \frac{U}{R}\right) \quad (9)$$

FIGURE 2. Local Deformed Tube Geometry

Now by substituting Equation (9) and (8) into equation (3) and making the appropriate simplifications

$$\frac{1}{R_1} = \frac{dS \frac{1}{R} + \frac{d^2U}{dS^2} dS}{dS (1 - \frac{U}{R})} \quad (10)$$

which can be reduced by assuming that $R \gg U$ and that $\frac{R}{R-U} \approx 1$. Then:

$$\frac{1}{R_1} = \frac{1}{R-U} + \frac{d^2U}{dS^2} \quad (11)$$

If $\frac{1}{R-U}$ is multiplied by $\frac{R+U}{R+U}$ and if it is noted that $R^2 \gg U^2$ and using Equation (6), Equation (11) can be rewritten.

$$\frac{d^2U}{dS^2} + \frac{U}{R^2} = - \frac{M}{EI} \quad (12)$$

Using Equation (2), a substitution of variables can be made to transform Equation (12) into a function of θ instead of S . Using this transformation Equation (12) becomes:

$$\frac{d^2U}{d\theta^2} + U = - \frac{R^2 M(\theta)}{EI} \quad (13a)$$

Equation (13a) is the basic equation which will be solved for both the total and inelastic component deflection analysis.

The expression for $M(\theta)$ can be determined from looking at the geometry of the problem shown in Figure 3.

$$U_T = U + U_0$$

BY SYMMETRY $V_1 = V_2 = 0$ AT $\theta = 0, \theta = 90^\circ$

$$P_1 \text{ \& } P_2 = (P_{OUT} - P_{IN}) R_m$$

$$M = P R_m (U + U_0)$$

$$P = (P_{OUT} - P_{IN})$$

$$R_m = \text{THE VALUE OF } R(\theta)$$

FIGURE 3. Forces and Deflections on an Infinite Tube Segment for the Initial Time Step. The Initial Profile is Assumed to Follow a $\cos 2\theta$ Distribution. The Deformations After All Following Time Steps are not Constrained to Conform to any Specific Distribution.

The distance $U_o(\theta)$ is the maximum unpressurized distortion. As soon as the pressure is applied the deflection increases by an amount $U(\theta)$. The total displacement at any point will then be the combined displacements such that:

$$U_T(\theta) = U_o(\theta) + U(\theta) \quad (13b)$$

Substituting the value of the plate stiffness for the value of EI and combining the displacement $U_T(\theta)$ expression into Equation (13a) a new differential equation can be written.

The elastic moment expression becomes:

$$M(\theta) = PRU_T(\theta), \text{ or}$$

$$M(\theta) = PR [U_o(\theta) + U(\theta)]. \quad (13c)$$

$$EI = D = \frac{t^3 E}{12(1-\mu^2)} \quad (\text{for plate stiffness}) \quad (13d)$$

where:

t = thickness of the tube wall

E = local elastic modulus

μ = Poissons Ratio

and;

$$\frac{d^2 U}{d\theta^2} + U = - \frac{PR^3}{D} [U_o(\theta) + U(\theta)] \quad (13e)$$

Or, collecting terms:

$$\frac{d^2 U}{d\theta^2} + \left(1 + \frac{PR^3}{D}\right) U = - \frac{PR^3}{D} U_o(\theta) \quad (14)$$

The initial deflection for the first time step only is assumed to be a $\cos 2\theta$ solution. Therefore, Equation (14) can be rewritten in a form that is used for the initial elastic solution of the tube deflection.

$$\frac{d^2U}{d\theta^2} + \left(\frac{PR^3}{D} + 1 \right) U = - \frac{PR^3}{D} U_0 \cos 2\theta \quad (15)$$

The boundary conditions for this problem take the form of:

$$\left. \frac{dU}{d\theta} \right|_{\theta=0} = 0.0 \quad \left. \frac{dU}{d\theta} \right|_{\theta=\pi/2} = 0.0 \quad (16)$$

The solution of this equation will be the elastic deflection of an infinite tube under external pressure P with an initial ovality U_0 . For all following time steps, the unpressurized distortion is no longer assumed to follow a $\cos 2\theta$ distribution. The distorted shape is changed by the inelastic creep strains and is based on incremental changes in the bending and direct strain that occurs (Eqn 14).

CREEP DIFFERENTIAL EQUATION

The elastic solution previously presented will now be extended to include creep deformation. Perhaps the best way to think of the creep solution is as an addition of a fictitious force that will provide additional deformation due to creep during a time increment ΔT . The inelastic deformation due to creep can then be identified and included for the next time step.

The differential equation that will be solved will be similar to Equation (13a) but with the addition of the creep moment $M_c(\theta)$. Therefore:

$$\frac{d^2U}{d\theta^2} + U = - \frac{R^2}{EI} [M(\theta) + M_c(\theta)] \quad (17a)$$

and:

$$M_c(\theta) = \frac{E}{(1-\mu^2)} \int_{-h/2}^{h/2} \epsilon_{ij}^c r dA \quad (17b)$$

The creep moment $M_c(\theta)$ is evaluated in terms of the creep strain that has taken place during the time increment ΔT . The amount of creep strain is based upon the stresses present at the end of the previous time step. The incremental creep strain for each time step is converted to a moment through multiplication by the equivalent plate stiffness. It should be pointed out that incremental inelastic strain at this point should be considered as an equivalent elastic force which justifies the use of the plate stiffness elastic properties. The inelastic strains should be allocated by the use of the correct inelastic Poisson ratios in the Prandtl-Reuss equations, but the evaluation of the equivalent elastic forces must use the elastic conditions. The corrections to the ratios in the Prandtl-Reuss equations are based on material anisotropy considerations.

Equation (17a) can be rewritten in terms of the expanded moment. It should be noted that value of the creep moment M_c becomes independent of the elastic properties. It is divided by the plate stiffness in Equation (17c).

$$\frac{d^2 U}{d\theta^2} + \left(1 + \frac{PR^3}{D}\right) U = -\frac{1}{D} PR^3 U_o(\theta) - \frac{1}{D} R^2 M_c(\theta) \quad (17c)$$

The solution of this equation will give an increase in ovality due to pressure and creep. The total ovality will then be

$$U_T(\theta) = U(\theta) + U_o(\theta) \quad (18)$$

where

$U_T(\theta)$ = Total combined displacement.

$U_o(\theta)$ = Initial ovality.

$U(\theta)$ = Increase in ovality due to the application of the pressure P and creep.

The new original or starting ovality U_o for the next time step has now changed by some amount due to the creep that has occurred. Therefore Equation (17a) must be solved with just the fictitious moment $M_c(\theta)$ applied to evaluate the inelastic change in U_o .

Therefore:

$$\frac{d^2 U_c}{d\theta^2} + U_c = \frac{-R^2}{D} M_c(\theta) \quad (19a)$$

The solution of this equation yields the incremental deflection of the tube due to creep. This deflection is added to the old initial ovality to find the new initial ovality:

$$U_o(\theta) = U_o(\theta) + U_c(\theta) \quad (19b)$$

where U_o is now the new initial ovality to be used in Equation 17 for the next time step.

DIFFERENTIAL EQUATION SOLUTION TECHNIQUE

The solution technique for Equations (17c) and (19a) requires a finite difference method or nodal point method. This is needed because, in general, $M_c(\theta)$ will not be an explicitly known function of θ due to the variation in creep laws and the dependence of the formulation upon stress and time.

The differential equation will be solved using a finite difference representation in a matrix solution technique. Numerov's equation will be used as the finite difference operator:

$$u_{n+1} - 2u_n + u_{n-1} = \frac{h^2}{12} \left(f(u)_{n+1} + 10 f(u)_n + f(u)_{n-1} \right) \quad (20)$$

$$\text{where } u_{n+1} - 2u_n + u_{n-1} = u'' h^2 \quad (21a)$$

The basic differential equation to be solved is of the form

$$u'' = f(u) \quad (21b)$$

In matrix notation this equation will become

$$Cu = R \quad (21c)$$

The solution consists of generating the coefficients for the C matrix for the solution of Equations (17a) and (19a).

Both of these equations can be rewritten in the form:

$$u'' = Au + B \quad (22)$$

The first term of Numerov's equation then becomes:

$$u_{n-1} - 2u_n + u_{n+1} = \frac{h^2}{12} \left(Au_{n-1} + B + 10 Au_n + 10 B + Au_{n+1} + B \right) \quad (23)$$

Collecting terms and writing out for a 3-term or 3-node problem:

$$\begin{aligned} \left(1 - \frac{Ah^2}{12}\right) u_{n-1} - \left(2 + \frac{10}{12} Ah^2\right) u_n + \left(1 - \frac{Ah^2}{12}\right) u_{n+1} &= Bh^2 \\ \left(1 - \frac{Ah^2}{12}\right) u_n - \left(2 + \frac{10}{12} Ah^2\right) u_{n+1} + \left(1 - \frac{Ah^2}{12}\right) u_{n+2} &= Bh^2 \\ \left(1 - \frac{Ah^2}{12}\right) u_{n+1} - \left(2 + \frac{10}{12} Ah^2\right) u_{n+2} + \left(1 - \frac{Ah^2}{12}\right) u_{n+3} &= Bh^2 \end{aligned} \quad (24)$$

The boundary condition becomes: $\left. \frac{dU}{d\theta} \right|_{\theta=0} = 0.0$
 $\theta = \pi/2$

By representing the slope $\frac{dU}{d\theta}$ in finite difference terms the boundary condition can be written in terms of the nodal displacements;

$$\frac{du}{d\theta} = \frac{1}{2h} (u_{n-1} - u_{n+1})$$

now applying the boundary conditions;

$$0 = (u_{n-1} - u_{n+1})$$

or,

$$u_{n-1} = u_{n+1} \quad (25)$$

This means that the slope boundary condition is in reality the reflection of the u_{n+1} nodal point. This displacement condition can then be added to the coefficients in the C matrix. Equation 26 shows the sample problem of Equation (24) with the coefficients for the nodes adjacent to the boundary nodes substituted in.

$$\begin{bmatrix} -\left(2 + \frac{10}{12} Ah^2\right) + 2\left(1 - \frac{Ah^2}{12}\right) & 0 \\ \left(1 - \frac{Ah^2}{12}\right) - \left(2 + \frac{10}{12} Ah^2\right)\left(1 - \frac{Ah^2}{12}\right) & \\ 0 & 2\left(1 - \frac{Ah^2}{12}\right) - \left(2 + \frac{10}{12} Ah^2\right) \end{bmatrix} \begin{Bmatrix} U_n \\ U_{n+1} \\ U_{n+2} \end{Bmatrix} = \begin{Bmatrix} Bh^2 \\ Bh^2 \\ Bh^2 \end{Bmatrix} \quad (26)$$

The Numerov's approximation to a second order differential equation provides an $(0)h^6$ error.

Creep Bending Moment

The evaluation of the creep bending moment for a given time increment is done by evaluating the integral shown in Equation (17b).

$$M_c(\theta) = \frac{E}{1-\mu} \int_{-h/2}^{h/2} \epsilon_{ij}^c(\theta) r \, dA \quad (27)$$

or:

$$M_c(\theta) = \frac{E}{1-\mu} \int_{-h/2}^{h/2} \epsilon_{11}^c(\theta) r \, dA \quad (28)$$

where: ϵ_{11} = the creep strain in hoop direction

r = the distance from the neutral axis of the wall to position of interest between $\pm h/2$.

(A similar expression for $M_c(x)$ can also be defined to be used in conjunction with the finite length effect, where ϵ_{ij} becomes ϵ_{22} in Equation (27).

This integration can be performed by using the Newton Cotes fifth order quadrature formula

$$\int f(r)dr = \frac{5}{288} h \left[19 f(r)_1 + 75 f(r)_2 + 50 f(r)_3 + 50 f(r)_4 + 75 f(r)_5 + 19 f(r)_6 \right] \quad (29)$$

This expression is evaluated for from 6 to 46 nodal points across the section. The number of radial quadrature points is one more than the number of radial segments (NRA).

The correction to the state of stress is then determined by the assumption that:

$$\epsilon_{ii}(r,\theta) = \epsilon_{ii_{\text{neutral axis}}} + r \frac{d\epsilon_{ii}}{dr} \quad (30)$$

which says that the strain at any point in the hoop direction is a function of the strain at the neutral axis and the rotation of the plane. This equation assumes that planes remain planar during creep bending in a biaxial stress state. This has been shown experimentally to be a reasonable approach.⁽⁴⁾

An example of the type of loading stresses that are present in the cladding wall is shown in Figure 4. The final stress distribution indicated in Figure 4 computed by the code has been verified with ANSYS,⁽⁵⁾ CAPT,⁽⁶⁾ and AXICRP.⁽⁷⁾ The stress distributions are similar for both the M_θ and M_x bending moments. Similar corrections for the stress distributions are applied as a function of time to stresses in both directions as is shown in Figure 5.

BASIC GEOMETRY

The basic geometry of COVE-1 is a three-dimensional model including bending in and out of the plane as well as radial, circumferential, and axial forces. Figure 6 shows the geometry of the segment that is analyzed in the computation.

FIGURE 4. Typical Stress and Strain Distributions Due to Creep

FIGURE 5. Element of Wall Considered by COVE Showing Elastic Stress Distributions

The geometry used in the code on input divides the tube segment into NRA radial segments and NTA tangential segments. These segments have a finite length equal to XLEN.

The number of radial nodes (NRA + 1) are used as quadrature points for evaluating Equation (29). The minimum number of radial nodes is 6 with the optimum being 21 or 26. It can be seen from Equation (29) that the number of radial nodes must be incremented by 5 due to the quadrature formula.

The number of tangential nodes NTA + 1 defines the size of the solution array Equation (26). By increasing the number of tangential nodes the approximation to the actual displacement curve improves. The total number of degrees of freedom are also increased in two ways. First of all, the size of the matrix equation array increases directly as a function of n^2

FIGURE 6. Basic Geometry Used to Define the Analytical Model

operations. In addition, the time required to create the coefficients used in the coefficient matrix is increased. For each tangential nodal point a quadrature must be performed over $NRA + 1$ radial nodes. The process is duplicated at each tangential node for $NTA + 1$ nodes.

FINITE LENGTH APPROXIMATION

The development to this point has considered only the deflection of an infinite tube. The deflection of the surface of such a tube is not a function of the axial position, and the principal change in curvature is only in one plane. As the unsupported deflected length decreases an anticlastic surface is developed, which is based on the fuel pellet's support of the segments' end conditions.

Where:

$$\left. \begin{array}{l} \frac{1}{R_x} > 0 \\ \frac{1}{R_x} \neq \frac{1}{R_\theta} \end{array} \right\} = \text{Principal curvatures of the deflected tube surface} \quad (31a)$$

R_x = Radius of curvature in the axial direction
 R_θ = Radius of curvature in the hoop or tangential direction

As a result of this change in the deflected shape a considerable stiffening of the section is obtained. The increase in stiffness sharply reduces the resultant deflection or ovality and increases the time to collapse.

The basic differential equations describing the deflections of a segment of a circular shell are quite involved. These equations can be simplified, and are shown here in simplified form. To be consistent with the literature, the coordinate system will be modified to allow it to be extended to a three dimensional deformation field. The basic coordinate system used for the finite length analysis is indicated in Figure 7a.

FIGURE 7a. Finite Length Geometry

Simplified Equilibrium Equations⁽⁸⁾:

$$\begin{aligned} \frac{\partial^2 u}{\partial x^2} + \frac{1-\mu}{2R^2} \frac{\partial^2 u}{\partial \theta^2} + \frac{1+\mu}{2R} \frac{\partial^2 v}{\partial x \partial \theta} - \frac{\mu}{R} \frac{\partial w}{\partial x} &= 0 \\ \frac{1+\mu}{2} \frac{\partial^2 u}{\partial x \partial \theta} + R \frac{1-\mu}{2} \frac{\partial^2 v}{\partial x^2} + \frac{1}{R} \frac{\partial^2 v}{\partial \theta^2} - \frac{1}{R} \frac{\partial w}{\partial \theta} &= 0 \\ \frac{\mu}{\partial x} + \frac{\partial v}{R \partial \theta} - \frac{w}{R} - \frac{h^2}{12} \left(R \frac{\partial^4 w}{\partial x^4} + \frac{2}{R} \frac{\partial^4 w}{\partial x^2 \partial \theta^2} + \frac{\partial^4 w}{R^3 \partial \theta^4} \right) &= \frac{Rq(1-\mu^2)}{Eh} \end{aligned} \quad (31b)$$

The displacement components can be described in terms of a series⁽⁸⁾:

$$\begin{aligned} u &= \sum \sum A_{mn} \sin \frac{n\pi\theta}{\alpha} \cos \frac{m\pi x}{\ell} \\ v &= \sum \sum B_{mn} \cos \frac{n\pi\theta}{\alpha} \sin \frac{m\pi x}{\ell} \\ w &= \sum \sum C_{mn} \sin \frac{n\pi\theta}{\alpha} \sin \frac{m\pi x}{\ell} \\ q &= \sum \sum D_{mn} \sin \frac{n\pi\theta}{\alpha} \sin \frac{m\pi x}{\ell} \end{aligned} \quad (31c)$$

Where:

- ℓ = length of the segment in the x direction
- α = included angle of the shell segment of interest
- w = radial displacement
- u = axial displacement
- v = tangential displacement
- h = shell thickness
- R = radius
- q = load intensity

The moments and forces acting on a segment of the shell surface can be represented by:

$$\begin{aligned}
 N_x &= \frac{K}{R} \left[\frac{\partial u}{\partial \xi} + \mu \left(\frac{\partial v}{\partial \theta} - w \right) \right], & N_\theta &= \frac{K}{R} \left[\frac{\partial v}{\partial \theta} - w + \mu \frac{\partial u}{\partial \xi} \right], \\
 N_{x\theta} &= \frac{K(1-\mu)}{2R} \left(\frac{\partial u}{\partial \theta} + \frac{\partial v}{\partial \xi} \right), & M_x &= \frac{D}{R^2} \left(\frac{\partial^2 w}{\partial \xi^2} + \mu \frac{\partial^2 w}{\partial \theta^2} \right), \\
 M_\theta &= -\frac{D}{R^2} \left(\frac{\partial^2 w}{\partial \theta^2} + \mu \frac{\partial^2 w}{\partial \xi^2} \right), & M_{x\theta} &= \frac{D(1-\mu)}{R^2} \frac{\partial^2 w}{\partial \xi \partial \theta}, \\
 Q_x &= -\frac{D}{R^3} \frac{\partial}{\partial \xi} \left(\frac{\partial^2 w}{\partial \xi^2} + \frac{\partial^2 w}{\partial \theta^2} \right), & Q_\theta &= -\frac{D}{R^3} \frac{\partial}{\partial \theta} \left(\frac{\partial^2 w}{\partial \xi^2} + \frac{\partial^2 w}{\partial \theta^2} \right)
 \end{aligned}$$

where:

$$\xi = x/R \quad C^2 = \frac{h^2}{12R^2} \quad K = \frac{Eh}{1-\mu^2} \quad D = \frac{Eh^3}{12(1-\mu^2)}$$

These equations can be represented in finite difference form and applied over the region of interest of the shell. Their simultaneous solution yields the displacements u , v , and w .

To obtain the actual deflection profile over the continuum on a point by point basis requires a significant amount of computation. This analysis, however, intends to provide only an approximate solution or coefficient that is sensitive to the actual length of the collapse zone. This means that if a nondimensional solution could be developed for peak deflections, an approximate influence coefficient approach would become readily available. The influence coefficient could then be used as a multiplier on the infinite tube solution. Although a complete solution would not be obtained this way, an estimate of the center deflections would be possible.

The infinite tube solution is

$$U = U(\theta) \tag{32}$$

An influence coefficient can be generated by using this type of approach such that:

$$C_x = \frac{w_x(\theta)_{\max}}{w_{\infty}(\theta)_{\max}} \quad (33a)$$

where:

$w_{\infty}(\theta)$ = infinite length solution (radial deflection)

$w_x(\theta)$ = finite length solution (radial deflection)

Combining both results,

$$U = C_x U(\theta) \quad (33b)$$

Some simplifications in the solution boundary conditions can be made by examining the deflection patterns and the acting loads. Figures 7b and 8 show orthogonal cuts of the deflected profile. It can be seen that for a segment of the tube located 45° to 135° a very interesting deflection pattern develops. The boundary conditions along the 45° and 135° line have $M_\theta = 0$. This type of condition is similar to a simple support. For $X = 0$ and $X = L$ the slope is zero for all values of θ . The zero slope is similar to a built-in or fixed support condition. Although the condition is not strictly adhered to around the entire tube circumference, it can be approximated by using an equivalent or effective active collapse length.

At this point it is well to ask if a substitute geometry could be used that would be easier to analyze or evaluate. As a first approximation it might be justified to use a plate solution with two sides with simple and two sides with fixed supports. The width of the equivalent flat plate would be equal to the mean circumferential distance from $\theta = 45^\circ$ to $\theta = 135^\circ$. The equivalent length of the plate would be equal to the length of the collapse zone. Figure 9a shows the plate approximation.

FIGURE 7b. Radial Deflection Profile for a Fundamental Deflection Mode as a Function of Tangential Position and for an Axial Position of $x = \ell/2$

FIGURE 8. Deflection Profile for Finite Axial Length Segments. Deflections are shown for $\theta = 0^0$, 45^0 , and 90^0

FIGURE 9a. Flat Plate Approximation Model Used to Evaluate the Effects of Axial Length on Collapse Time

The form of the solution would again be a ratio of the fixed length solution to the infinite length solution for the flat plate:

$$COR = \frac{w_x(R\theta, X)}{w_\infty(R\theta, \infty)} \quad (34)$$

Where combining the results with Equation (32) the final approximation to the solution becomes:

$$U = COR U(\theta) \quad (35)$$

The rationale for using this solution lies in the relative dependence of the deflection of both the cylindrical and flat plate on length. It is recognized that the difference in absolute magnitude of the deflection between the cylindrical shell and the flat plate will be significant. The dependence of both solutions on the length of the sections should be somewhat similar however. This can be seen from the basic differential equations describing both the plate and the cylindrical surface (Equations 31b and 36). The dependence of the radial displacement w with respect to the axial length x is a fourth order partial differential equation.

The basic plate equation is

$$\frac{\partial^4 w}{\partial x^4} + 2 \frac{\partial^4 w}{\partial x^2 \partial y^2} + \frac{\partial^4 w}{\partial y^4} = \frac{q}{D} \quad (36)$$

It would appear from observing these equations that the displacement in the radial or w direction has the same basic dependence on the x or axial direction. If this is indeed true then the dependence of the deflection on changes in the axial length should be similar.

Therefore, as an approximation it will be assumed that

$$COR \approx Cx$$

The solution to the plate problem has been developed by Timoshenko⁽⁸⁾
Case No. 42:

$$w = \frac{4qR\theta}{\pi^5 D} \sum_{m=1,3,5}^{\infty} \frac{1}{m^5} \sin \frac{m\pi Y}{R\theta} \left(1 - \frac{\alpha_m \tanh \alpha_m + 2}{2 \cosh \alpha_m} \cosh \frac{m\pi x}{R\theta} + \frac{1}{2 \cosh \alpha_m} \frac{m\pi x}{R\theta} \sinh \frac{m\pi x}{R\theta} \right) \quad (37a)$$

where:

$$\alpha_m = \frac{m\pi \text{ XLEN}}{2R\theta} \quad (37b)$$

XLEN = equivalent active collapse length

R = mean tube radius

θ = angular segment in radians

Similar expressions can be developed for the bending moments M_θ and M_x , where M_x corresponds to the fixed end boundary condition and M_θ corresponds to the simple support condition. The peak bending moments at the center of the plate can be written in series form:

$$M_\theta = \frac{2(R\theta)^2 q}{\pi^3} \sum_{m=1,3,5}^{\infty} \frac{(-1)^{(m-1)/2}}{m^3 \cosh \alpha_m} \cdot \frac{\alpha_m - \tanh \alpha_m (1 + \alpha_m \tanh \alpha_m)}{\alpha_m - \tanh \alpha_m (\alpha_m \tanh \alpha_m - 1)} \cdot [(2\mu + (1 - \mu) \alpha_m \tanh \alpha_m)]$$

$$\text{CORM} = \frac{(M_\theta)_x}{(M_\theta)_\infty} \quad (38a)$$

and in a similar manner:

$$M_x = \frac{2q(R\theta)^2}{\pi^3} \sum_{m=1,3,5}^{\infty} \frac{(-1)^{(m-1)/2}}{m^3 \cosh \alpha_m} \frac{\alpha_m - \tanh \alpha_m (1 + \alpha_m \tanh \alpha_m)}{\alpha_m - \tanh \alpha_m (\alpha_m \tanh \alpha_m - 1)} \cdot [2 - (1 - \mu) \alpha_m \tanh \alpha_m]$$

$$\text{CORX} = \frac{(M_x)_x}{(M_x)_\infty} \quad (38b)$$

In terms of the tube geometry the M_θ moment is that moment whose vector is parallel to the major axis of the tube; it is evaluated in Equations (13) and (13c). The M_x moment is orthogonal to the major tube axis. The orientation of these quantities is defined in Figure 5.

In order to simplify the actual calculational procedure in the code, relationships for w , M_x , M_θ can be developed in a nondimensional or unit basis. The nondimensional form will be a function of the variables $XLEN$ and $R\theta$. An approximation to the unit solution of peak deflections can be made and takes the basic form:

Deflection

$$COR = \left[0.0267 (1 - e^{-RT/1.170}) - 0.013 \right] / 0.01302 \quad (39a)$$

where:

$$RT = XLEN/R\theta$$

Hoop Moments

$$CORM = \left[0.285 (1 - e^{-RT/0.985}) - 0.1605 \right] / 0.1250$$

Axial Moments

$$CORX = (-0.00475RT + 0.0565) / 0.0375 \quad (39b)$$

The axial moment is referenced to an RT value of 5; at values beyond 5, the value of $CORX$ is gradually reduced to zero such that the infinite tube solution is obtained. The fixed end condition in this model contains an expression for the moment which by itself does not decrease: Therefore additional terms were needed to reduce the contribution of this term.

The validity of implementing these coefficients into the solution procedure is based upon the linearity of the elastic solution. The basic differential equation used in the elastic solution of the infinite tube (Equation 13) is a linear second order equation. The material, however, is nonlinear with respect to time and stress. For any given time step the deformation for that increment is considered as an equivalent linear elastic system. The correction for the nonlinearity of material and the resulting inelastic deformation is made at the end of the time step in a separate set of calculations.

It appears that within limits this approach is a reasonable alternative to solving the actual problem and that it is possible to ratio the solution to the current increment of an incremental path dependent solution. It should be noted that the solution is incremented and not a total solution. The major difference is that these correction factors are applied at each incremental step for an incremental change in load, not for a large deflection analysis. This method of analysis will be accepted with the following restrictions and assumptions:

1. The finite length approximation outlined will be considered only as a first approximation to the actual solution. In the limit as the value of $R \rightarrow \infty$ the solution approaches a true solution. For this application there has been a significant departure from this limit.
2. The errors involved in this solution approximation are within the uncertainty of the material data used in the computation.
3. The influence coefficient must be applied for each time step and not on the final total solution. This allows the material dependence on stress and time to be corrected at each point to develop the correct path dependence.
4. It will be assumed that the deflection for the positive as well as the negative values will have a similar dependence on segment length.
5. It will be assumed that the reduction in incremental deflection for the entire surface will be proportional to the peak incremental deflection ratio.

The finite length coefficient has been incorporated into the solution algorithm in the following steps:

1. Compute the elastic solution for an infinite tube.
2. Compute the equivalent aspect ratio

$$\text{Ratio} = 2 \cdot \text{XLEN}/\pi \cdot \text{RAO} \quad \text{where RAO is outside radius.}$$

3. Using the equation for the coefficient of deflection compute C_p

$$\text{Deflection} = \text{COR} \cdot \text{Deflection}$$

Now multiply all the computed deflections by this value.

4. Using corrections for bending moments CORM compute the correction to the bending moment

$$M_{\theta} = M_{\theta} \cdot \text{CORM}$$

Compute the bending moment using the corrected deflections and then apply this correction factor for the moment. This is necessary because the moment is a function of deflection, regardless of the deflection pattern with a finite length. The finite length shares or distributes the bending moment caused by pressure between all the supporting boundaries.

5. Now compute bending moment out of plane in the axial direction using the coefficient CORX.

$$M_x = M_{\theta} \cdot \text{CORX}/0.125$$

This expression is further corrected to make $M_x \rightarrow 0$ for large values of XLEN.

6. Compute effective stress and creep strain.
7. Compute creep bending moment and stress correction.
8. In order to reduce the calculations for this step it will be assumed that the inelastic deflection will equal that caused by the creep bending moment previously computed.
9. Compute correction to the out-of-plane deflection stress condition. Compute creep strains for out-of-plane stress conditions and corrections.
10. Combine deflections.
11. Compute new stress states and apply corrections to the stress distribution.

12. Check to see if yield condition or ovality limit has been reached.

13. Go to the next time step.

This concludes the basic algorithm needed to compute an approximation to the creep collapse of an oval tube. As was previously stated the degree of uncertainty in the basic creep data has a far greater effect on the collapse times than any other single factor outlined above.

ANISOTROPY APPROXIMATIONS

Zircaloy in a fabricated condition displays a significant amount of anisotropy. The degree of anisotropy and the significant effects it can have can be seen when the creep data from various load configurations are examined. It appears that some means of analysis is needed to account for, or at least be sensitive to, the observed apparent inconsistency in material properties.

The first step is to determine a new effective stress that will include the effects of anisotropy. This can be done using the results reported by Berman.⁽¹⁾ The effective stress relationships will be developed using the direction of rolling as the uniaxial test direction. The form of the coefficients is subject to the testing orientation and must be changed depending on the test configuration. For this work the majority of the testing results are in the uniaxial direction; therefore, for all ensuing calculations this direction will be used as the reference axis.

$$P(\sigma_x - \sigma_y)^2 + R(\sigma_y - \sigma_z)^2 + P(\sigma_z - \sigma_x)^2 = P(R + 1) X^2 = 2 \sigma_{eff}^2 \quad (40)$$

where P and R become:

$$\left. \begin{array}{l} P = R + 1 \\ R = 1 \rightarrow 1.7 \end{array} \right\} \text{anisotropy coefficients}$$

X = stress in the x direction from a uniaxial test

x = axial direction

y = hoop direction

z = radial direction

As a second step, a value of creep strain can be determined by using the value of χ^2 and the constitutive equation

$$\chi = \sigma_{\text{equivalent}}$$

$$d\epsilon^P = f(\sigma_{\text{equivalent}})$$

For this relationship to be correct the orientation of test must correspond to the orientation in the triaxial stress condition.

Based upon this it will be possible to develop a relationship for the Prandtl-Reuss equations that includes the anisotropy effects. The desired relationship can be developed by comparing the work reported in References (1), (2) and (9).

The plastic potential "f" is defined by:

$$2f = \left[\alpha_{12} (\sigma_{11} - \sigma_{22})^2 + \alpha_{23} (\sigma_{22} - \sigma_{33})^2 \right. \\ \left. + \alpha_{31} (\sigma_{33} - \sigma_{11})^2 + 3\alpha_{44} \tau_{12}^2 + 3\alpha_{55} \tau_{23}^2 + 3\alpha_{66} \tau_{31}^2 \right] \quad (41)$$

By letting the stresses alternately equal zero the coefficient for the Prandtl-Reuss equations can be found.

$$d\epsilon_{11}^P = \frac{d\epsilon^P}{\bar{\sigma}} \left[\alpha_{11}\sigma_{11} - \alpha_{12}\sigma_{22} - \alpha_{31}\sigma_{33} \right]$$

$$d\epsilon_{22}^P = \frac{d\epsilon^P}{\bar{\sigma}} \left[\alpha_{22}\sigma_{22} - \alpha_{23}\sigma_{33} - \alpha_{12}\sigma_{11} \right]$$

$$d\epsilon_{33}^P = \frac{d\epsilon^P}{\bar{\sigma}} \left[\alpha_{33}\sigma_{33} - \alpha_{31}\sigma_{11} - \alpha_{23}\sigma_{22} \right] \quad (42)$$

where:

$$\begin{aligned}\alpha_{11} &= \alpha_{12} + \alpha_{31} \\ \alpha_{22} &= \alpha_{23} + \alpha_{12}\end{aligned}\tag{43}$$

$$\alpha_{33} = \alpha_{31} + \alpha_{23}$$

$\bar{\sigma}$ = effective stress

$d\epsilon^P$ = incremental plastic or inelastic strain

For the principal planes the shear stress is zero.

The coefficients P and R must now be used to evaluate the α 's. This can be done by examining Equations (40) and (41) for the plastic potential.

$$\begin{aligned}\alpha_{12} &= \frac{PR}{P(R+1)} & \alpha_{23} &= \frac{R}{P(R+1)} & \alpha_{31} &= \frac{P}{P(R+1)} \\ \alpha_{11} &= \alpha_{12} + \alpha_{31} = \frac{PR}{P(R+1)} + \frac{P}{P(R+1)} = 1 \\ \alpha_{22} &= \alpha_{23} + \alpha_{12} = \frac{R}{P(R+1)} + \frac{PR}{P(R+1)} = \frac{R(1+P)}{P(R+1)} \\ \alpha_{33} &= \alpha_{31} + \alpha_{23} = \frac{P}{P(R+1)} + \frac{R}{P(R+1)} + \frac{P+R}{P(R+1)}\end{aligned}\tag{44}$$

Berman,⁽¹⁾ states that P is usually equal to $R + 1$, therefore, $P = R + 1$ for most ranges. By examining the equations it can be seen that the value of P and R must approach 1.0 for the isotropic case. It can also be seen that these equations degenerate to the standard Von Mises equation and Prandtl-Reuss equation for isotropic behavior when $P = 1$ and $R = 1$.

ANALYTICAL CREEP MODEL

The analytical creep model was developed from published zirconium alloy creep data obtained from both uniaxial stress tests on strip and tubing and biaxial stress tests on a wide range of tube sizes. Much of the creep data used was obtained under biaxial tension stress conditions for Zircaloy-2 tubing.

Two creep equations are used to describe the transient and steady-state creep behavior over a fairly wide range of temperatures in a neutron flux environment. The basis for using two equations is that at the lower temperatures ($\sim 630^\circ\text{K}$), the activation of creep mechanisms is influenced significantly by neutron flux energy as well as by thermal energy. At higher temperatures, the activation of creep mechanisms appears to be predominantly influenced by thermal energy alone. There are some indications that there may be a slight strengthening effect from the neutron flux. For steady-state creep the analytical models are as follows:

- Low temperature range

$$\dot{\epsilon} = B I \phi^n \exp (QI/RT) \sinh (SC I \cdot \sigma)$$

- High temperature range

$$\dot{\epsilon} = B \exp (Q/RT) \sinh (SC \cdot \sigma)$$

where

B = high temperature creep coefficient
BI = low temperature creep coefficient
 ϕ = fast flux - E > MeV
n = fast flux exponent
Q = high temperature activation energy - calories/mole °K
QI = low temperature activation energy
R = universal gas constant
T = temperature °K
 σ = tangential stress - psi
SC = stress coefficient for high temperature range
SCI = stress coefficient for low temperature range

To accommodate the initial loading and any subsequent change in loading, a transient creep model has been included and has the form:

$$\dot{\epsilon}_T = \alpha k \exp(-k\tau) \cdot f(\phi, Q, QI, T, \sigma)$$

where

$\dot{\epsilon}_T$ = transient creep rate - inches/inch hr

For the Zircalloys, the stress dependency does not appear to be a power function with a single-valued exponent. To accommodate a changing exponent, the form, $\sinh(k\sigma)$, is used. The form, $\exp(-Q/RT)$, is used to define temperature dependency. However, as stated previously, neutron flux energies appear to activate creep mechanisms as well as thermal energy. At the lower temperatures, two activation energies are used. The neutron flux dependency takes the form ϕ^n with the exponent n having a single value. For a specified set of conditions, the larger creep equation is always used in calculating the incremental generalized strain component.⁽¹⁰⁾

The code is developed to use a change in creep strain rather than a creep strain rate. This makes it possible to change the code to have an actual path dependence for the material and to include the integrated effects of the transient creep. The equations that have been developed must be integrated with respect to time and then evaluated from time T_1 to time T_2 . This procedure is performed for time steps small enough that the actual change in stress states is approximated as closely as is practical.

The creep equations and coefficients listed in the Appendix are given only to illustrate how the code should work. Those users who wish to use a specific creep law can do so by either specifying the coefficients for the equations or writing their own. As has been indicated the creep rate equations shown are used in an integral form. Therefore those users who write their own subroutine should put it in a form to compute strain increment from time T_1 to time T_2 .

The creep strain equations should be sensitive to the generalized state of stress for a three dimensional stress state. The effects of anisotropy are included in computing both the generalized stress and the incremental flow equations.

INCREMENTAL HARDENING OPTIONS

The analytical hardening options define the means for accommodating the time dependent changes in the stress state in the clad wall. As the tube deflects, the primary hoop stress changes from pure compression to a combination of bending and compression. By using different methods of going from the stress at time 1 to the stress at time 2 an entirely different incremental strain can be computed. Figure 9b compares the strain hardening and time hardening computational methods.

It can be seen in Figure 9b that the summation of incremental strains is significantly greater for the strain hardening option than for the time hardening approach. This is exactly what happens in a problem where the stress state is constantly increasing. The time hardening option tends to

under-predict the resultant strain. For the case of decreasing stress the exact opposite occurs. As the stresses are reduced, the strain hardening option tends to under-predict while the time hardening approach is more realistic.

FIGURE 9b. A Comparison of Strain Hardening and Time Hardening Computational Approaches to Changes in Stress State.

In all cases it should be pointed out that the yield surface or inelastic strain surface is assumed the same for both tension and compression. There is reason to believe that there is a significant difference between the tension-tension quadrant and the compression-compression quadrant for Zircaloy. It should be realized that the effects of the material constitutive law have an overriding influence on the resulting computed results compared to the effect of the mathematical model used.

At present, the experimental data bases for correctly formulating the constitutive laws in the compression quadrant are not available. Until such time that a more generalized law can be developed, symmetry of the yield surface in Quadrants 1 and 3 and Quadrants 2 and 4 will be assumed. The result of this assumption provides a well defined generalized stress strain relationship with no discontinuities.

ALGORITHM DESCRIPTION

The algorithm used in COVE is based on an incremental solution procedure. Using this concept, inelastic changes are computed as small changes to the initial elastic stress state. As time or conditions change, only the incremental value is computed as a correction to the previous stress state. The code logic proceeds in the following manner:

1. Read problem input specifications and interpolate material data for the correct temperature.
2. Compute initial elastic deformation and correction for the finite length. The infinite tube calculation is performed using the closed form solution to the differential equation, with the correction for finite length being applied here.
3. Perform detailed elastic stress calculation.
4. Compute effective stress for all nodal points.
5. For the initial time ($t=0$) print the initial elastic conditions.
6. Compute creep strains for all nodal points based on the effective stress at these points.
7. Using creep strains, compute bending strain profiles for inplane (M_θ) and out-of-plane (M_x) bending. Corrections to the bending stress distributions and creep of the neutral surfaces are also computed. Equations (27) and (28) are used for this calculation.
8. Simultaneous solving for the differential Equations (17c) and (19) using the Numerov approximation shown in Equation (20).
9. Correct the computed deflection results for the finite length approximation and combine in Equations (18) and (19b).
10. Compute bending moment corrections to inplane M_θ and out-of-plane M_x for the finite length.
11. Compute stresses.

12. Compute corrections to the stress states for the inelastic stresses.
13. Compute the rigid body motion or net clad creepdown.
14. Print results.
15. Examine the collapse criteria; if tube has exceeded its criteria the solution is terminated. If not, go on to new time step starting with (3).

CODE EVALUATION AND COMPUTED RESULTS

The numerical features that are available in COVE provide a means of evaluating the states of stress and strain in a tube wall subjected to an external pressure gradient. The evaluation includes the effects of initial geometry and operating history and the effects of temperature on material properties. An estimate of the anisotropy in Zircaloy on the generalized stresses and on the incremental inelastic strains are also made. The capability of the solution procedure in the code is quite general; it is limited however by the availability of data required for supportive model development.

The following set of calculated results provides a basis for selecting the variables needed in the solution. The results indicate sensitivity and optimum ranges for mesh sizes and time steps.

MESH SIZE

Figures 10 and 11 show effect of radial and tangential mesh size on the computed results. The optimum selection for mesh size should include the deflection as well as the computed collapse time. Because the solution uses a finite difference method of analysis, the most accurate result would be one computed with the maximum number of radial and tangential nodes. This of course takes maximum computation time; for long running problems this increase in computation time is significant.

Figure 10 shows that for collapse time, the optimum number of radial segments is 20 with 10 tangential segments. Increasing the radial segments to 45 approximately doubles the computation with very little increase in accuracy. Increasing the number of tangential segments beyond 10 also has little effect on improving the solution.

Figure 11 shows the effect of mesh size on the peak deflection at the start of collapse. By using both these figures it can be seen that for a mesh using 10 tangential segments and 20 radial elements an acceptable result can be determined.

FIGURE 10. Comparison of Collapse Time Vs. Mesh Size

FIGURE 11. Comparison of Maximum Deflection at Yield Condition Vs. Mesh Size for 0.001 In. Initial Ovality Tube

It should be noted that each point for collapse time and deflection in these two figures is based upon an incremental time step of 50 hr. The effect of time step size is shown in Figure 12. This figure is computed for a given set of radial and tangential segments. Changing the mesh size will change the sensitivity to time step size and collapse time. The general trends of time step size and collapse time are similar.

INITIAL OVALITY AND ACTIVE LENGTH

The relationships between collapse time and the controlling geometric variables of the tube are shown in Figure 13. Initial ovality and active length effects are shown to have a dramatic impact on the computed collapse time.

Figure 14 shows the effect on the initial elastic deflection of the active or unsupported length. It can be seen that the effect in terms of deflection is almost completely damped out by 2 in. or 5 diam.

FIGURE 12. The Effect of Time Step Size on Collapse Time

FIGURE 13. The Relationship Between Initial Ovality, Active Length and Collapse Time

FIGURE 14. Active Length Effect on the Initial Elastic Deflection of an Oval Tube

The creep deflections, however, shown in Figures 13 and 15 show a greater dependence upon the active length. This is primarily due to the added effect on the fictitious creep bending moments both in and out of the primary curvature plane. The results of this effect on the nonlinear time-dependent bending moment points up a sensitivity in the solution of the nonlinear problem which cannot be identified from the elastic solution alone. The difference in the comparative results for BUCKLE⁽¹⁰⁾ and COVE point this out. If a comparative creep solution for ANSYS were also to be plotted on Figure 15 it would be above the COVE curve showing a greater sensitivity to the finite length.

Figure 15 compares BUCKLE and COVE for computed collapse. The difference between the results can be explained by the presence of bending moments in COVE not included in BUCKLE. Specifically, BUCKLE neglects the redistribution of the stresses and the out-of-plane nonlinear bending

FIGURE 15. A Comparison of Collapse Time Vs. Active Collapse Length

moments. The results show that the COVE solution is a more rigid solution than BUCKLE but not as rigid as ANSYS would be due to the out-of-plane bending. The results of this dependence are longer computed collapse times and reduced deflections.

Figures 14 and 15 display what initially appears to be conflicting results. Figure 14 shows the elastic deflection for the initial solution. It does not represent the condition of stress or the distribution of bending moments. Figure 14 shows an increasing sensitivity to the finite length for ANSYS and BUCKLE, while the computed collapse times for these codes shown in Figure 15 indicate the opposite effect. The basis for the difference has already been explained; the conclusion that should be reached is that BUCKLE is the most conservative. COVE is consistently more optimistic than BUCKLE but less optimistic than a finite element solution would be. The advantage of this solution as compared to a finite element approach is the detailed analysis and speed of computation.

ANISOTROPY CONSIDERATIONS

The anisotropy present in the material can add significantly to the stiffness of the tube walls. The computational procedures present in the code allow estimating the effects on collapse time and deflections. Figure 16 shows a comparison for a specific set of conditions. It can be seen for the maximum anisotropy condition, an increase of 45% in collapse time results from this effect. It is realized that for the data presently available, the material has some texture effects present. The results of this analysis indicate the importance of evaluating the material in terms of its anisotropy to realize the full mechanical potential.

HARDENING OPTIONS

The results of the different inelastic hardening methods can be seen in Figures 17 and 18. The creep calculations shown earlier in the report are based upon a creep equation with a very small primary term. The results shown in Figures 17 and 18 have a primary term that has been increased to more accurately represent the primary creep data available.

For the case where the primary term was very small, both the time hardening and the strain hardening give very similar results. In the limit as the primary term goes to zero the two methods should compute identically the same results.

CODE LIMITATIONS AND EXTENSIONS

The analytical features included in COVE provide a general solution procedure that can be easily changed by further expansion and improvement. One of the more obvious areas for improvement involves thermal or temperature gradient effects.

The present coding in COVE does not include the thermal gradient in either the stress calculation or creep calculation. The tube is assumed to be at a uniform temperature through the thickness. This means that the creep strains and thermal stress effects due to the thermal gradients are not included. For collapse calculations where densification has removed

FIGURE 16. Anisotropy Considerations for Collapse

or displaced the fuel this is valid. However, for cases where the code is being used to compute creep down onto a fuel pellet, an error is incurred.

To enable this code to compute creep down onto a fuel pellet producing power, two things must be changed. A thermal stress calculation must be performed to compute the correct bending stress state. In addition, the temperature gradient must be used in computing the correct creep strains.

The computational mechanisms needed to compute these items could easily be adapted to the existing procedure. All calculations are evaluated in a nodal point manner, which lends itself very well to this type of calculation.

An area that also has a very significant effect on the solution is the anisotropy and yield surface in the compression quadrant. The present solution takes tension creep data and assumes that it can be used in compression. It is very doubtful if the material responds in the compression quadrant identically to the tension quadrant.

The solution procedure could be expanded to handle general deformed tube shapes. The code could also be expanded to include creep down onto a solid pellet. The general differential solution is quite flexible and could easily handle geometric differences of this type.

FIGURE 17. Collapse Showing Both Time and Strain Hardening Options

FIGURE 18. Typical Displacement Vs. Time Relationship for Strain and Time Hardening Options

The numerical procedure for evaluating the anisotropy and computing the incremental inelastic strain could easily be modified to account for this. All that is needed is basic data tested in the correct manner to expand this capability.

The finite length approximation in COVE has been selected only to indicate the effect of the active length zone. The method provides a quick way of assessing the effect of length. It must be recognized that it is only used as a correction for one incremental step in the total solution. A detailed analysis using a finite element solution with creep, plasticity, and thermal, as well as geometric nonlinearities, would require a tremendous analytical effort. The present method requires only a very modest increase in computation and provides an estimate of the solution. The material data effects have a far greater effect on the solution than any errors in the mechanical finite length approximation.

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APPENDIX A

INPUT INSTRUCTIONS FOR COVE - 1

APPENDIX A

INPUT INSTRUCTIONS FOR COVE -1

The COVE program was written to minimize the amount of required card input. With the exception of the first card which is the title, or problem description card, all of the program variables are read as integer or floating point. Any number of cases can be stacked, but a complete set of data cards must be used for each case. The last card in the input deck must be a STOP in Columns 1 through 4. A description of the data cards with the associated format follows:

A. TITLE CARD

<u>Variable</u>	<u>Format</u>	<u>Column(s)</u>
Any Alphanumeric Information	13A6	1-78

B. DATA CARD 1

<u>Variable Name</u>	<u>Variable Description</u>	<u>Format</u>	<u>Column(s)</u>
RAO	Outside radius of clad, inches	F10.0	1-10
TH	Clad wall thickness, inches	F10.0	11-20
DELTAT	Time steps, hours	F10.0	21-30
TMAX	Maximum time for which iterations are desired, hours	F10.0	31-40
OVAL	Initial ovality of clad, inches	F10.0	41-50
POUT	External pressure on clad, psi	F10.0	51-60
YIELD	Material yield strength, psi (If yield = 0, a value internal to the program will be interpolated based on the clad temperature)	E10.4	61-70

C. DATA CARD 2

Creep Coefficients Card

<u>Coefficient</u>	<u>Format</u>	<u>Column(s)</u>
ALPHA = Transient creep coefficient	F10.0	1-10
TCOEF = Transient creep time coefficient	F10.0	11-21
BETA = High temperature creep equation coefficient	F10.0	21-30
BETAI = Low temperature creep equation coefficient	F10.0	31-40
Q = High temperature activation energy	F10.0	41-50
QIR = Low temperature activation energy	F10.0	51-60
SC = High temperature stress coefficient	F10.0	61-70
SCI = Low temperature stress coefficient	F10.0	71-80

D. DATA CARD 3

<u>Variable Name</u>	<u>Variable Description</u>	<u>Format</u>	<u>Column(s)</u>
XLEN	Length of Collapse zone, inches	F10.0	1-10
CR	Anisotropic Coefficients	F10.0	11-20
CP	Anisotropic Coefficients	F10.0	21-30
NRA	Number of radial segments	15	31-35
NTA	Number of tangential segments	15	36-40
NPI	Tangential node for which stresses will be printed for MINI = 0	15	41-45
MINI	Type of output desired. If MINI < 0 only major time increments with effective and tangential segments MINI = 0 all time steps MINI > 0 all time steps with effective and tangential segments at major time increments (refer to Data Card 4 for time increment information)	15	46-50
NSH	Strain hardening option NSH = 1 for strain hardening NSH = 0 for time hardening	15	51-55
ICFORM	Creep option 0 = PNL 1 = Optional creep law configurations	15	56-60

<u>Variable Name</u>	<u>Variable Description</u>	<u>Format</u>	<u>Column(s)</u>
<u>E. DATA CARD 4</u>			
MATOPT	Material option, if MATOPT = TRUE then material properties as a function of temperature (°F) will be input for Data Cards 8-12. If MATOPT = FALSE, material properties for Zircaloy-2, internal to the program, will be used.	15	1-5
NTEMP	Number of temperatures for which material properties will be input if MATOPT = TRUE, if MATOPT = FALSE, NTEMP = 0	15	6-10
NTIME	Number of tube temperatures as a function of time, internal pressure, and fast flux. Each temperature must have a corresponding time, internal pressure, and fast flux value. (MIN-3, MAX-16)	15	11-15
<u>F. DATA CARD 5 AND 5A (Etc.)</u>			
TINC(I)	Major time increments in hours where temperature, internal pressure, and fast flux values change. Increments must start at 0.0 and end with the value used for maximum time (TMAX). I = NTIME	8(F10.0)	1-80
<u>G. DATA CARD 6 AND 6A</u>			
TEMPI(I)	Clad temperatures corresponding to Data Card 3 and 3A [TINC(I)] I = NTIME	8F10.0	1-80
<u>H. DATA CARD 7 AND 7A</u>			
PRESI(I)	Internal pressure corresponding to Data Card 3 and 3A [TINC(I)] I = NTIME	8F10.0	1-80
<u>I. DATA CARD 8 AND 8A</u>			
FLUX(I)	Fast Flux corresponding to Data Card 3 and 3A [TINC(I)] I = NTIME	8F10.0	1-80
NOTE: The following cards are required only if MATOPT=TRUE on Data Card 3			

<u>Variable Name</u>	<u>Variable Description</u>	<u>Format</u>	<u>Column(s)</u>
J. <u>DATA CARD 9</u>			
TF(I)	Temperatures for which clad material properties will correspond (MAX-16) I = NTEMP	8F10.0	1-80
K. <u>DATA CARD 10</u>			
PMAT(1,I)	Elastic moduli for temperature on Data Card 8 (I = NTEMP)	8F10.0	1-80
L. <u>DATA CARD 11</u>			
PMAT(2,I)	Poisson Ratio for temperature on Data Card 8 (I = NTEMP)	8F10.0	1-80
M. <u>DATA CARD 12</u>			
PMAT(3,I)	Material yield strength for tem- perature on Data Card 8 (I = NTEMP)	8F10.0	1-80

APPENDIX B

CODE LISTING

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*COMPLEX CONVECON
COMMON/AA/AN(25),RMC(25),ALPHA(10,10),DTHSG,DELTH,E,PCR
COMMON//PIN,POUT,RM,TH,SIGFT(50,25),SIGFR(50,25)
+PR,S(50,25,4),RAOVAL
COMMON/CC/DEPT(50,25,4),SE(50,25)
COMMON/CD/TIME(500),TEMP,OV,CRATE(50,25),CSTRN(50,25),
+BETA,TEMP
COMMON/EE/PAO,DELTAT,TMAX,YIELD,FFLUX,MINI,
+MATOPT,NTMP,NTIME,TINC(15),TEMP(16),
+PRESI(16),WORD1,TITLE(13),TF(16),MATP(3,16),M,TEMPK(16),
+OVAL,PROVALS,FLUX(16),XLEN,NPI,NPJ,PRR(16),YMM(16),YLD(16)
+PMAT(3,16)
COMMON/EE/NTA,NRA/R/BAR(50)
+NSH
COMMON/H/BR(25),AB(25,25)/R/RC(25),AC(25,25)
COMMON/CR/CP/ MC(25),Z(25),CSTRN(50,25),
+DCRP(50,25),ACRP(25),CORST(50,25),Y(25)
COMMON/XNEW/JO(25),U(25),SIGMA(50,25)
COMMON/L/U(25),RM(25),V(25),TEMPM(16),R(25),RR(27),DTH
COMMON/UJ/CRPG(50,25),CRPH(50,25),CRPX(50,25)
COMMON/PROP/CP,CR,D
COMMON/FL/RT,COR,CORP,CORX,DSAX(50,25),BMCY(25),DCRY(50,25),
+ACRY(25),CRSTY(50,25)
COMMON/FLS/TRY(50,25),SIGAX(50,25)
COMMON/CRP/DETI,BET,G,QIR,ALPHA,TCCEF,SC,SCI
REAL MC,MATP
LOGICAL MATOPT
END

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A 1
A 2
A 3
A 4
A 5
A 6
A 7
A 8
A 9
A 10
A 11
A 12
A 13
A 14
A 15
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A 22
A 23
A 24
A 25
A 26
A 27
A 28

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*DECK COVE
PROGRAM COVE (INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
C *****
C *** UNITS ***
C LENGTH=INCHES
C STRAIN=INCHES PER INCH
C ANGLE=RADIANS
C TIME = HOURS
C TEMPERATURE = DEGREES KELVIN
C FORCE=POUNDS
C MOMENT=INCH PER POUND
C PRESSURE = PSIG
C STRESS = PSI
C
C *** VARIABLE DEFINITIONS ***
C YIELD = YIELD STRENGTH, PSI
C BMO = BENDING MOMENT AT THETA *PI/2, WHERE N=0,1,2,3 OR 4 INCH-LBS
C DTHSG = DELTA THETA SQUARED
C BM(I) = BENDING MOMENT AT ANY THETA VALUE, INCH-LBS
C RM = MEAN TUBE RADIUS, INCHES
C OV = RADIAL DEFLECTION OF TUBE WALL, INCHES
C POUT = EXTERNAL PRESSURE, PSIG
C V(I) = RADIAL DISPLACEMENT OF TUBE WALL AT ANY THETA
C TH = 2 * THETA , RADIANS
C RHO(I) = MEAN RADIUS OF CURVATURE OF THE DEFORMED TUBE, INCHES
C TH = TUBE WALL THICKNESS, INCHES
C T = TIME IN HOURS
C DELTAT = TIME INCREMENT, HOURS
C RAI = INSIDE TUBE RADIUS, INCHES
C RAO = EXTERNAL TUBE RADIUS, INCHES
C R(I) = TUBE RADIUS OF ANY THETA
C RO = RADIUS OF CURVATURE FOR THE EXTERNAL SURFACE, INCHES
C RI = RADIUS OF CURVATURE FOR THE INTERNAL SURFACE, INCHES
C RR = RADIUS OF CURVATURE AT ANY RADIUS, INCHES
C U(I) = INCREMENTAL RADIAL DISPLACEMENT DUE TO CREEP
C DP = DEFORMATION PARAMETER
C DPMAX = MAXIMUM INCREMENTAL CHANGE ALLOWED FOR DP
C ALPHA(I,J) = VALUE OF THE ALPHA STAR MATRIX
C
C SIGFT(I,J) = TANGENTIAL FLEXURE STRESS, PSI
C SIGFR(I,J) = RADIAL FLEXURE STRESS, PSI
C S(I,J,K) = STEP MATRIX WHERE I=RADIAL INCREMENT
C J=ANGULAR INCREMENT
C K=1 CORRESPONDS TO THE RADIAL STRESS
C K=2 CORRESPONDS TO THE TANG. STRESS
C K=3 CORRESPONDS TO THE AXIAL STRESS
C K=4 CORRESPONDS TO THE SHEAR STRESS
C
C SE(I,J) = THE EFFECTIVE STRESS FOR A MULTIAXIAL STRESS STATE, PSI
C DEPT(I,J,K) = INCREMENTAL CREEP STRAIN
C CRATE = EFFECTIVE CREEP RATE , INCH/INCH
C CSTRN(I,J) = ACCUMULATED TANGENTIAL CREEP STRAIN
C AN(I) = RADIAL DISPLACEMENT PARAMETER
C INPUT
C DELTH = INCREMENTAL RADIAL THICKNESS
C NRA = NUMBER OF RADIAL SEGMENTS
C NTA = NUMBER OF TANGENTIAL SEGMENTS
C NSH = 0 FOR TIME HARDENING OPTION AND = 1 FOR STRAIN HARDENING OPT

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B 1
B 2
B 3
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B 56

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	CALL CFEEND	B 231
	CALL CFLEND	B 232
C	NOW SOLVE THE PROBLEM - NOTE THAT FOR THE FIRST	B 233
C	INCREMENTAL SOLUTION UO IS THE ORIGINAL DUALITY	B 234
C	THE COEF. MATRIX WILL BE HANDLED THEREFORE A	B 235
C	BANDID SOLUTION TECHNIQUE WILL BE USED.	B 236
C	NOW CREATE THE FIRST COEF. MATRIX	B 237
C	WE WILL USE A GAUSS ELIMINATION SOLUTION ROUTINE	B 238
C	NOTE - FOR USE ON IBM OR UNIVAC THIS CAN BE CHANGED TO	B 239
C	DOUBLE PRECISION	B 240
C	NOW SETUP AND SOLVE THE TOTAL PROBLEM	B 241
C	INPUT COEF. MATRIX IS A	B 242
	DO 160 I=1,N	B 243
	BB(I)=0.0	B 244
	DO 160 J=1,N	B 245
	AB(I,J)=0.0	B 246
160	CONTINUE	B 247
	H=OTHS4	B 248
	DO 170 I=1,N	B 249
	DO 170 J=1,N	B 250
	IF (I.EQ.1) AB(I,J)=-(2.-10./12.*H*(1.+10.*S+4.*S**3/12.*H)	B 251
	IF (J.EQ.1-1) AB(I,J)=(1.+(1.+10.*S+4.*S**3/12.*H)	B 252
	IF (J.EQ.1-1) AB(I,J)=(1.+(1.+10.*S+4.*S**3/12.*H)	B 253
	IF (I.EQ.1.AND.J.EQ.2) AB(1,2)=2.*(1.+(1.+10.*S+4.*S**3/12.*H)	B 254
	IF (I.EQ.N.AND.J.EQ.N-1) AB(I,J)=2.*(1.+(1.+10.*S+4.*S**3/12.*H)	B 255
170	CONTINUE	B 256
C	HAVE CREATED THE COEF. MATRIX	B 257
C	NOW CREATE THE VECTOR RB	B 258
	DO 180 J=1,N	B 259
	MC(J)=MC(J)	B 260
	RB(J)=-(PRES*RM**3/D)*UO(J)*H+(MC(J)*RM**2/D)*H	B 261
180	CONTINUE	B 262
	KS=0	B 263
	KX=N*N	B 264
	DO 190 I=1,NK	B 265
	AAAA(I)=0.0	B 266
190	CONTINUE	B 267
	DO 200 J=1,N	B 268
	DO 200 I=1,N	B 269
	K=(J-1)*N+I	B 270
	AAAA(K)=AB(I,J)	B 271
200	CONTINUE	B 272
	CALL SING (AAAA,BB,N,KS)	B 273
C	WE NOW HAVE SOLUTION BB	B 274
C	NOW CREATE THE LIMITED CREEP SOLUTION ARRAY	B 275
	DO 210 I=1,N	B 276
	BC(I)=0.0	B 277
	DO 210 J=1,N	B 278
	AC(I,J)=0.0	B 279
210	CONTINUE	B 280
	DO 220 I=1,N	B 281
	DO 220 J=1,N	B 282
	IF (I.EQ.J) AC(I,J)=-(2.-10./12.*H)	B 283
	IF (J.EQ.1-1) AC(I,J)=(1.+1./12.*H)	B 284
	IF (J.EQ.1+1) AC(I,J)=(1.+1./12.*H)	B 285
	IF (I.EQ.1.AND.J.EQ.2) AC(1,2)=2.*(1.+1./12.*H)	B 286
	IF (I.EQ.N.AND.J.EQ.N-1) AC(I,J)=2.*(1.+1./12.*H)	B 287
220	CONTINUE	B 288
C	HAVE NOW COMPUTED THE CREEP SOLUTION ARRAY	B 289
C	NOW COMPUTE THE LOAD VECTOR	B 290
	DO 230 J=1,N	B 291
	BC(J)=(MC(J)*RM**2/D)*H	B 292
230	CONTINUE	B 293
	DO 240 I=1,NK	B 294
	AAAA(I)=0.0	B 295
240	CONTINUE	B 296
	DO 250 J=1,N	B 297
	DO 250 I=1,N	B 298
	K=(J-1)*N+I	B 299
	AAAA(K)=AC(I,J)	B 300
250	CONTINUE	B 301
	CALL SING (AAAA,BC,N,KS)	B 302
C	NOW HAVE PLASTIC DEFORMATION DUE TO CREEP	B 303
	DO 260 J=1,N	B 304
	UJ(J)=RB(J)*COR*JO(J)	B 305
	UO(J)=LO(J)*COR*BC(J)	B 306
	RJ(J)=RM*UJ(J)	B 307
260	CONTINUE	B 308
C	NOW COMPUTE THE BENDING MOMENT	B 309
	DO 270 I=1,N	B 310
	BM(I)=-PRES*RM*UJ(I)	B 311
	BM(I)=BM(I)*CORM	B 312
270	CONTINUE	B 313
	CALL CURVE	B 314
	CALL PRESS (PO,PI)	B 315
	CALL BEND	B 316
	CALL SIGMAZ (PO,PI)	B 317

C	NOW CORRECT THE FLEXURE STRESS DISTRIBUTION	B 318
C	FOR THE INELASTIC CREEP BEHAVIOR	B 319
	DO 280 I=1,N	B 320
	DO 280 J=1,N	B 321
	TCRP(J,I)=TCRP(J,I)+CORST(J,I)	B 322
	SIGMA(J,I)=E/(1.-PR**2)*TCRP(J,I)	B 323
	TRY(J,I)=TRY(J,I)+CRSTY(J,I)	B 324
	SIGAX(J,I)=E/(1.-PR**2)*TRY(J,I)	B 325
280	CONTINUE	B 326
C	COMBINE STRESS VECTOR AFTER CURRENT CREEP ITERATION	B 327
	DO 290 I=1,N	B 328
	DO 290 J=1,N	B 329
	S(J,I,3)=S(J,I,3)+SIGAX(J,I)	B 330
	S(J,I,2)=S(J,I,2)+SIGMA(J,I)	B 331
	S(J,I,1)=S(J,I,1)+SIGFR(J,I)	B 332
	S(J,I,2)=S(J,I,2)+SIGFT(J,I)	B 333
290	CONTINUE	B 334
C	WE NOW HAVE THE NEW STRESS DISTRIBUTION	B 335
	CALL SHEAR	B 336
	CALL EFFECT	B 337
C	NOW CALCULATE THE NET RIDGE BODY MOTION INVOLVED	B 338
C		B 339
C	THIS CAN BEST BE DONE BY INTEGRATING ALONG THE SEGMENT	B 340
C		B 341
C	SO USING THE TRAPEZOIDAL RULE FOR INTEGRATION	B 342
C		B 343
	NM=N*2	B 344
	SUM=0.	B 345
	SSM=0.	B 346
	DO 300 I=1,NM*2	B 347
	SUM=1./2.*(ACRP(I)+2.*ACRP(I+1)*ACRP(I+2))	B 348
	SSM=SSM+SUM	B 349
300	CONTINUE	B 350
	AVE=SSM/FLOAT(NTA)	B 351
C		B 352
C	CALCULATION OF THE GENERALIZED PLASTIC STRAIN - NOTE THAT	B 353
C	THIS IS COMPUTED UPON THE INCREMENTAL FORM OF THE GENERALIZED	B 354
C	STRAIN USING X ORIENTATION FOR THE ANISOTROPY COEFFICIENTS.	B 355
C		B 356
	IF (NSH.EQ.0) GO TO 320	B 357
	CONC=CR/(CR+1.0)	B 358
	CTWO=CR/CP*(CR+1.0)	B 359
	CTHR=1.0/(CR+1.0)	B 360
	GE=CONC*CTWO*CTWO*CTHR*CTHR*CONC	B 361
C		B 362
C	COMPUTE INCREMENTAL VALUE OF STRAIN	B 363
C		B 364
	DO 310 I=1,N	B 365
	DO 310 J=1,N	B 366
	CRHO=CRP(J,I)	B 367
	CRAX=CRPX(J,I)	B 368
	CRRA=-(CRHO*CRAX)	B 369
	DEPE=((1.0/GE)*(CONC*(CTWO*CRAX-CTHR*CRHO)**2+CTWO*(CTHR*CRHO-CONC	B 370
	+*CRRA)**2+CTHR*(CONC*CRRA-CTWO*CRAX)**2)**0.5	B 371
	CRPG(J,I)=CRPG(J,I)+DEPE	B 372
310	CONTINUE	B 373
320	CONTINUE	B 374
C		B 375
C	THE CHANGE IN RADIUS	B 376
C		B 377
	RNEW=RM+AVE	B 378
	RM=RM+RNEW	B 379
	DO 330 I=1,N	B 380
	R(I)=R(I)+RNEW	B 381
330	CONTINUE	B 382
	VTEMP=OV	B 383
C	CALCULATE NEW OVALITY	B 384
	OVALS=(R(1)-R(N))*2.	B 385
	OV=(R(NTA+1)-R(1))/2.	B 386
	M=M+1	B 387
	IF (TIME(M).GE.TMAX) GO TO 340	B 388
	IF (ABS(S(M,N,2)).GE.YIELD) GO TO 350	B 389
	IF (OVALS.GE.RAOVAL) GO TO 360	B 390
	IF (MINI.LT.0) CALL OUTTAB	B 391
	IF (MINI.EQ.0) CALL OUTPUT	B 392
	IF (MINI.GT.0) CALL OPTUT	B 393
C	RESET TIME TO LAST STEP AND RECYCLE CALCULATIONS FOR CREEP	B 394
C	DEFORMATIONS	B 395
	GO TO 300	B 396
340	WRITE (6,340)	B 397
	GO TO 10	B 398
350	WRITE (6,390)	B 399
	GO TO 10	B 400
360	WRITE (6,400)	B 401
	GO TO 10	B 402
370	STOP	B 403
C		B 404
380	FORMAT (////,' TIME EXCEEDS MAX TIME. EXECUTION TERMINATED.')	B 405
390	FORMAT (//2X,'TANGENTIAL STRESS EXCEEDS YIELD STRENGTH',)	B 406
400	FORMAT (//2X,'OVALITY EXCEEDS CLAD RADIUS LIMITS',)	B 407
	END	B 408

*DECK CREAND	C	1
SUBROUTINE CREAND	C	2
*CALL COVECOM	C	3
C CALCULATE THE NEW VALUES OF Z	C	4
N=NTA+1	C	5
NNNS=NTA+1	C	6
DO 10 I=1,NNNS	C	7
Z(I)=-1.+(RHO(I)/TH)*ALOG((RHO(I)+TH/2.)/(RHO(I)-TH/2.))	C	8
10 CONTINUE	C	9
C USE CREEP STRAIN VECTOR DEPT(J,I,2)	C	10
C WHERE J IS THE RADIAL I IS THE TANGENTIAL	C	11
NN=NRA+1	C	12
NNS=NN-5	C	13
DO 20 I=1,N	C	14
MC(I)=0.	C	15
20 CONTINUE	C	16
DO 40 J=1,N	C	17
CCC=0.	C	18
CD=0.	C	19
DO 30 J=1,NNS+5	C	20
CCC=19.*DSTRN(J,I)*BAR(J)+75.*DSTRN(J+1,I)*BAR(J+1)+50.*DSTRN(J+2,	C	21
+I)*BAR(J+2)+50.*DSTRN(J+3,I)*BAR(J+3)+75.*DSTRN(J+4,I)*BAR(J+4)+19	C	22
+.*DSTRN(J+5,I)*BAR(J+5)	C	23
CD=CD+CCC*5.*DELTH/258.	C	24
30 CONTINUE	C	25
MC(I)=CD*E/(1+PR**2)	C	26
40 CONTINUE	C	27
C HAVE NOW CALCULATED THE INCREMENTAL BENDING MOMENT	C	28
C	C	29
C NOW CALCULATE THE EQUIVALENT STRAIN PROFILE	C	30
DO 50 I=1,N	C	31
DO 50 J=1,NN	C	32
DCRP(J,I)=MC(I)*BAR(J)/D	C	33
50 CONTINUE	C	34
C NOTE THAT THESE ARE COMPUTED AT ELEMENT MIDPOINTS	C	35
C NOW SOLVE THE PROBLEM	C	36
C CALCULATE THE SHIFT IN THE NEUTRAL SURFACE AND	C	37
C CALCULATE THE CREEP ON THE NEUTRAL SURFACE	C	38
DO 60 I=1,N	C	39
Y(I)=-Z(I)*R(I)/(Z(I)+1.)	C	40
60 CONTINUE	C	41
DO 80 I=1,N	C	42
CN=0.	C	43
CS=0.	C	44
DO 70 J=1,NNS+5	C	45
CN=19.*DSTRN(J,I)+75.*DSTRN(J+1,I)+50.*DSTRN(J+2,I)+50.*DSTRN(J+3,	C	46
+I)+75.*DSTRN(J+4,I)+19.*DSTRN(J+5,I)	C	47
CS=CS+CN*5.*DELTH/258.	C	48
70 CONTINUE	C	49
ACRP(I)=CS/TH	C	50
80 CONTINUE	C	51
DO 90 I=1,N	C	52
DO 90 J=1,NN	C	53
COPST(J,I)=DCRP(J,I)+ACRP(I)-DSTRN(J,I)	C	54
CRPH(J,I)=DCRP(J,I)+ACRP(I)	C	55
90 CONTINUE	C	56
RETURN	C	57
END	C	58


```

*DECK CFLAND
SUBROUTINE CFLAND
CALL COMCOM
N=NTA+1
NN=NRA+1
NNS=NN-5
DO 10 I=1,N
BMCY(I)=0.0
10 CONTINUE
DO 30 I=1,N
CCC=0.0
CD=0.0
DO 20 J=1,NNS,5
CCC=19.*DSAX(J,I)+34.*DSAX(J+1,I)+75.*DSAX(J+2,I)+50.*DSAX(J+3,I)+
+BAR(J+2)+50.*DSAX(J+3,I)+84.*DSAX(J+4,I)+19.*DSAX(J+5,I)+
+X(J+5,I)*BAR(J+5)
CD=CD+CCC*5.*DELTH/218.
20 CONTINUE
BMCY(I)=CD*E/(1-PR**2)
30 CONTINUE
C HAVE NOW COMPUTED THE INCREMENTAL BENDING MOMENT FOR OUT OF PLANE
C AT THE CENTER OF THE OF THE LONGITUDINAL SPAN
C NOW CALCULATE THE EQUIVALENT STRAIN PROFILE
DO 40 I=1,N
DO 40 J=1,NN
DCRY(J,I)=BMCY(I)*34*(J)/D
40 CONTINUE
C NOW COMPUTE THE AVERAGE STRAIN
DO 60 I=1,N
CN=0.0
CS=0.0
DO 50 J=1,NNS,5
CN=19.*DSAX(J,I)+75.*DSAX(J+1,I)+50.*DSAX(J+2,I)+50.*DSAX(J+3,I)+7
+5.*DSAX(J+4,I)+19.*DSAX(J+5,I)
CS=CS+CN*5.0*DELTH/218.
50 CONTINUE
ACRY(I)=CS/TH
60 CONTINUE
DO 70 I=1,N
DO 70 J=1,NN
CRSTY(J,I)=ACRY(I)+DCRY(J,I)-DSAX(J,I)
CRPX(J,I)=ACRY(I)+JCRY(J,I)
70 CONTINUE
RETURN
END

```

```

*DECK INPUT
SUBROUTINE INPUT
C TINC= TIME INCREMENTS , HOURS
C TEMPI = TEMPERATURE INCREMENTS, DEG F
C PRESI = CLAD INTERVAL PRESSURE INCREMENTS PSI
C MATOPT= MATERIALS OPTION, IF TRUE MATERIAL PROPERTIES AS A
C FUNCTION OF TEMPERATURE WILL BE INPUT FOLLOWING THE
C PRESI CARDS, IF FALSE MATERIAL PROPERTIES FOR ZR-2,
C INTERNAL TO THE PROGRAM WILL BE USED.
C NTEMP= NUMBER OF TEMPERATURES FOR MATOPT = TRUE
CALL COMCOM
DATA WORD1/6HSTOP /
C READ TITLE
READ (5,40) (TITLE(I),I=1,13)
IF (TITLE(1).EQ.WORD1) GO TO 20
READ (5,50) RAD,TH,DELTAT,TMAX,OVAL,POUT,YIELD
READ (5,80) ALPHA,CDEF,BET,BETI,G,GIR,SC,SCI
READ (5,30) XLEN,C,CP,NRA,NTA,NPI,MINI,NSH
READ (5,60) MATOPT,NTEMP,NTIME
READ (5,70) (TINC(I),I=1,NTIME)
READ (5,70) (TEMP(I),I=1,NTIME)
READ (5,70) (PRESI(I),I=1,NTIME)
READ (5,70) (FLUX(I),I=1,NTIME)
C NTIME=NUMBER OF VALUES FOR TINC, TEMPI, AND PRESI (MAX=16,-
C MIN=3)
IF (.NOT.MATOPT) GO TO 10
IF TEMPERATURE NODES FOR MATERIAL PROPERTIES (MAX=641
READ (5,70) (T=(I),I=1,NTEMP)
C NEW MATERIAL PROPERTIES
READ (5,70) (MATP(1,I),I=1,NTEMP)
READ (5,70) (MATP(2,I),I=1,NTEMP)
READ (5,70) (MATP(3,I),I=1,NTEMP)
10 IF (.NOT.MATOPT) NTEMP=5
RETURN
20 STOP

```

```

C      CHECK SING
C      SUBROUTINE SING (A,B,N,KS)
C
C      PURPOSE
C      OBTAIN SOLUTION OF A SET OF SIMULTANEOUS LINEAR EQUATIONS,
C      AX=B
C
C      USAGE
C      CALL SING(A,B,N,KS)
C
C      DESCRIPTION OF PARAMETERS
C      A = MATRIX OF COEFFICIENTS STORED COLUMNWISE. THESE ARE
C      DESTROYED IN THE COMPUTATION. THE SIZE OF MATRIX A IS
C      N BY N.
C      B = VECTOR OF ORIGINAL CONSTANTS (LENGTH N). THESE ARE
C      REPLACED BY FINAL SOLUTION VALUES, VECTOR X.
C      N = NUMBER OF EQUATIONS AND VARIABLES, N MUST BE > 0, ONE.
C      KS = OUTPUT DIGIT
C      0 FOR A NORMAL SOLUTION
C      1 FOR A SINGULAR SET OF EQUATIONS
C
C      REMARKS
C      MATRIX A MUST BE GENERAL.
C      IF MATRIX IS SINGULAR, SOLUTION VALUES ARE MEANINGLESS.
C      AN ALTERNATIVE SOLUTION MAY BE OBTAINED BY USING MATRIX
C      INVERSION (MINV) AND MATRIX PRODUCT (GNPRD).
C
C      SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED
C      NONE
C
C      METHOD
C      METHOD OF SOLUTION IS BY ELIMINATION USING LARGEST PIVOTAL
C      DIVISOR. EACH STAGE OF ELIMINATION CONSISTS OF INTERCHANGING
C      ROWS WHEN NECESSARY TO AVOID DIVISION BY ZERO OR SMALL
C      ELEMENTS.
C      THE FORWARD SOLUTION TO OBTAIN VARIABLE N IS DONE IN
C      N STAGES. THE BACK SOLUTION FOR THE OTHER VARIABLES IS
C      CALCULATED BY SUCCESSIVE SUBSTITUTIONS. FINAL SOLUTION
C      VALUES ARE DEVELOPED IN VECTOR B, WITH VARIABLE 1 IN B(1),
C      VARIABLE 2 IN B(2),....., VARIABLE N IN B(N).
C      IF NO PIVOT CAN BE FOUND EXCEEDING A TOLERANCE OF 0.0,
C      THE MATRIX IS CONSIDERED SINGULAR AND KS IS SET TO 1. THIS
C      TOLERANCE CAN BE MODIFIED BY REPLACING THE FIRST STATEMENT,
C
C      .....
C
C      DIMENSION A(1),B(1)
C
C      FORWARD SOLUTION
C
C      TOL=0.0
C      KS=0
C      JJ=-N
C      DO 80 J=1,N
C      JY=J+1
C      JJ=JJ+N+1
C      BIGA=0
C      IT=JJ-J
C      DO 20 I=J,N
C
C          SEARCH FOR MAXIMUM COEFFICIENT IN COLUMN
C
C      IJ=IT+1
C      IF (ABS(BIGA)-ABS(A(IJ))) 10,20,20
C10  BIGA=A(IJ)
C      IMAX=I
C20  CONTINUE
C
C      TEST FOR PIVOT LESS THAN TOLERANCE (SINGULAR MATRIX)
C
C      IF (ABS(BIGA)-TOL) 30,30,40
C30  KS=1
C      RETURN
C
C      INTERCHANGE ROWS IF NECESSARY
C
C40  I1=J+N*(J-2)
C      IT=IMAX-J
C      DO 50 K=J,N
C      I1=I1+N
C      I2=I1+IT
C      SAVE=A(I1)
C      A(I1)=A(I2)
C      A(I2)=SAVE
C
C      DIVIDE EQUATION BY LEADING COEFFICIENT
C
C50  A(I1)=A(I1)/BIGA
C      SAVE=B(IMAX)
C      B(IMAX)=B(J)
C      B(J)=SAVE/BIGA

```

C		H	92
C	ELIMINATE NEXT VARIABLE	H	93
C		H	94
	IF (J=N) 60,90,60	H	95
60	IGS=N*(J-1)	H	96
	DO 60 IX=JY,N	H	97
	IXJ=IGS+IX	H	98
	IT=J-IX	H	99
	DO 70 JX=JY,N	H	100
	IXJX=N*(JX-1)+IX	H	101
	JJX=IXJX+IT	H	102
70	A(IX,X)=A(IXJX)-(A(IXJ)*A(JJX))	H	103
80	B(IX)=B(IX)-(B(J)*A(IXJ))	H	104
C		H	105
C	BACK SOLUTION	H	106
C		H	107
90	NY=N-1	H	108
	IT=N*N	H	109
	DO 100 J=1,NY	H	110
	IA=IT-J	H	111
	IB=N-J	H	112
	IC=N	H	113
	DO 100 K=1,J	H	114
	B(IB)=B(IB)-A(IA)*B(IC)	H	115
	IA=IA-N	H	116
100	IC=IC-1	H	117
	RETURN	H	118
	END	H	119

*DECK	OPTUT	I	1
	SUBROUTINE OPTJT	I	2
*CALL	COVECOM	I	3
	KJ=NRA+1	I	4
	KI=NTA+1	I	5
	NPU=1	I	6
	IF (TIME(4),GT.1) GO TO 20	I	7
	WRITE (6,90) (TITLE(I),I=1,13)	I	8
	WRITE (6,140) RAO,TH,DELTAT,TMAX,OVAL,POUT,CR,CP,XLEN,PCR,MATOPT,N	I	9
	TEMP=TIME	I	10
	WRITE (6,150) NPJ,KJ,NPI,NRA,NTA,MINI	I	11
	IF (NSH,E3,0) GO TO 10	I	12
	WRITE (6,70)	I	13
10	CONTINUE	I	14
	IF (NSH,E3,0) WRITE (6,80)	I	15
	WRITE (6,100)	I	16
	WRITE (6,110) (TEMPK(I),PRR(I),TEMPK(I),YMM(I),TEMPK(I),YLD(I),I=1	I	17
	+ ,NTEMP)	I	18
	WRITE (6,120)	I	19
	WRITE (6,130) (TINC(I),FLUX(I),I=1,NTIME)	I	20
	WRITE (6,160) NPJ,NPI,KJ,NPI	I	21
20	CONTINUE	I	22
	WRITE (6,170) TIME(M),PIN,TEMP,OVALS,RM,S(1,K1,2),S(KJ,K1,2),SE(I,	I	23
	+KI),SE(KJ,K1)	I	24
	DO 30 I=1,NTIME	I	25
	IF (TIME(M),EQ,TINC(I)) GO TO 40	I	26
	IF (ABS(S(KJ,K1,2)),GE,YIELD) GO TO 40	I	27
	IF (CVALS,GE,RAOVAL) GO TO 40	I	28
30	CONTINUE	I	29
	RETURN	I	30
40	CONTINUE	I	31
	K1=1	I	32
	K2=.25*NTA+1	I	33
	K3=.50*NTA+1	I	34
	K4=.75*NTA+1	I	35
	K5=KI	I	36
	WRITE (6,180) <1,K2,K3,K4,K5	I	37
	DO 50 J=1,KJ	I	38
	WRITE (6,190) J,S(J,K1,2),S(J,K2,2),S(J,K3,2),S(J,K4,2),S(J,K5,2)	I	39
50	CONTINUE	I	40
	WRITE (6,200) <1,K2,K3,K4,K5	I	41
	DO 60 J=1,KJ	I	42
	WRITE (6,190) J,SE(J,K1),SE(J,K2),SE(J,K3),SE(J,K4),SE(J,K5)	I	43
60	CONTINUE	I	44
	WRITE (6,210)	I	45
	RETURN	I	46

```

C 70 FORMAT (///,10X,'STRAIN HARDENING OPTION IS USED IN THIS CALCULATION',/
+N',//)
80 FORMAT (10X,'TIME HARDENING OPTION USED IN THIS CALCULATION',/)
90 FORMAT (1H1,//////,13A6)
100 FORMAT (//,10X,'POISSONS RATIO',10X,'YOUNGS MODULUS',25X,'YIELD ST
+RENGTH',10X,'TEMP. VALUE',25X,'TEMP. VALUE',25X,'TEMP. VAL
+UE',/)
110 FORMAT (3(1X,F7.1,3X,E10.4,10X))
120 FORMAT (/1 X,'FAST FLUX',10X,'TIME VALUE',/)
130 FORMAT (1X,F7.1,3X,E10.4)
140 FORMAT (20X,///,30X,'.....',//,30X,'* SUMMARY OF
+ INPUT DATA *',//,30X,'.....',//,10X,'CLADDING
+RADIUS',25X,' RAD',2X,F10.5,2X,' INCHES',10X,'CLAD WALL THICKNESS'
+,20X,' TH',2X,F10.5,2X,' INCHES',10X,'TIME INCREMENTS',24X,'DEL
+TAT',2X,F10.2,2X,' HOURS',10X,'MAXIMUM OPERATING TIME',19X,'TMAX',
+2X,F10.2,2X,' HOURS',10X,'INITIAL OVALITY',25X,'OVAL',2X,F10.6,2X,
+,' INCHES',10X,'CLADDING EXTERNAL PRESSURE',15X,'POUT',2X,F10.2,2X,
+,' PSI',10X,'THE ANISOTROPIC PROPERTIES',17X,'CR',2X,F10.4,10X,'53X',C
+,'P',2X,F10.4,10X,'EFFECTIVE SECTION LENGTH',15X,' XLEN',2X,F10.2,
+2X,' INCHES',10X,'ELASTIC COLLAPSE PRESSURE',17X,'PCR',2X,F10.2,2X
+,' PSI',10X,'MATERIAL PROPERTIES TRUE PROPERTIES INPUT',10X,'
+ FALSE PROPERTIES INTERNAL TO',10X,'
+ PROGRAM ',10X,'MATERIAL',2X,LS,10X,'NUMBER OF TEMP. NODES FOR MAT
+, PROP. NTEMP',2X,15,10X,'NUMBER OF TIME STEPS MAX=16',10X,'
+ MIM=3',13X,'NTIME',2X,15,/)
150 FORMAT (10X,'NODES TO BE PRINTED NPOJ,1',16X,'J=',2X,15,'',15,/,
+53X,'I=',2X,15,10X,'NUMBER OF RADIAL SEGMENTS',17X,'NRA',2X,15,/,1
+0X,'NUMBER OF RADIAL TANGENTIAL SEGMENTS',6X,'NTA',2X,15,10X,'VAL
+UE OF NINI FOR OUTPUT OPTIONS',9X,'NINI',2X,15,/)
160 FORMAT (1H1,5X,'TIME INTERNAL CLADDING OVALITY MEA
+N TAN STRESS TANG STRS EFFECTIVE EFFECTIVE',15X,'(HOURS)
+ PRESS. WALL TEMP. (IN.) RADIUS ID SURFACE OD
+ SURFACE STRESS ID STRESS OD',17X,'(PSI) (DEG. F)',15X,' J
+ DECREASE NODE NO. NODE NO. (PSI) (PSI)',163X,'J=',1
+2,2X,'I=',12,1X,'J=',12,3X,'I=',12,6X,'(J,1)',5X,'(J,1)',/)
170 FORMAT (3(2X,F10.2),2X,F10.5,5(2X,E10.4),/)
180 FORMAT (//,15X,' TANGENTIAL STRESS SEGMENTS',//,17X,'I=',
+12,10X,'I=',13,9X,'I=',13,9X,'I=',13,9X,'I=',13,/)
190 FORMAT (5X,'J=',13,5(2X,E12.4))
200 FORMAT (//,15X,'EFFECTIVE STRESS SEGMENTS',//,17X,'I=',12,9X,'I=',1
+3,9X,'I=',13,9X,'I=',13,9X,'I=',13,/)
210 FORMAT (/)
END

```

```

*DECK RATE
SUBROUTINE RATE
*CALL COVECOM
DIMENSION CLOW(2),CHGH(2)
C GAS = UNIVERSAL GAS CONSTANT, CAL/MOLE-DEG F
GAS=1.987
NN=NRA+1
N=NTA+1
C
C STRAIN HARDENING OPTION DECISION POINT
C STRAIN HARDENING OPTION VARIABLE = NSH
C NSH = 1 MEANS THE STRAIN HARDENING OPTION IS USED
C
IF (NSH,EQ,1.AND,M,GT,1) GO TO 40
DO 30 J=1,N
DO 30 I=1,N
TT=638.0*(7,DE-4)*SE(I,J)
IT=0
IF (TEMK,GE,TT) IT=1
CLOW(1)=0.0
CLOW(2)=0.0
CHGH(1)=0.0
CHGH(2)=0.0
DO 20 KK=1,2
K=KK
IF (M,EQ,1) V=2
L=N-1+K
IF (IT,EQ,1) GO TO 10
CLOW(K)=BET*(TIME(L)-ALPHA*EXP(-TCOEF*TIME(L))+ALPHA)
CLOW(K)=CLOW(K)*(EXP((-Q/R+.05*SE(I,J))/(GAS*TEMK))-(FFLUX*.85))*
+SINH(SE(I,J)*SCI)
GO TO 20
10 CONTINUE
CHGH(K)=BET*(TIME(L)-ALPHA*EXP(-TCOEF*TIME(L))+ALPHA)
CHGH(K)=CHGH(K)*(EXP(-Q/(GAS*TEMK)))*SINH(SC*SE(I,J))
20 CONTINUE
DCHGH=CHGH(2)-CHGH(1)
DCLW=CLOW(2)-CLOW(1)

```

	CRATE(I,J)=DCLOW	J	39
	IF (DCHGH,GT,DCLOW) CRATE(I,J)=DCHGH	J	40
30	CONTINUE	J	41
	GO TO 120	J	42
C	CHANGES TO ALLOW FOR STRAIN HARDENING OPTION	J	43
C	PROVIDE FOR TEMPERATURE BREAK POINT CALCULATION TO	J	44
C	SHOW WHICH CREEP LAW TO USE	J	45
C	TEMPERATURE CALCULATION SECTION	J	46
C		J	47
40	CONTINUE	J	48
C		J	49
C	START STRAIN HARDENING OPTION	J	50
	DO 110 J=1,N	J	51
	DO 110 I=1,N	J	52
	TT=578.0-(7.0E-4)*SE(I,J)	J	53
	IT=0	J	54
	IF (TEMK,GE,TT) IT=1	J	55
C		J	56
C	SELECT CORRECT CREEP EQUATION BASED ON TEMPERATURE	J	57
C	PREPARE STARTING POINT VALUES	J	58
C		J	59
	ZETA=TIME(")	J	60
50	CONTINUE	J	61
C	LOW VALUE OF CREEP STRAIN	J	62
	IF (IT.EQ,1) GO TO 60	J	63
	XFUN1=BET*((ZETA-ALPHA*EXP(-TCOEF*ZETA))+ALPHA)	J	64
	XFUN2=(EXP((-QIR+.05*SE(I,J))/(GAS*TEMK))*(FFLUX**.85))*SINH(SE(I,	J	65
	+J)*SCI)	J	66
	XFUN3=BET*((1+TCOEF*ALPHA*EXP(-TCOEF*ZETA))	J	67
	XXFUN=XFUN2*XFUN1	J	68
	DELXF=XFUN3*XFUN2	J	69
	GO TO 70	J	70
60	CONTINUE	J	71
C		J	72
C	HIGH VALUE OF CREEP	J	73
C		J	74
	XFUN1=BET*(ZETA-ALPHA*EXP(-TCOEF*ZETA))+ALPHA)	J	75
	XFUN2=(EXP((-Q/(GAS*TEMK)))*SINH(SC*SE(I,J))	J	76
		J	77
	XFUN3=BET*((1+ALPHA*TCOEF*EXP(-TCOEF*ZETA))	J	78
	XXFUN=XFUN2*XFUN1	J	79
	DELXF=XFUN3*XFUN2	J	80
70	CONTINUE	J	81
	ERROR=CRPG(I,J)-XXFUN	J	82
	XFACT=0.001*CRPG(I,J)	J	83
	ABERR=ABS(ERROR)	J	84
	IF (ABERR,LT,XFACT) GO TO 80	J	85
	H=ERROR/DELXF	J	86
	ZETA=ZETA+H	J	87
	GO TO 50	J	88
80	CONTINUE	J	89
C		J	90
C	NOW COMPARE INCREMENTAL STRAIN INCREMENT FOR STRAIN HARDENING	J	91
C	MODE	J	92
C		J	93
	ZETAN=ZETA*DELTAT	J	94
	IF (IT.EQ,1) GO TO 90	J	95
	XMAX=BET*((ZETAN-ALPHA*EXP(-TCOEF*ZETAN))+ALPHA)	J	96
	XMAX=XMAX*(EXP((-QIR+.05*SE(I,J))/(GAS*TEMK))*(FFLUX**.85))*SINH(S	J	97
	+E(I,J)*SCI)	J	98
	GO TO 100	J	99
90	CONTINUE	J	100
	XMAX=BET*((ZETAN-ALPHA*EXP(-TCOEF*ZETAN))+ALPHA)	J	101
	XMAX=XMAX*(EXP((-Q/(GAS*TEMK)))*SINH(SC*SE(I,J))	J	102
100	CONTINUE	J	103
C		J	104
C	COMPUTE INCREMENTAL STRAIN FOR TIME STEP	J	105
C		J	106
	CRATE(I,J)=XMAX-XXFUN	J	107
110	CONTINUE	J	108
120	CONTINUE	J	109
	RETURN	J	110
	END	J	111

```

*DECK TEMP
FUNCTION TEMP (TC,CRF,CRFT,N)
C TEMP IS A LINEAR INTERPOLATION FUNCTION WHOSE VALUE IS EQUAL TO TH
C INTERPOLATED VALUE.
C TC IS THE VALUE OF THE INDEPENDENT VARIABLE
C CRF=DEPENDENT VARIABLE ARRAY
C CRFT=INDEPENDENT VARIABLE ARRAY
C N=NUMBER OF POINTS IN VARIABLE ARRAYS
C DIMENSION CRF(N),CRFT(N)
I=1
IF (TC.LT.CRF(1)) GO TO 20
I=N
IF (TC.GT.CRF(N)) GO TO 20
DO 10 I=1,N
IF (TC-CRF(I)) 40,30,10
10 CONTINUE
20 TEMP=CRF(I)
RETURN
30 TEMP=CRF(I)
RETURN
40 TEMP=CRF(I-1)*(CRF(I)-CRF(I-1))*(TC-CRF(I-1))/(CRFT(I)-CRFT(I-1))
RETURN
END

```

```

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

```

```

*DECK SIGMAZ
SUBROUTINE SIGMAZ (PO,PI)
*CALL COVECOM
C EVALUATES SIGMA(Z) TO ENSURE AXIAL EQUILIBRIUM
XI=TH**3/12,
RAO=RM+.5*TH
RAI=RM-.5*TH
AXST=(PI*RAI-RAI-PO*RAO*RAO)/(RAO*RAO-RAI*RAI)
NN=NRA+1
N=NTA+1
DO 10 I=1,N
DO 10 J=1,NN
FY=0.0375
IF (RT,LT,4,) FY=-0.00475*FT+0.0565
IF (RT,GT,5,) FY=0.0375*EXP(-(RT-5.0)/5.0)
CORX=FY/0.0375
BMY=BM(I)*FY/0.125
SIGMAZ=BMY*BAR(J)/YI
C NOW HAVE COMPUTED THE BENDING STRESS
SIGMAZ=-SIGMAZ
S(J,I,3)=SIGMAZ+AXST
10 CONTINUE
RETURN
END

```

```

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

```

```

*DECK SHEAR
SUBROUTINE SHEAR
*CALL COVECOM
C EVALUATES SHEAR STRESSES BY CENTRAL DIFFERENCES AT I+1, I-1 AND
C DEVELOP THE ALGORITHM
N=NTA+1
SSOM=0.0
SSUM=0.0
SIM=0.0
SSS=0.0
DO 20 I=1,N
L=I-1
IF (L.LT.1) L=I+1
MMK=I+1
IF (MMK.GT.N) MMK=I-1
NN=NRA+1
NUP=NN-NA/2
NNUP=NUP-1
S(1,I,4)=0.0
S(NN,I,4)=0.0
DO 10 J=2,NRA
SLM=DELTA*(S(J-1,L,2)+S(J,L,2))/2.0
SSUM=SSUM+SLM
SMN=DELTA*(S(J-1,MMK,2)+S(J,MMK,2))/2.0
SIM=SIM+SMN
C I+1 AND I-1 NOW FIND SHEAR STRESS TAU(R,THETA)
C HAVE NOW COMPUTED THE INTEGRAL OF THE AXIAL STRESS FOR SECTIONS
C SHEAR STRESS OF THE SURFACE IS = 0.0
C SHEAR STRESS COMPUTED FROM INSIDE TO CENTER
S(J,I,4)=(SIM-SSUM)/(2.*R(I)*DTH)
10 CONTINUE
SSS=0.0
SIM=0.0
SSUM=0.0
SSOM=0.0
20 CONTINUE
C NOW COMPUTE THE OUT OF PLANE SHEAR STRESS ON THE CENTER SPAN
C NODE 'I'
RETURN
END

```

```

M 1
M 2
M 3
M 4
M 5
M 6
M 7
M 8
M 9
M 10
M 11
M 12
M 13
M 14
M 15
M 16
M 17
M 18
M 19
M 20
M 21
M 22
M 23
M 24
M 25
M 26
M 27
M 28
M 29
M 30
M 31
M 32
M 33
M 34
M 35
M 36
M 37
M 38
M 39
M 40

```

```

•DECK CURVE
SUBROUTINE CURVE
•CALL COVECOM
C EVALUATES RADIUS OF CURVATURE OF OVAL TUBE USING CLOSED FORM SOLN
C TO FINITE DIFFERENCES METHOD
N=NTA+1
DO 10 I=1,N
RR(I+1)=R(I)
10 CONTINUE
RR(1)=R(2)
RR(NTA+3)=R(NTA)
NN=NTA+2
DO 20 I=2,NN
RHO(I-1)=(RR(I)**2+((RR(I+1)-RR(I-1))/(2.*DTH))**2)**1.5/(RR(I)**2
+2.*((RR(I+1)-RR(I-1))/(2.*DTH))**2-RR(I)*(RR(I+1)-2.*RR(I)+RR(I-1
+))/DTH**2)
20 CONTINUE
RETURN
END

```

N	1
N	2
N	3
N	4
N	5
N	6
N	7
N	8
N	9
N	10
N	11
N	12
N	13
N	14
N	15
N	16
N	17
N	18
N	19

```

•DECK BEND
SUBROUTINE BEND
•CALL COVECOM
C EVALUATES SIGMA FLEXURE
NN=NTA+1
N=NRA+1
DO 10 I=1,NN
Z(I)=-1.*(RHO(I)/TH)*ALOG((RHO(I)+TH/2.)/(RHO(I)-TH/2.))
XI=TH**3/12.
RO=RHO(I)+TH*.5
RI=RHO(I)-TH*.5
BETA=(RO*RO-RI*RI)**2-4.*RO*RO*RI*RI*(ALOG(RO/RI))**2
DO 10 J=1,N
A=J-1
RJ=RI+A*TH/FLOAT(NRA)
SIGFT(J,I)=-4.*BM(I)/BETA*(-RI*RI*RO*RO/(RJ*RJ)*ALOG(RO/RI)+RO*RO*
+ALOG(RJ/RO)+RI*RI*ALOG(RI/RJ)+PO*RO-RI*RI)
SIGFR(J,I)=-4.*BM(I)/BETA*(RI*RI*RO*RO/(RO*RO)*ALOG(RO/RI)+RO*RO*A
+LOG(RJ/RO)+RI*RI*ALOG(RI/RJ))
SIGFT(J,I)=0.C
SIGFT(J,I)=BM(I)/(TH*RHO(I))*(1.+1./Z(I))*BAR(J)/(RHO(I)*BAR(J))
SIGFT(J,I)=BM(I)*BAR(J)/XI
SIGFT(J,I)=-SIGFT(J,I)
10 CONTINUE
RETURN
END

```

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

```

•DECK PRESS
SUBROUTINE PRESS (PO,PI)
•CALL COVECOM
C EVALUATES SIGMA PRESSURE
RAI=RM-TH*.5
RAO=RM+TH*.5
RAIO=RAO*RAO-RAI*RAI
NN=NTA+1
N=NRA+1
DO 10 I=1,N
A=I-1
RO=RAI+A*TH/FLOAT(NRA)
S(I,1,1)=PI*RAI*RAI/RAIO*(1.-RAO*RAO/(RO*RO))-PO*RAO*RAO/RAIO*(1.-
+RAI*RAI/(RO*RO))
S(I,1,2)=PI*RAI*RAI/RAIO*(1.+RAO*RAO/(RO*RO))-PO*RAO*RAO/RAIO*(1.+
+RAI*RAI/(RO*RO))
S(I,1,2)=(PI*2.*RAI-PO*2.*RAO)/(2.*TH)
DO 10 J=2,N
S(I,J,1)=S(I,1,1)
10 S(I,J,2)=S(I,1,2)
RETURN
END

```

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

*DECK EFFECT	0	1
SUBROUTINE EFFECT	0	2
*CALL CONECON	0	3
C ADD FLEXURE STRESSES TO S ARRAY THEN COMPUTE EFFECTIVE STRESSES	0	4
C CORRECTIONS TO SUBROUTINE EFFECT TO ACCOUNT FOR ANISOTROPY	0	5
C	0	6
C CALCULATE A NEW EFFECTIVE STRESS BASED ON THE R AND P VALUES	0	7
C THIS EFFECTIVE STRESS IS BASED ON THE DIRECTION OF ROLLING	0	8
C AND THE DIRECTION OF TEST BEING COINCIDENT	0	9
C FOR OTHER DIRECTIONS CONSULT THE DOCUMENT COVER-1 TO DETERMINE	0	10
C THE NECESSARY CHANGES TO THE COEF CONTAINED HEREIN	0	11
C HAVE NEGLECTED SHEAR	0	12
C NN=NR+1	0	13
C N=NTA+1	0	14
C DO 10 I=1,N	0	15
C DO 10 J=1,NN	0	16
C SE(J,I)=SQRT((CR*CP/(CP*(CR+1.))*(S(J,I,3)-S(J,I,2))**2+CR/(CP*(CR+	0	17
C +1.))*(S(J,I,2))**2+CP/(CP*(CR+1.))*(S(J,I,3))**2+3.0*(S(J,I,4))**2	0	18
C +)	0	19
10 CONTINUE	0	20
RETURN	0	21
END	0	22

*DECK SINH	R	1
FUNCTION SINH (X)	R	2
DX=EXP(X)	R	3
SINH=0.5*(DX-1./DX)	R	4
RETURN	R	5
END	R	6

*DECK CLEAR	S	1
SUBROUTINE CLEAR (NIN,I)	S	2
DIMENSION PIN(1)	S	3
DO 10 J=1,I	S	4
PIN(J)=0	S	5
10 CONTINUE	S	6
RETURN	S	7
END	S	8

APPENDIX C

COVE SAMPLE OUTPUT

This appendix presents output using 3 different code options: MINI=1, MINI=0, and MINI=-1.

THE USER IS WARNED THAT THE CREEP COEFFICIENTS AND MATERIAL PROPERTIES, INPUT VIA DATA CARDS FOR THIS EXAMPLE PROBLEM, ARE TO DEMONSTRATE THE USER OPTION IN SPECIFYING THESE VALUES AND MAY NOT BE REPRESENTATIVE OF ANY REAL MATERIAL. THE VALUES OF INTERNAL PRESSURE, TEMPERATURE AND NEUTRON FLUX WERE SELECTED TO DEMONSTRATE THE USER OPTION IN SPECIFYING THESE SO AS TO APPROXIMATE AN ACTUAL OR EXPECTED FUEL CYCLE HISTORY. THESE 11 CARDS SHOULD BE REMOVED FROM THE OUTPUT SUBROUTINE BEFORE FURTHER USE.

SAMPLE PROBLEM TO DEMONSTRATE USER'S OPTIONAL FEATURES, MINI=1

• SUMMARY OF INPUT DATA •

CLADDING RADIUS	RA0	.21000	INCHES
CLAD WALL THICKNESS	TH	.02500	INCHES
TIME INCREMENTS	DELTAT	200.00	HOURS
MAXIMUM OPERATING TIME	TMAX	2000.00	HOURS
INITIAL OVALITY	OVAL	.000700	INCHES
CLADDING EXTERNAL PRESSURE	POUT	2200.00	PSI
THE ANISOTROPIC PROPERTIES	CR	1.0000	
	CP	1.0000	
EFFECTIVE SECTION LENGTH	XLEN	5.00	INCHES
ELASTIC COLLAPSE PRESSURE	PCR	6643.76	PSI
MATERIAL PROPERTIES	TRUE=PROPERTIES INPUT FALSE=PROPERTIES INTERNAL TO PROGRAM		
	MATOPT	T	
NUMBER OF TEMP. NODES FOR MAT. PROP.	NTEMP	5	
NUMBER OF TIME STEPS MAX=16			
	NIM=3		
NODES TO BE PRINTED NP(J,I)	J=	1.	21
	I=	11	
NUMBER OF RADIAL SEGMENTS	NRA	20	
NUMBER OF RADIAL TANGENTIAL SEGMENTS	NTA	10	
VALUE OF MINI FOR OUTPUT OPTIONS	MINI	1	

STRAIN HARDENING OPTION IS USED IN THIS CALCULATION

POISSONS RATIO		YOUNGS MODULUS		YIELD STRENGTH	
TEMP.	VALUE	TEMP.	VALUE	TEMP.	VALUE
500.0	.3000-00	500.0	.1200+08	500.0	.7500+05
550.0	.3500-00	550.0	.1150+08	550.0	.7000+05
600.0	.4000-00	600.0	.1100+08	600.0	.6500+05
650.0	.4500-00	650.0	.1050+08	650.0	.6000+05
700.0	.5000-00	700.0	.1000+08	700.0	.5500+05

FAST FLUX	
TIME	VALUE
.0	.6000+14
500.0	.6900+14
1000.0	.6900+14
1500.0	.6000+14
2000.0	.7500+14

TIME (HOURS)	INTERNAL PRESS. (PSI)	CLADDING WALL TEMP. (DEG. F)	OVAILITY (IN.)	MEAN RADIUS DECREASE	TAN STRESS ID SURFACE NODE NO. J= 1 I=11	TANG STRS OD SURFACE NODE NO. J=21 I=11	EFFECTIVE STRESS ID (PSI) (J,I)	EFFECTIVE STRESS OD (PSI) (J,I)
.00	600.00	610.00	.00092	.1975-00	-.1334+05	-.1474+05	.1160+05	.1277+05

TANGENTIAL STRESS SEGMENTS

	I= 1	I= 3	I= 6	I= 8	I= 11
J= 1	-.1474+05	-.1461+05	-.1404+05	-.1363+05	-.1334+05
J= 2	-.1467+05	-.1455+05	-.1404+05	-.1367+05	-.1341+05
J= 3	-.1460+05	-.1449+05	-.1404+05	-.1371+05	-.1344+05
J= 4	-.1453+05	-.1444+05	-.1404+05	-.1375+05	-.1355+05
J= 5	-.1446+05	-.1439+05	-.1404+05	-.1379+05	-.1362+05
J= 6	-.1439+05	-.1432+05	-.1404+05	-.1383+05	-.1369+05
J= 7	-.1432+05	-.1427+05	-.1404+05	-.1388+05	-.1376+05
J= 8	-.1425+05	-.1421+05	-.1404+05	-.1392+05	-.1383+05
J= 9	-.1418+05	-.1415+05	-.1404+05	-.1396+05	-.1390+05
J= 10	-.1411+05	-.1410+05	-.1404+05	-.1400+05	-.1397+05
J= 11	-.1404+05	-.1404+05	-.1404+05	-.1404+05	-.1404+05
J= 12	-.1397+05	-.1398+05	-.1404+05	-.1408+05	-.1411+05
J= 13	-.1390+05	-.1393+05	-.1404+05	-.1412+05	-.1418+05
J= 14	-.1383+05	-.1387+05	-.1404+05	-.1416+05	-.1425+05
J= 15	-.1376+05	-.1381+05	-.1404+05	-.1420+05	-.1432+05
J= 16	-.1369+05	-.1376+05	-.1404+05	-.1425+05	-.1439+05
J= 17	-.1362+05	-.1370+05	-.1404+05	-.1429+05	-.1446+05
J= 18	-.1355+05	-.1364+05	-.1404+05	-.1433+05	-.1453+05
J= 19	-.1348+05	-.1359+05	-.1404+05	-.1437+05	-.1467+05
J= 20	-.1341+05	-.1353+05	-.1404+05	-.1441+05	-.1467+05
J= 21	-.1334+05	-.1347+05	-.1404+05	-.1445+05	-.1474+05

EFFECTIVE STRESS SEGMENTS

	I= 1	I= 3	I= 6	I= 8	I= 11
J= 1	.1277+05	.1266+05	.1218+05	.1184+05	.1160+05
J= 2	.1271+05	.1261+05	.1218+05	.1187+05	.1166+05
J= 3	.1265+05	.1256+05	.1218+05	.1191+05	.1172+05
J= 4	.1259+05	.1251+05	.1218+05	.1194+05	.1177+05
J= 5	.1253+05	.1247+05	.1218+05	.1197+05	.1183+05
J= 6	.1247+05	.1242+05	.1218+05	.1201+05	.1189+05
J= 7	.1242+05	.1237+05	.1218+05	.1204+05	.1195+05
J= 8	.1236+05	.1232+05	.1218+05	.1208+05	.1201+05
J= 9	.1230+05	.1228+05	.1218+05	.1211+05	.1206+05
J= 10	.1224+05	.1223+05	.1218+05	.1215+05	.1212+05
J= 11	.1218+05	.1218+05	.1218+05	.1218+05	.1218+05
J= 12	.1212+05	.1213+05	.1218+05	.1222+05	.1224+05
J= 13	.1206+05	.1209+05	.1218+05	.1225+05	.1230+05
J= 14	.1201+05	.1204+05	.1218+05	.1228+05	.1236+05
J= 15	.1195+05	.1199+05	.1218+05	.1232+05	.1242+05
J= 16	.1189+05	.1194+05	.1218+05	.1235+05	.1247+05
J= 17	.1183+05	.1190+05	.1218+05	.1239+05	.1255+05
J= 18	.1177+05	.1185+05	.1218+05	.1242+05	.1259+05
J= 19	.1172+05	.1180+05	.1218+05	.1246+05	.1265+05
J= 20	.1166+05	.1176+05	.1218+05	.1249+05	.1271+05
J= 21	.1160+05	.1171+05	.1218+05	.1253+05	.1277+05

200.00	600.00	610.00	.00101	.1975-00	-.1322+05	-.1484+05	.1151+05	.1286+05
400.00	580.00	610.00	.00111	.1974-00	-.1325+05	-.1509+05	.1153+05	.1307+05
600.00	560.00	610.00	.00122	.1974-00	-.1328+05	-.1535+05	.1157+05	.1329+05
800.00	540.00	610.00	.00133	.1974-00	-.1331+05	-.1560+05	.1160+05	.1351+05
1000.00	520.00	610.00	.00145	.1973-00	-.1334+05	-.1586+05	.1163+05	.1373+05

TANGENTIAL STRESS SEGMENTS

	I= 1	I= 3	I= 6	I= 8	I= 11
J= 1	-.1565+05	-.1544+05	-.1451+05	-.1383+05	-.1334+05
J= 2	-.1555+05	-.1536+05	-.1453+05	-.1391+05	-.1346+05
J= 3	-.1546+05	-.1528+05	-.1454+05	-.1399+05	-.1361+05
J= 4	-.1536+05	-.1520+05	-.1455+05	-.1408+05	-.1374+05
J= 5	-.1526+05	-.1513+05	-.1456+05	-.1416+05	-.1387+05
J= 6	-.1516+05	-.1505+05	-.1458+05	-.1424+05	-.1400+05
J= 7	-.1506+05	-.1497+05	-.1459+05	-.1432+05	-.1413+05
J= 8	-.1495+05	-.1488+05	-.1460+05	-.1440+05	-.1426+05
J= 9	-.1485+05	-.1480+05	-.1461+05	-.1447+05	-.1438+05
J= 10	-.1474+05	-.1472+05	-.1462+05	-.1455+05	-.1451+05
J= 11	-.1464+05	-.1464+05	-.1463+05	-.1463+05	-.1464+05
J= 12	-.1453+05	-.1455+05	-.1464+05	-.1471+05	-.1476+05
J= 13	-.1443+05	-.1447+05	-.1465+05	-.1479+05	-.1489+05
J= 14	-.1432+05	-.1438+05	-.1466+05	-.1486+05	-.1501+05
J= 15	-.1421+05	-.1429+05	-.1467+05	-.1494+05	-.1513+05
J= 16	-.1410+05	-.1421+05	-.1467+05	-.1501+05	-.1525+05
J= 17	-.1399+05	-.1412+05	-.1468+05	-.1509+05	-.1538+05
J= 18	-.1388+05	-.1403+05	-.1469+05	-.1517+05	-.1550+05
J= 19	-.1376+05	-.1394+05	-.1470+05	-.1524+05	-.1562+05
J= 20	-.1365+05	-.1385+05	-.1471+05	-.1532+05	-.1574+05
J= 21	-.1353+05	-.1376+05	-.1471+05	-.1539+05	-.1586+05

EFFECTIVE STRESS SEGMENTS

	I= 1	I= 3	I= 6	I= 8	I= 11			
J= 1	.1356+05	.1337+05	.1359+05	.1202+05	.1163+05			
J= 2	.1347+05	.1331+05	.1360+05	.1209+05	.1174+05			
J= 3	.1339+05	.1324+05	.1361+05	.1216+05	.1164+05			
J= 4	.1331+05	.1317+05	.1362+05	.1223+05	.1195+05			
J= 5	.1322+05	.1311+05	.1363+05	.1229+05	.1206+05			
J= 6	.1313+05	.1304+05	.1364+05	.1236+05	.1216+05			
J= 7	.1305+05	.1297+05	.1365+05	.1243+05	.1227+05			
J= 8	.1296+05	.1290+05	.1366+05	.1249+05	.1238+05			
J= 9	.1287+05	.1283+05	.1367+05	.1256+05	.1248+05			
J= 10	.1279+05	.1277+05	.1368+05	.1263+05	.1259+05			
J= 11	.1270+05	.1270+05	.1369+05	.1269+05	.1269+05			
J= 12	.1261+05	.1262+05	.1370+05	.1276+05	.1280+05			
J= 13	.1252+05	.1255+05	.1371+05	.1282+05	.1290+05			
J= 14	.1243+05	.1243+05	.1371+05	.1289+05	.1301+05			
J= 15	.1234+05	.1241+05	.1372+05	.1295+05	.1311+05			
J= 16	.1225+05	.1234+05	.1373+05	.1301+05	.1322+05			
J= 17	.1215+05	.1223+05	.1373+05	.1308+05	.1332+05			
J= 18	.1206+05	.1217+05	.1374+05	.1314+05	.1342+05			
J= 19	.1197+05	.1212+05	.1375+05	.1321+05	.1353+05			
J= 20	.1187+05	.1204+05	.1375+05	.1327+05	.1363+05			
J= 21	.1178+05	.1197+05	.1376+05	.1333+05	.1373+05			
1200.00	500.00	610.00	.00158	.1973-00	-.1337+05	-.1612+05	.1165+05	.1396+05
1400.00	540.00	610.00	.00168	.1973-00	-.1302+05	-.1586+05	.1136+05	.1374+05
1600.00	580.00	610.00	.00175	.1973-00	-.1269+05	-.1559+05	.1108+05	.1350+05
1800.00	630.00	610.00	.00182	.1973-00	-.1231+05	-.1522+05	.1076+05	.1318+05
2000.00	690.00	610.00	.00189	.1973-00	-.1187+05	-.1477+05	.1038+05	.1279+05

TANGENTIAL STRESS SEGMENTS

	I= 1	I= 3	I= 6	I= 8	I= 11
J= 1	-.1457+05	-.1432+05	-.1325+05	-.1245+05	-.1187+05
J= 2	-.1446+05	-.1423+05	-.1327+05	-.1254+05	-.1203+05
J= 3	-.1434+05	-.1414+05	-.1328+05	-.1264+05	-.1218+05
J= 4	-.1423+05	-.1405+05	-.1329+05	-.1273+05	-.1234+05
J= 5	-.1411+05	-.1396+05	-.1330+05	-.1282+05	-.1249+05
J= 6	-.1399+05	-.1385+05	-.1331+05	-.1292+05	-.1264+05
J= 7	-.1387+05	-.1377+05	-.1332+05	-.1301+05	-.1279+05
J= 8	-.1375+05	-.1367+05	-.1333+05	-.1310+05	-.1294+05
J= 9	-.1363+05	-.1357+05	-.1334+05	-.1319+05	-.1309+05
J= 10	-.1351+05	-.1343+05	-.1335+05	-.1328+05	-.1323+05
J= 11	-.1338+05	-.1338+05	-.1336+05	-.1337+05	-.1338+05
J= 12	-.1326+05	-.1328+05	-.1337+05	-.1346+05	-.1352+05
J= 13	-.1313+05	-.1319+05	-.1338+05	-.1355+05	-.1367+05
J= 14	-.1300+05	-.1307+05	-.1339+05	-.1363+05	-.1381+05
J= 15	-.1287+05	-.1297+05	-.1340+05	-.1372+05	-.1395+05
J= 16	-.1274+05	-.1287+05	-.1341+05	-.1381+05	-.1409+05
J= 17	-.1261+05	-.1276+05	-.1342+05	-.1389+05	-.1423+05
J= 18	-.1247+05	-.1265+05	-.1343+05	-.1398+05	-.1436+05
J= 19	-.1234+05	-.1255+05	-.1343+05	-.1407+05	-.1450+05
J= 20	-.1220+05	-.1244+05	-.1344+05	-.1415+05	-.1464+05
J= 21	-.1206+05	-.1233+05	-.1345+05	-.1423+05	-.1477+05

EFFECTIVE STRESS SEGMENTS

	I= 1	I= 3	I= 6	I= 8	I= 11
J= 1	.1262+05	.1241+05	.1150+05	.1084+05	.1038+05
J= 2	.1252+05	.1233+05	.1151+05	.1092+05	.1051+05
J= 3	.1242+05	.1225+05	.1152+05	.1100+05	.1063+05
J= 4	.1233+05	.1217+05	.1154+05	.1107+05	.1075+05
J= 5	.1223+05	.1210+05	.1155+05	.1115+05	.1086+05
J= 6	.1213+05	.1202+05	.1156+05	.1123+05	.1100+05
J= 7	.1203+05	.1194+05	.1157+05	.1130+05	.1112+05
J= 8	.1193+05	.1186+05	.1157+05	.1138+05	.1125+05
J= 9	.1182+05	.1179+05	.1158+05	.1145+05	.1137+05
J= 10	.1172+05	.1167+05	.1159+05	.1153+05	.1149+05
J= 11	.1162+05	.1161+05	.1160+05	.1160+05	.1161+05
J= 12	.1151+05	.1153+05	.1161+05	.1168+05	.1173+05
J= 13	.1140+05	.1144+05	.1162+05	.1175+05	.1185+05
J= 14	.1130+05	.1136+05	.1162+05	.1182+05	.1197+05
J= 15	.1119+05	.1127+05	.1163+05	.1190+05	.1209+05
J= 16	.1108+05	.1119+05	.1164+05	.1197+05	.1221+05
J= 17	.1097+05	.1110+05	.1164+05	.1204+05	.1233+05
J= 18	.1086+05	.1101+05	.1165+05	.1212+05	.1244+05
J= 19	.1075+05	.1092+05	.1166+05	.1219+05	.1256+05
J= 20	.1064+05	.1083+05	.1166+05	.1226+05	.1268+05
J= 21	.1052+05	.1074+05	.1167+05	.1233+05	.1279+05

TIME EXCEEDS MAX TIME. EXECUTION TERMINATED.

SAMPLE PROBLEM TO DEMONSTRATE USER'S OPTIONAL FEATURES. MINI=C

 * SUMMARY OF INPUT DATA *

CLADDING RADIUS	RAO	.21000	INCHES
CLAD WALL THICKNESS	TH	.02500	INCHES
TIME INCREMENTS	DELTA T	200.00	HOURS
MAXIMUM OPERATING TIME	TMAX	2000.00	HOURS
INITIAL OVALITY	OVAL	.000700	INCHES
CLADDING EXTERNAL PRESSURE	POUT	2200.00	PSI
THE ANISOTROPIC PROPERTIES	CR	1.0000	
	CF	1.0000	
EFFECTIVE SECTION LENGTH	XLEN	5.00	INCHES
ELASTIC COLLAPSE PRESSURE	PCR	6643.76	PSI
MATERIAL PROPERTIES: TRUE=PROPERTIES INPUT FALSE=PROPERTIES INTERNAL TO PROGRAM	MATOPT	T	
NUMBER OF TEMP. NODES FOR MAT. PROP.	NTEMP	5	
NUMBER OF TIME STEPS MAX=14 MIN=3	NTIME	5	
NODES TO BE PRINTED NP(J,I)	J=	1, 21	
	I=	11	
NUMBER OF RADIAL SEGMENTS	NRA	20	
NUMBER OF RADIAL TANGENTIAL SEGMENTS	NITA	10	
VALUE OF MINI FOR OUTPUT OPTIONS	MINI	0	

STRAIN HARDENING OPTION IS USED IN THIS CALCULATION

POISSONS RATIO		YOUNGS MODULUS		YIELD STRENGTH	
TEMP.	VALUE	TEMP.	VALUE	TEMP.	VALUE
500.0	.3000-00	500.0	.1200+08	500.0	.7500+05
550.0	.3500-00	550.0	.1150+08	550.0	.7000+05
600.0	.4000-00	600.0	.1100+08	600.0	.6500+05
650.0	.4500-00	650.0	.1050+08	650.0	.6000+05
700.0	.5000-00	700.0	.1000+08	700.0	.5500+05

FAST FLUX	
TIME	VALUE
.0	.6000+14
500.0	.6900+14
1000.0	.6900+14
1500.0	.6000+14
2000.0	.7500+14

TIME (HOURS)	INTERNAL PRESS. (PSI)	CLADDING WALL TEMP. (DEG. F)	OVALITY (IN.)	MEAN RADIUS DECREASE	TAN STRESS ID SURFACE NODE NO.		TANG STRS OD SURFACE NODE NO.		EFFECTIVE STRESS ID (PSI) (J,I)	EFFECTIVE STRESS OD (PSI) (J,I)
					J= 1 I=11	J=11 I=11	J=21 I=11	J=11 I=11		
.00	600.00	610.00	.00092	.1975-00	-.1334+05	-.1474+05	-.1474+05	-.1474+05	.1160+05	.1277+05
200.00	600.00	610.00	.00101	.1975-00	-.1322+05	-.1484+05	-.1484+05	-.1484+05	.1151+05	.1286+05
400.00	580.00	610.00	.00111	.1974-00	-.1325+05	-.1506+05	-.1506+05	-.1506+05	.1153+05	.1307+05
600.00	560.00	610.00	.00122	.1974-00	-.1324+05	-.1535+05	-.1535+05	-.1535+05	.1157+05	.1329+05
800.00	540.00	610.00	.00133	.1974-00	-.1331+05	-.1560+05	-.1560+05	-.1560+05	.1160+05	.1351+05
1000.00	520.00	610.00	.00145	.1973-00	-.1334+05	-.1586+05	-.1586+05	-.1586+05	.1163+05	.1373+05
1200.00	500.00	610.00	.00158	.1973-00	-.1337+05	-.1612+05	-.1612+05	-.1612+05	.1165+05	.1396+05
1400.00	540.00	610.00	.00168	.1973-00	-.1302+05	-.1586+05	-.1586+05	-.1586+05	.1136+05	.1374+05
1600.00	580.00	610.00	.00175	.1973-00	-.1269+05	-.1559+05	-.1559+05	-.1559+05	.1108+05	.1350+05
1800.00	630.00	610.00	.00182	.1973-00	-.1231+05	-.1522+05	-.1522+05	-.1522+05	.1076+05	.1318+05
2000.00	690.00	610.00	.00189	.1973-00	-.1187+05	-.1477+05	-.1477+05	-.1477+05	.1038+05	.1279+05

SAMPLE PROBLEM TO DEMONSTRATE USER'S OPTIONAL FEATURES, MINI=-1

 * SUMMARY OF INPUT DATA *

CLADDING RADIUS	RAO	.21000	INCHES
CLAD WALL THICKNESS	TH	.02500	INCHES
TIME INCREMENTS	DELTAT	200.00	HOURS
MAXIMUM OPERATING TIME	TMAX	2000.00	HOURS
INITIAL OVALITY	OVAL	.000700	INCHES
CLADDING EXTERNAL PRESSURE	PCUT	2200.00	PSI
THE ANISOTROPIC PROPERTIES	CR	1.0000	
	CP	1.0000	
EFFECTIVE SECTION LENGTH	XLEN	5.00	INCHES
ELASTIC COLLAPSE PRESSURE	PCR	6643.76	PSI
MATERIAL PROPERTIES	TRUE=PROPERTIES INPUT		
	FALSE=PROPERTIES INTERVAL TO		
	PROGRAM	MATOPT	T
NUMBER OF TEMP. NODES FOR MAT. PROP.	NTMP	5	
NUMBER OF TIME STEPS MAX=16			
	MIM=3	NTIME	5
NODES TO BE PRINTED NP(J,I)	JF	1,	21
	IF	11	
NUMBER OF RADIAL SEGMENTS	NRA	20	
NUMBER OF RADIAL TANGENTIAL SEGMENTS	NTA	10	
VALUE OF MINI FOR OUTPUT OPTIONS	MINI	-1	

STRAIN HARDENING OPTION IS USED IN THIS CALCULATION

POISSONS RATIO		YOUNGS MODULUS		YIELD STRENGTH	
TEMP.	VALUE	TEMP.	VALUE	TEMP.	VALUE
500.0	.3000-00	500.0	.1200+08	500.0	.7500+25
550.0	.3500-00	550.0	.1150+08	550.0	.7000+25
600.0	.4000-00	600.0	.1100+08	600.0	.6500+25
650.0	.4500-00	650.0	.1050+08	650.0	.6000+25
700.0	.5000-00	700.0	.1000+08	700.0	.5500+25

FAST FLUX	
TIME	VALUE
.0	.6000+14
500.0	.6900+14
1000.0	.6900+14
1500.0	.6000+14
2000.0	.7500+14

TIME (HOURS)	INTERNAL PRESS. (PSI)	CLADDING WALL TEMP. (DEG. F)	OVALITY (IN.)
.00	600.00	610.00	.00092

TANGENTIAL STRESS SEGMENTS

	I= 1	I= 3	I= 6	I= 8	I= 11
J= 1	-.1474+05	-.1461+05	-.1404+05	-.1363+05	-.1334+05
J= 2	-.1467+05	-.1455+05	-.1404+05	-.1367+05	-.1341+05
J= 3	-.1460+05	-.1449+05	-.1404+05	-.1371+05	-.1348+05
J= 4	-.1453+05	-.1444+05	-.1404+05	-.1375+05	-.1355+05
J= 5	-.1446+05	-.1438+05	-.1404+05	-.1379+05	-.1362+05
J= 6	-.1439+05	-.1432+05	-.1404+05	-.1383+05	-.1369+05
J= 7	-.1432+05	-.1427+05	-.1404+05	-.1388+05	-.1376+05
J= 8	-.1425+05	-.1421+05	-.1404+05	-.1392+05	-.1383+05
J= 9	-.1418+05	-.1415+05	-.1404+05	-.1396+05	-.1390+05
J= 10	-.1411+05	-.1410+05	-.1404+05	-.1400+05	-.1397+05
J= 11	-.1404+05	-.1404+05	-.1404+05	-.1404+05	-.1404+05
J= 12	-.1397+05	-.1393+05	-.1404+05	-.1408+05	-.1411+05
J= 13	-.1390+05	-.1393+05	-.1404+05	-.1412+05	-.1418+05
J= 14	-.1383+05	-.1387+05	-.1404+05	-.1416+05	-.1425+05
J= 15	-.1376+05	-.1381+05	-.1404+05	-.1420+05	-.1432+05
J= 16	-.1369+05	-.1375+05	-.1404+05	-.1425+05	-.1439+05
J= 17	-.1362+05	-.1370+05	-.1404+05	-.1429+05	-.1446+05
J= 18	-.1355+05	-.1364+05	-.1404+05	-.1433+05	-.1453+05
J= 19	-.1348+05	-.1359+05	-.1404+05	-.1437+05	-.1463+05
J= 20	-.1341+05	-.1353+05	-.1404+05	-.1441+05	-.1467+05
J= 21	-.1334+05	-.1347+05	-.1404+05	-.1445+05	-.1474+05

EFFECTIVE STRESS SEGMENTS

	I= 1	I= 3	I= 6	I= 8	I= 11
J= 1	.1277+05	.1266+05	.1218+05	.1184+05	.1160+05
J= 2	.1271+05	.1261+05	.1218+05	.1187+05	.1166+05
J= 3	.1265+05	.1256+05	.1218+05	.1191+05	.1172+05
J= 4	.1259+05	.1251+05	.1218+05	.1194+05	.1177+05
J= 5	.1253+05	.1247+05	.1218+05	.1197+05	.1183+05
J= 6	.1247+05	.1242+05	.1218+05	.1201+05	.1189+05
J= 7	.1242+05	.1237+05	.1218+05	.1204+05	.1195+05
J= 8	.1236+05	.1232+05	.1218+05	.1208+05	.1201+05
J= 9	.1230+05	.1228+05	.1218+05	.1211+05	.1206+05
J= 10	.1224+05	.1223+05	.1218+05	.1215+05	.1212+05
J= 11	.1218+05	.1218+05	.1218+05	.1218+05	.1218+05
J= 12	.1212+05	.1213+05	.1218+05	.1222+05	.1224+05
J= 13	.1206+05	.1209+05	.1218+05	.1225+05	.1230+05
J= 14	.1201+05	.1204+05	.1218+05	.1228+05	.1236+05
J= 15	.1195+05	.1199+05	.1218+05	.1232+05	.1242+05
J= 16	.1189+05	.1194+05	.1218+05	.1235+05	.1247+05
J= 17	.1183+05	.1190+05	.1218+05	.1239+05	.1253+05
J= 18	.1177+05	.1185+05	.1218+05	.1242+05	.1259+05
J= 19	.1172+05	.1183+05	.1218+05	.1246+05	.1263+05
J= 20	.1166+05	.1176+05	.1218+05	.1249+05	.1271+05
J= 21	.1160+05	.1171+05	.1218+05	.1253+05	.1277+05

TIME (HOURS)	INTERNAL PRESS. (PSI)	CLADDING WALL TEMP. (DEG. F)	OVALITY (IN.)
1000.00	520.00	610.00	.00145

TANGENTIAL STRESS SEGMENTS

	I= 1	I= 3	I= 6	I= 8	I= 11
J= 1	-.1565+05	-.1544+05	-.1451+05	-.1383+05	-.1334+05
J= 2	-.1555+05	-.1536+05	-.1453+05	-.1391+05	-.1348+05
J= 3	-.1546+05	-.1528+05	-.1454+05	-.1399+05	-.1361+05
J= 4	-.1536+05	-.1520+05	-.1455+05	-.1406+05	-.1374+05
J= 5	-.1526+05	-.1513+05	-.1456+05	-.1416+05	-.1387+05
J= 6	-.1516+05	-.1505+05	-.1458+05	-.1424+05	-.1400+05
J= 7	-.1506+05	-.1497+05	-.1459+05	-.1432+05	-.1413+05
J= 8	-.1495+05	-.1488+05	-.1460+05	-.1440+05	-.1426+05
J= 9	-.1485+05	-.1480+05	-.1461+05	-.1447+05	-.1436+05
J= 10	-.1474+05	-.1472+05	-.1462+05	-.1455+05	-.1451+05
J= 11	-.1464+05	-.1464+05	-.1463+05	-.1463+05	-.1464+05
J= 12	-.1453+05	-.1455+05	-.1464+05	-.1471+05	-.1476+05
J= 13	-.1443+05	-.1447+05	-.1465+05	-.1479+05	-.1489+05
J= 14	-.1432+05	-.1438+05	-.1466+05	-.1486+05	-.1501+05
J= 15	-.1421+05	-.1429+05	-.1467+05	-.1494+05	-.1513+05
J= 16	-.1410+05	-.1421+05	-.1467+05	-.1501+05	-.1525+05
J= 17	-.1399+05	-.1412+05	-.1468+05	-.1509+05	-.1538+05
J= 18	-.1388+05	-.1403+05	-.1469+05	-.1517+05	-.1550+05
J= 19	-.1376+05	-.1394+05	-.1470+05	-.1524+05	-.1562+05
J= 20	-.1365+05	-.1385+05	-.1471+05	-.1532+05	-.1574+05
J= 21	-.1353+05	-.1376+05	-.1471+05	-.1539+05	-.1586+05

EFFECTIVE STRESS SEGMENTS

	I= 1	I= 3	I= 6	I= 8	I= 11
J= 1	.1356+05	.1337+05	.1250+05	.1202+05	.1163+05
J= 2	.1347+05	.1331+05	.1267+05	.1209+05	.1174+05
J= 3	.1339+05	.1324+05	.1261+05	.1216+05	.1184+05
J= 4	.1331+05	.1317+05	.1267+05	.1223+05	.1195+05
J= 5	.1322+05	.1311+05	.1263+05	.1229+05	.1206+05
J= 6	.1313+05	.1304+05	.1264+05	.1236+05	.1216+05
J= 7	.1305+05	.1297+05	.1265+05	.1243+05	.1227+05
J= 8	.1296+05	.1291+05	.1266+05	.1249+05	.1238+05
J= 9	.1287+05	.1283+05	.1267+05	.1256+05	.1246+05
J= 10	.1279+05	.1277+05	.1268+05	.1263+05	.1259+05
J= 11	.1270+05	.1273+05	.1269+05	.1269+05	.1269+05
J= 12	.1261+05	.1262+05	.1270+05	.1276+05	.1260+05
J= 13	.1252+05	.1255+05	.1271+05	.1282+05	.1290+05
J= 14	.1243+05	.1244+05	.1272+05	.1289+05	.1301+05
J= 15	.1234+05	.1241+05	.1272+05	.1295+05	.1311+05
J= 16	.1225+05	.1234+05	.1273+05	.1301+05	.1322+05
J= 17	.1215+05	.1220+05	.1273+05	.1308+05	.1332+05
J= 18	.1206+05	.1217+05	.1274+05	.1314+05	.1342+05
J= 19	.1197+05	.1212+05	.1275+05	.1321+05	.1353+05
J= 20	.1187+05	.1204+05	.1275+05	.1327+05	.1363+05
J= 21	.1178+05	.1197+05	.1276+05	.1333+05	.1373+05

TIME (HOURS)	INTERNAL PRESS. (PSI)	CLADDING WALL TEMP. (DEG. F)	QUALITY (IN.)
2000.00	690.00	610.00	.00189

TANGENTIAL STRESS SEGMENTS

	I= 1	I= 3	I= 6	I= 8	I= 11
J= 1	-.1457+05	-.1432+05	-.1325+05	-.1245+05	-.1187+05
J= 2	-.1446+05	-.1423+05	-.1327+05	-.1254+05	-.1203+05
J= 3	-.1434+05	-.1414+05	-.1328+05	-.1264+05	-.1218+05
J= 4	-.1423+05	-.1405+05	-.1329+05	-.1273+05	-.1234+05
J= 5	-.1411+05	-.1396+05	-.1330+05	-.1282+05	-.1249+05
J= 6	-.1399+05	-.1386+05	-.1331+05	-.1292+05	-.1264+05
J= 7	-.1387+05	-.1377+05	-.1332+05	-.1301+05	-.1279+05
J= 8	-.1375+05	-.1367+05	-.1333+05	-.1310+05	-.1294+05
J= 9	-.1363+05	-.1357+05	-.1334+05	-.1319+05	-.1309+05
J= 10	-.1351+05	-.1343+05	-.1335+05	-.1328+05	-.1323+05
J= 11	-.1339+05	-.1339+05	-.1336+05	-.1337+05	-.1338+05
J= 12	-.1326+05	-.1324+05	-.1337+05	-.1346+05	-.1352+05
J= 13	-.1313+05	-.1314+05	-.1338+05	-.1355+05	-.1367+05
J= 14	-.1300+05	-.1307+05	-.1339+05	-.1363+05	-.1381+05
J= 15	-.1287+05	-.1297+05	-.1340+05	-.1372+05	-.1395+05
J= 16	-.1274+05	-.1287+05	-.1341+05	-.1381+05	-.1409+05
J= 17	-.1261+05	-.1276+05	-.1342+05	-.1389+05	-.1423+05
J= 18	-.1247+05	-.1265+05	-.1343+05	-.1398+05	-.1436+05
J= 19	-.1234+05	-.1255+05	-.1343+05	-.1407+05	-.1450+05
J= 20	-.1220+05	-.1244+05	-.1344+05	-.1415+05	-.1464+05
J= 21	-.1206+05	-.1233+05	-.1345+05	-.1423+05	-.1477+05

EFFECTIVE STRESS SEGMENTS

	I= 1	I= 3	I= 6	I= 8	I= 11
J= 1	.1262+05	.1241+05	.1157+05	.1084+05	.1038+05
J= 2	.1252+05	.1233+05	.1151+05	.1092+05	.1051+05
J= 3	.1242+05	.1225+05	.1152+05	.1100+05	.1063+05
J= 4	.1233+05	.1217+05	.1154+05	.1107+05	.1075+05
J= 5	.1223+05	.1210+05	.1155+05	.1115+05	.1088+05
J= 6	.1213+05	.1202+05	.1156+05	.1123+05	.1100+05
J= 7	.1203+05	.1194+05	.1157+05	.1130+05	.1112+05
J= 8	.1193+05	.1186+05	.1157+05	.1138+05	.1125+05
J= 9	.1182+05	.1174+05	.1158+05	.1145+05	.1137+05
J= 10	.1172+05	.1169+05	.1159+05	.1153+05	.1149+05
J= 11	.1162+05	.1161+05	.1160+05	.1160+05	.1161+05
J= 12	.1151+05	.1153+05	.1161+05	.1168+05	.1173+05
J= 13	.1140+05	.1144+05	.1162+05	.1175+05	.1185+05
J= 14	.1130+05	.1136+05	.1162+05	.1182+05	.1197+05
J= 15	.1119+05	.1127+05	.1163+05	.1190+05	.1209+05
J= 16	.1108+05	.1119+05	.1164+05	.1197+05	.1221+05
J= 17	.1097+05	.1110+05	.1164+05	.1204+05	.1233+05
J= 18	.1086+05	.1101+05	.1165+05	.1212+05	.1244+05
J= 19	.1075+05	.1092+05	.1166+05	.1219+05	.1256+05
J= 20	.1064+05	.1083+05	.1166+05	.1226+05	.1268+05
J= 21	.1052+05	.1074+05	.1167+05	.1233+05	.1279+05

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