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DISCRETE ELEMENT ANALYSIS OF THE CREEP OF STAINLESS STEEL TUBING FOR LMFBR APPLICATION

B. R. Dewey

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METALS AND CERAMICS DIVISION

DISCRETE ELEMENT ANALYSIS OF THE CREEP OF STAINLESS STEEL TUBING FOR LMFBR APPLICATION

B. R. Dewey

MARCH 1971

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DISCRETE ELEMENT ANALYSIS OF THE CREEP OF STAINLESS STEEL TUBING FOR LMFBR APPLICATION

B. R. Dewey[1]

ABSTRACT

As a specialized form of finite element stress analysis, the discrete element method is developed for hollow cylindrical solids subjected to pressure and thermal loading. The solution allows arbitrary radial variation of mechanical properties and temperature, computes elastic and inelastic stresses and displacements, and predicts time-dependent deformation based on empirical creep laws. Particular attention is given to the analysis of stainless steel tubing typical of that used in the LMFBR, wherein the creep, stress relaxation, and stress rupture predictions are compared with experimental results.

INTRODUCTION

"Discrete element" is a general approach to stress and displacement analysis. The basic idea has long been used in analyses where a structure is broken down into component parts which are treated individually. For example, Timoshenko[2] describes a procedure for finding the stresses induced by shrink-fitting elastic cylindrical shells of different diameters. Recently, Derby of ORNL[3] applied this simplified procedure to reinforced concrete shells and computed results which

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[1]Consultant from the University of Tennessee.

[2]S. Timoshenko, Strength of Materials, Van Nostrand (1956).

[3]R. W. Derby, "An Approximate Analysis of a Large Prestressed Concrete Cylindrical Section," Nucl. Engr. Design 10, 361 (1969).

compared favorably in accuracy with those from a finite-element code. The procedure also has been used for orthotropic rings[4] where good agreement was attained between experimental data and the simple discrete element theory.

In the present analysis, LMFBR fuel pins are treated as an assemblage of nested concentric hollow circular cylinders. The properties and loading conditions of individual cylinders may be specified arbitrarily so that any thermal- or radiation-induced effects may be accounted for. The elastic solution for the individual cylindrical elements loaded by pressure and temperature is the well-known Lamé problem.[5] The assemblage of elements is effected by equating forces and displacements at the common boundaries.

This approach differs from the popular finite element methods which assume the form of the displacement field (usually linear) within the element. Thus, for equivalent accuracy, far fewer of the sophisticated "discrete" elements than "finite" elements need to be stored and handled in the computer. In addition, the discrete elements allow the very simple treatment of inelastic action due to plastic strain and creep.

The discrete elements share with finite elements the advantage of extension into problems involved with axial variations,

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[4]B. R. Dewey and C. E. Knight, Jr., Experimental and Theoretical Determination of Residual Stresses in Filament-Wound Rings, Y-1701 (January 1970).

[5]S. Timoshenko and J. N. Goodier, Theory of Elasticity, McGraw-Hill (1951).

$f(r, z)$, and perhaps those involved with bowing of fuel pins, $f(r, z, \theta)$. Such extensions do not appear as tractable for established procedures[6] which treat radial variations, $f(r)$.

The work that follows has its main applicability to stainless steel cladding, although it is possible to treat fuel materials that do not develop cracks. In the following stress and displacement analysis, the thermal and metallurgical conditions must be supplied externally. Plasticity is treated through the common elastic-perfectly plastic assumption. In this regard, it should be remarked that cladding intended for long service should not have much plastic yielding upon initial loading. Hence, the lack of inclusion of a strain-hardening rule should not impose a serious limitation for the intended purpose. Deformation by creep is very significant; and experimental data which may be relied upon for the thermal and nuclear conditions encountered in the LMFBR is meager.

As it is dimensioned, a maximum of 30 elements (concentric tubes) may be used in the program. Allowance is made for ten different kinds of materials, with the elastic modulus, Poisson's ratio, thermal expansion coefficient, and the flow stress being specified as arbitrary functions of temperature. These thermally dependent functions are derived by linear extrapolation between

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[6]C. M. Cox and F. J. Homan, Fuels and Materials Development Program Quart. Progr. Rept. Sept. 30, 1969, ORNL-4480, pp. 59–61.

as many as 10 points. Stresses and displacements are printed at selected times during the creep calculation. The computation ends when the maximum time is reached.

A first-trial stress calculation is based on the assumption of entirely elastic properties. If the equivalent stress in an inner or outer layer is found to be greater than the flow stress, the equivalent stress is set equal to the flow stress. Then, the radial and tangential components of stress are recomputed as a function of the flow stress; the assumption that the axial normal stress remains elastic is used. Plasticity is allowed to propagate one layer at a time until the equivalent stresses are all less than or equal to the flow stress. In accordance with the treatment of perfectly plastic solids, if the entire structure reaches yield, it becomes unstable. In many actual situations, however, strain hardening inhibits large plastic flow. In this program, the solution is allowed to continue with the artifice that one interior layer of the structure is assigned some arbitrary stress, and the creep strains are computed from a stress distribution which may not satisfy equilibrium. The output under these conditions should show a very rapid rate of creep, and this condition should be interpreted as imminent failure.

Computing time for this program for a typical problem is less than one minute on the IBM 360/91. Approximately 130-k of core are required for execution. The core storage can be decreased considerably by cutting down the "number of materials" dimension from ten to the number actually used.

ASSIGNMENT OF MATERIAL PROPERTIES

Nonhomogeneity of materials may be handled in two ways. First, up to ten "kinds" of materials are allowed (Number may be increased or decreased by alteration of dimensions in the program). Second, certain material properties may have any arbitrary variation with temperature.

Material properties used in this program are of two types. First, there are creep properties which fit a creep equation of a typical form such as:

$$\dot{\epsilon} = A\,\sigma_e^{\,N}\ \exp\left(-\frac{Q}{RT}\right)\ , \tag{1}$$

where A, N, and Q may be entered as input parameters and are not extrapolated as functions of temperature. Second, the mechanical properties of Young's modulus, Poisson's ratio, yield strength, and coefficient of thermal expansion may all be tabulated functions of temperature. Other creep equations may be used instead of Eq. (1) by altering FØRTRAN statements in the subroutine used for calculating creep deformation.

In the operation of the program, the mean temperature of the ith layer is computed as for steady conduction without sources or sinks in a hollow cylinder:

$$T_i^{\,mean} = (T_a - T_b)\left[\frac{1}{\ln\,(b/a)} - \frac{a}{b-a}\right] + T_b\ , \tag{2}$$

where a and b refer to the inner and outer radii of the elements and where the interface temperatures are supplied externally to

the present program. For volumetric heat sources such as the fuel region or gamma heating, the error introduced by computation of T^{mean} from Eq. (2) is very small if a sufficient number (say 5 or 10) of layers is used. The interpolation of material properties to the layer in question is based on the mean temperature of that layer with a linear fit between the corresponding points of the material property description. Typically, for the ith layer,

$$E_i = E(T_m) + \frac{T_i^{mean} - T_m}{T_n - T_m} \left[E(T_n) - E(T_m)\right] , \qquad (3)$$

where $T_n \leq T_i^{mean} \leq T_m$. The yield strength, Poisson's ratio, and the thermal expansion coefficient are interpolated in a similar fashion. In the event that T_i^{mean} is not bracketed by temperatures on the material properties curves, the values at the lowest (or highest) available temperature are used. Ordinarily, the temperature range of materials properties used as data input should be sufficiently broad to cover actual temperatures in the fuel element.

ELASTIC STRESS ANALYSIS

The elastic stress analysis, which is the first step in every time increment and which is repeated until elastic and plastic conditions are satisfied, is performed in the subroutine DELAST. The elastic stress analysis is based on the concept of fitting together concentric rings (hollow cylinders)

with conditions of compatibility at their boundaries.[7–9] Each of the rings may have arbitrary elastic properties. For this reason, the circumferential stresses are not necessarily continuous at the interfaces between the boundaries.

For individual rings, the stress analysis is based on the pressures at the inside and outside surfaces of the ring and on the temperatures (specified externally) on the inside and outside surfaces. It is assumed that the temperature distribution in each individual layer is logarithmic with the radial coordinate, Eq. (2). This assumption fits the solution to the steady-state heat conduction problem with the sources or sinks concentrated at the interfaces between layers. The pressures at the inner and outer surfaces of the entire fuel pin are specified; the interface pressures are computed from the simultaneous equations formulated in the elastic stress analysis.

A thermoelastic solution for the thick-walled cylinder with an axially symmetric temperature distribution and with internal and external pressure loadings is found by superposing solutions available in Timoshenko and Goodier.[10]

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[7]S. Timoshenko, Strength of Materials, Van Nostrand (1956).

[8]R. W. Derby, "An Approximate Analysis of a Large Prestressed Concrete Cylindrical Section," Nucl. Engr. Design 10, 361 (1969).

[9]B. R. Dewey and C. E. Knight, Jr., Experimental and Theoretical Determination of Residual Stresses in Filament-Wound Rings, Y-1701 (January 1970).

[10]S. Timoshenko and J. N. Goodier, Theory of Elasticity, McGraw-Hill (1951).

The solutions for displacements due to thermal effects may be shown to be for plane stress as:

$$u_o^H(a) = \alpha\ (T_a - T_b)\ (1 + \nu)\ a \left(\frac{0.5}{\ln b/a} - \frac{a^2}{b^2 - a^2}\right) + \alpha\ T_b\ (1 + \nu)\ a \tag{4}$$

$$u_o^H(b) = \alpha\ (T_a - T_b)\ (1 + \nu)\ b \left(\frac{0.5}{\ln b/a} - \frac{a^2}{b^2 - a^2}\right) + \alpha\ T_b\ (1 + \nu)\ b\ , \tag{5}$$

where a and b are the inner and outer radii, respectively. Equations (4) and (5) are modified for plane strain by replacing the quantity $(1 + \nu)$ with $(1 + \nu)^2$ in each term.

If the individual rings could expand freely, the radial component of thermal stress σ_r^H would be zero on the inner and outer surfaces of the rings. The circumferential component σ_t^H is nonzero because of the nonuniformity of temperature in the ring. However, the individual rings do not undergo expansion free of radial stress because of the interaction with adjacent rings. The restraint develops σ_r^H stresses at the surface of each ring and u^H displacements which must be equilibrated in the solution. Such stresses and displacements are designated "thermomechanical."

The solution for the thermomechanical stresses and displacements is accomplished through the system of equations given by:

$$
\begin{bmatrix}
\frac{1}{r_1^2} & 1 & 0 & 0 & 0 & 0 & \cdots & \\
\frac{1}{r_2^2} & 1 & -\frac{1}{r_2^2} & -1 & 0 & 0 & \cdots & \\
-\frac{1-\nu_1}{r_2 E_1} & \frac{(1-\nu_1)r_2}{E_1} & \frac{(1-\nu_2)}{r_2 E_2} & -\frac{(1-\nu_2)r_2}{E_2} & 0 & 0 & \cdots & \\
0 & 0 & \frac{1}{r_3^2} & 1 & -\frac{1}{r_3^2} & -1 & 0 & \cdots \\
0 & 0 & \frac{1-\nu_2}{r_3 E_2} & \cdots & & & & \\
 & & & & & & \cdots & \\
\cdots & & \cdots & & & 0 & \frac{1}{r_m^2} & 1
\end{bmatrix}
\begin{bmatrix} A_1 \\ A_2 \\ A_3 \\ A_4 \\ A_5 \\ \cdots \\ A_{2m} \end{bmatrix}
=
\begin{bmatrix} 0 \\ 0 \\ u_o^H(r_1) - u_o^H(r_2) \\ 0 \\ u_o^H(r_2) - u_o^H(r_3) \\ 0 \\ \cdots \end{bmatrix}
\qquad (6)
$$

where m is the number of layers. The solutions for stresses are given by the following equations with n = 2, 4, 6, ... , 2m.

$$\sigma_r^H(a) = \frac{A_{n-1}}{a^2} + A_n \tag{7a}$$

$$\sigma_r^H(b) = \frac{A_{n-1}}{b^2} + A_n \tag{7b}$$

$$\sigma_t^H(a) = -\frac{A_{n-1}}{a^2} + A_n + \frac{\alpha E\,(T_a - T_b)}{1-\nu}\left(\frac{0.5}{\ln b/a} - \frac{a^2}{b^2 - a^2}\right) \tag{8a}$$

$$\sigma_t^H(b) = -\frac{A_{n-1}}{b^2} + A_n + \frac{\alpha E\,(T_a - T_b)}{1-\nu}\left(\frac{0.5}{\ln b/a} - \frac{b^2}{b^2 - a^2}\right) \tag{8b}$$

$$u^H(a) = u_o^H(a) + \frac{1}{E}\left(\frac{-(1+\nu)\,A_{n-1}}{a} + A_n\,(1-\nu)\,a\right) \tag{9a}$$

$$u^H(b) = u_o^H(b) + \frac{1}{E}\left(\frac{-(1+\nu)\,A_{n-1}}{b} + A_n\,(1-\nu)\,b\right) \tag{9b}$$

The stresses due to internal and external pressure are then superposed upon the thermomechanical stresses given in Eqs. (7) and (8). The pressure stresses are found from the array where the left-hand side of Eq. (6) is set equal to the internal and external pressures as shown:

$$\text{L.H.S. Eq. (6)} = \begin{bmatrix} p_o \\ 0 \\ 0 \\ 0 \\ \cdots \\ 0 \\ p_i \end{bmatrix} \tag{10}$$

A new set of constants, A_n, is obtained from Eq. (10). The stresses σ_t^P (b) and displacements u^P (a) and u^H (b) are found from the corresponding right-hand sides of Eqs. (7) through (9).

The total elastic stresses now may be found by superposition:

$$\sigma_r^e (a) = \sigma_r^P (a) + \sigma_r^H (a) , \quad \text{etc.}$$

When the pressures or thermal gradients are sufficiently high to cause plasticity to commence at the inner and/or outer surfaces, the elastic solution is used only for those layers which have not been shown to be inelastic. In the present program, perfectly elastic-plastic material is assumed; as a consequence, a minimum of one layer should be elastic to prevent the condition where the deformation increases rapidly without bound. For strain-hardening material the elastic solutions described here could be incorporated into the method of successive elastic approximations,[11] whereby a reduced modulus is used in the displacement equations.

The axial stress σ_z is assumed to always be elastic. This assumption is supported by Bland[12] for the pressure and thermal conditions expected in the present circumstances. The axial stress depends upon the kind of restraint on the ends of the fuel elements.

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[11]A. Mendelson, Plasticity: Theory and Application, MacMillan Company (1968).

[12]D. R. Bland, "Elastoplastic Thick-Walled Tubes of Work-Hardening Material Subject to Internal and External Pressures and to Temperature Gradients," J. Mech. Phys. Sci. 4, 209 (1956).

The two extreme cases of: (1) no restraint and (2) built-in ends are considered. It appears that case (1) is more realistic for service conditions; while case (2) is more conservative for design purposes.

For the case (1) of no restraint, the axial stress is given by:

$$\sigma_z = \sigma_r^{\,e} + \sigma_t^{\,e} , \tag{11}$$

which is a direct result of equilibrium.[13] Case (1) is sometimes erroneously called "plane stress." It actually is one case of "generalized plane strain" (ϵ_z = const).

With complete restraint at the ends of the elements, a state of plane strain ($\epsilon_z = 0$) results. Thus, case (2) results[13] for σ_z are:

$$\sigma_z = \nu\,(\sigma_r + \sigma_t) - E\,\alpha\,\Delta T . \tag{12}$$

In the event that σ_r and σ_t are not elastic, σ_z does not enter into the computation of the equivalent stress which affects the creep. Hence, σ_z is not recomputed in any case.

PLASTIC STRESS ANALYSIS

In this program the relatively simple assumption of elastic-perfectly plastic material is used in the plastic (as distinguished from creep) stress analysis. The accuracy of the results obtained

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[13] S. Timoshenko and J. N. Goodier, Theory of Elasticity, McGraw-Hill (1951).

here may be improved by taking thinner (and more) layers. In general, the plastic stress analysis benefits more than does the elastic stress analysis by thinner layers; in an efficient program the plastic layers might be made thin while the elastic ones are relatively thick.

The equivalent stress,

$$\sigma_e = \frac{1}{\sqrt{2}} \sqrt{(\sigma_r{}^e - \sigma_t{}^e)^2 + (\sigma_t{}^e - \sigma_z{}^e)^2 + (\sigma_r{}^e - \sigma_z{}^e)^2} , \qquad (13)$$

is compared with the yield stress σ_y. The plasticity criterion is $\sigma_e > \sigma_y$. In the event that the layer is plastic, we may use the following approximate solution based on the assumption that $\sigma_r \ll \sigma_t$, which improves as the ring gets thinner. From equilibrium of a ring element with $\sigma_t \approx \sigma_e$, we have

$$\sigma_r\ (b) = [\sigma_y - \sigma_r\ (a)]\ (a/b) - \sigma_y\ . \qquad (14)$$

The pressure loading on the layer is simply the negative of σ_r. Since the pressure transmitted across the interfaces between layers is equal, the corresponding radial components of stress are equal. The new pressure is used for the solution of a new elastic problem where the stress distribution is recalculated for the remaining elastic layers.

Checking of the equivalent stress occurs first at the outer layer, and the appropriate assignment of stresses is made. The inner layer is checked next, and the appropriate stresses are assigned to this layer. In the event that both the inner and outer layers are elastic ($\sigma_e < \sigma_y$ on both), it is assumed that the entire structure is elastic. This assumption is justified by the examination of the form of the solutions for the stresses. On the other hand, plastic

conditions on the inner and/or outer layers of the structure initiate further checking of the equivalent stresses in the outermost and innermost remaining elastic layers. The plastic solutions [Eq. (14)] are propagated until the conditions on the equivalent stress are met. One layer, however, is set at some arbitrary stress level. The output should be examined with a cautious view toward any solutions which show that this condition has been imposed. Such a condition should be interpreted as indicating the possibility that the pressure and temperature loading are sufficiently high to cause instantaneous failure. This limitation in the procedure is not judged serious, as any reasonable design of fuel element should not be at anywhere near this high level of loading.

It is noted that deformation due to creep may initiate "plastic" action. This occurs if the creep displacements are such that the equivalent stress is increased. Since the stresses are recomputed after each creep increment, the change of a layer from elastic to plastic (or vice-versa) is possible.

CREEP ANALYSIS

Upon completion of the elastic and plastic stress analysis, the deformations and corresponding changes in stress due to creep are computed. The procedure may be visualized as taking the following form: Each of the layers is separated from the structure, and the

amount of radial deformation in that layer (as based on equivalent stress) is computed from the creep equation. Next, the layers are forced into a configuration dictated by compatibility conditions on the mutual boundaries; creep deformations are treated in the same manner as are deformations due to pressure and temperature. The creep strains accumulated with time are printed out at selected times.

The creep law is contained in subroutine DCREEP and has four arguments which may be entered from data input. One form used for the creep law is:

$$\dot{\varepsilon} = A\, \sigma_e^{\,N}\, G^{-2} \quad \exp\,(-\,Q/RT)\ , \tag{15}$$

where A, N, and Q are empirical constants and G is grain size. Another form of the creep law that has been used is:

$$\dot{\varepsilon} = A \exp\,(-\,Q/RT) \quad [\sinh\,(\sigma_e/G)]^N\ , \tag{16}$$

where A, Q, N, and G are appropriate empirical constants.

Another form of the creep law that is recommended for stainless steel is:

$$\dot{\varepsilon} = A \exp\,(-\,Q/RT)\ [\sinh\,(G\,\sigma_e/T)]^N\ . \tag{17}$$

where the empirical constants A, G, N, and Q take on appropriate values. Whatever creep law is selected may be written in FØRTRAN and placed in the subroutine DCREEP.

Numerical values of the empirical constants need to be carefully chosen to assure applicability for the conditions under consideration. These experimental constants probably are the weakest link in the

entire procedure, since there are meager experimental data for the nuclear and thermal conditions encountered in the projected service requirements. The solution for the creep strain increment $\Delta\epsilon$ is simply computed by replacing $\dot{\epsilon}$ by $\Delta\epsilon/\Delta t$ in Eqs. (15) and (16). The accuracy of the creep computation is improved by decreasing the time increment, Δt; but this is at the expense of computer running time. The numerical scheme used here should provide reasonable stability (see Mendelson[14]) in computation, since the procedure is linked to increments in strain as the independent variable and increments in stress as the dependent variable. A slight improvement might be effected in the creep computation by adding an iterative scheme to compute the stress and displacement distribution due to creep. Such an improvement might be noticeable for long-time solutions.

TYPICAL RESULTS

Experimental data for the creep and stress rupture behavior of stainless steel tubes have been reported by Atomics International.[15–17] Most of their tests have been with cold-worked (as-received) type 304 stainless steel and involve

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[14]A. Mendelson, Plasticity: Theory and Application, MacMillan Company (1968).

[15]W. T. Lee, Biaxial Stress-Rupture Properties of Austenitic Stainless Steels in Static Sodium, AI-AEC-12694 (June 1968).

[16]J. H. Shively, Thermal Gradient Effects on Stress Rupture Behavior of Thin-Walled Tubing, AI-AEC-12695 (June 1968).

[17]J. H. Shively and M. W. Mahoney, Thermal Gradient Effects on Stress-Rupture Behavior of Thin-Walled Tubing, AI-AEC-12896 (January 1970).

pressurization with NaK at approximately 1200°F. In a series of stress-rupture tests with flowing sodium, there was approximately a 50°F temperature gradient through the tube wall which was maintained by a high flux heating element inside the tube.

The circumferential strain reported in these references was computed from diameter measurements, and hence, is assumed to represent the strain on the outer fibers of the tubes. The internal pressure was inferred from the results reported for hoop stress. It should be noted for the cases involving thermal stress that the thermal components of stress relaxed in a few hours, leaving only the pressure-induced stress distribution.

All specimens in the AI tests have a nominal 0.295-in. outside diameter and a 0.010-in. wall. Table 1 shows tabulations for the mechanical properties with the assumed temperature dependence.

The creep law used in the program is of the form suggested,[15,17] where the creep rate is:

$$\dot{\epsilon} = A\,\sigma_e^{\,N}\,\exp(-Q/RT), \tag{18}$$

where

$A = 5.8$

$N = 3.0$

$Q = 78{,}000$ cal/mole

$R = 2$ cal/mole/°K

T = temperature (Kelvin), and

σ_e = equivalent stress (psi).

Table 1. Mechanical Properties Type 304 Cold-Worked Stainless Steel

Temperature (°C)	E, Elastic Modulus (psi)	α, Expansion Coefficient ($°C^{-1}$)	ν, Poisson's Ratio	σ_y, Flow Stress (psi)
	$\times 10^6$	$\times 10^{-6}$		
316	25.0	16.0	0.28	76,570
538	23.0	18.0	0.28	50,000
593	22.5	18.5	0.28	45,000
649	22.0	19.0	0.28	40,000
704	20.0	20.0	0.28	32,000

Creep of Stainless Steel Tubes

In an attempt to duplicate creep data generated by Atomics International,[15,17] the discrete element code was run with Eq. (18) for two hoop stresses in tubes of type 304 cold-worked stainless steel.

The calculated creep rates compare favorably with the earlier data.[15] At a hoop stress of 20,000 psi, the experiments indicate the average strain rate is from 9×10^{-5} to 1.0×10^{-3} %/hr, while the discrete element code predicts a strain rate of 9.0×10^{-5} %/hr on the outer fibers and 1.37×10^{-3} %/hr on the inner fibers. For the same material and temperature, but a hoop stress of 24,000 psi, experimental creep rates are from

1.5×10^{-3} to 2.1×10^{-3} %/hr, while the computed rates are 1.55×10^{-3} to 2.36×10^{-3} %/hr on the outer and inner fibers, respectively.

In the more recent report[17] which is presently also referenced for stress rupture, creep data for what appear to be the same conditions show a decrease in creep rate by a factor of 5. While the empirical constants in creep law, Eq. (18), could be changed to match these data, the empirical constants give good agreement with the stress-rupture data[17] and the previous creep data.[15] It is not known if these differences are due to scatter in the data or some other cause.

It should be noted that the discrete element program is presently set up for secondary creep. In situations where primary and tertiary creep are significant, a scheme could be added which makes appropriate modifications.

Stress Relaxation and Stress Rupture

Tests were performed[16,17] on tubular specimens which were pressurized and heated internally and externally cooled by flowing sodium. The internal heating produces thermal stresses in the wall, and the internal pressurization simulates fission gas and swelling effects.

The time-dependent variations of the hoop and radial stress distributions are shown in Figs. 1 and 2, respectively. For purposes of comparison, the results from the so-called "thin-wall" theory are also shown in Fig. 1. (The thin-wall theory does not treat the radial stress.) The larger hoop stress gradient predicted by the discrete element code is mainly due to the inclusion of the radial variation of material properties in the code. For this same reason, the initial values of the hoop stress are double values. As the stress relaxes, the hoop stress values at the interface become equal. The relaxation of the radial stress, Fig. 2, is not as pronounced as that of the hoop stress. The inclusion of the radial stress becomes increasingly important as the tubing thickness and/or the temperature gradient is increased.

By computing the strain in the tubing as a function of time, we can roughly duplicate the stress rupture tests.[18] It happens that as the tube creeps outward at constant stress, the circumferential component of strain at the inner radius increases more rapidly than that at the outer radius. The values thus computed in Table 2 bracket the experimentally determined values for peak strain at rupture. Based on the two experimental data points at the same loading conditions, however, the prediction of stress rupture is subject to a great deal of scatter and depends on variables (e.g., flaws) not considered in this analysis.

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[18] J. H. Shively and M. W. Mahoney, Thermal Gradient Effects on Stress-Rupture Behavior of Thin-Walled Tubing, AI-AEC-12896 (January 1970).

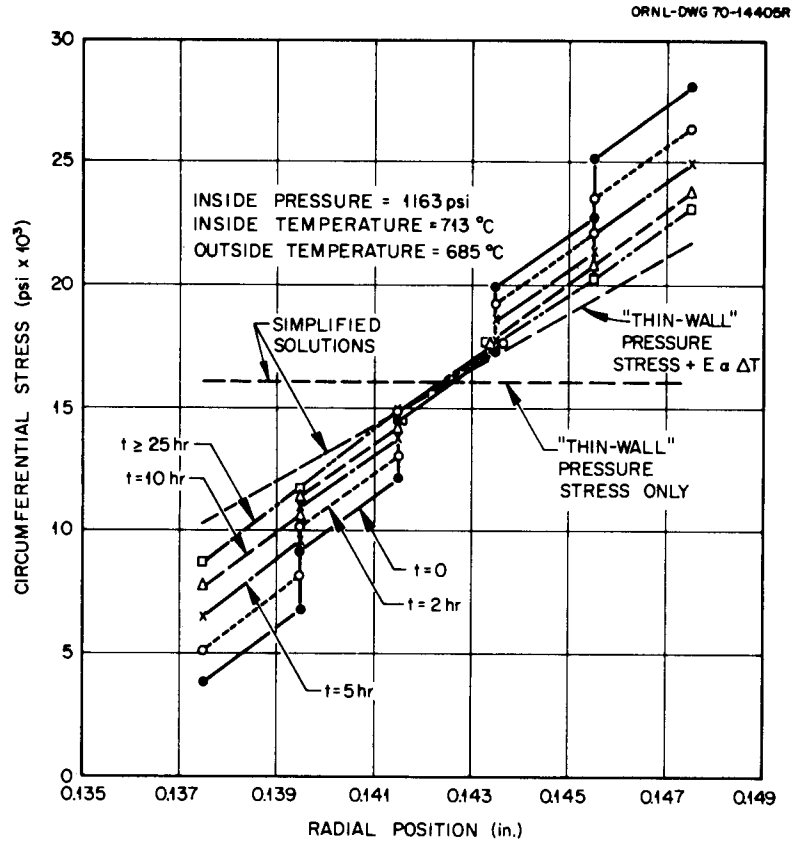

Fig. 1. Relaxation of Hoop Stress.

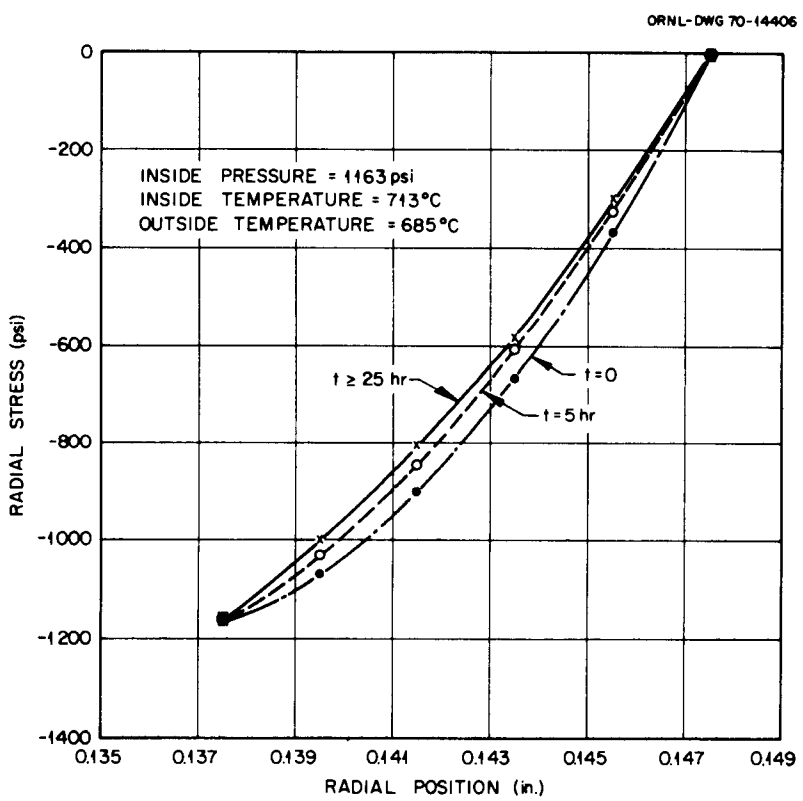

Fig. 2. Relaxation of Radial Stress.

Table 2. Stress Rupture of Cold-Worked Type 304 Stainless Steel Tubing with Internal Pressure and Thermal Gradient

Experimental (8)				Computed	
Specimen Number	σ_θ (psi)	Rupture Time (hr)	Peak Strain (%)	Outer ϵ_θ (%)	Inner ϵ_θ (%)
	$\times 10^3$				
30	21	177	2.2	2.4	1.2
36	16	558	2.8	4.2	1.0
53	16	392	2.5	2.9	0.7

It is desirable to predict strain-time behavior for pressurized tubes having a temperature gradient by means of data from pressurized tubes at constant temperature. Apparently, consideration of the effect of the radial variation of properties leads to better such predictions than does the use of the over-simplified "thin-wall" treatment.

Effect of Time-Interval Size

The magnitude of the time increment, Δt, plays an important role in the accuracy of incremental creep calculations.[19] The selection of Δt is guided largely by experience, with consideration given to the amount of nonlinearity expected and the computing time.

[19] A. Mendelson, Plasticity: Theory and Application, MacMillan Company (1968).

For the five-element configuration used in test problems, approximately 18 iterations are performed per second on the ORNL IBM/360/91. (The program was compiled on the ORNL Fortran compiler.) Two different interval sizes were used, with other variables held constant. The comparisons of the creep strains predicted are given in Table 3 for a tube having the same conditions as those in Figs. 1 and 2.

It may be advantageous to improve the efficiency of the code by causing it to run with a small Δt in the region of nonlinear creep and increase the size of Δt automatically in regions of linear creep. Such a procedure would be advantageous for calculations involving very long running times.

Table 3. Effect of Time-Interval Size upon Maximum Creep Strain in the Circumferential Direction

Time Interval, Δt (hr)	Strain at Time 30 hr (%)	Strain at Time 60 hr (%)
0.2	0.255	0.481
2.0	0.269	0.495

CONCLUSIONS

The discrete element analysis, as presently constituted, appears capable of treating the time-dependent mechanical analysis of cladding with thermal and pressure loads for steady-state conditions where axial symmetry exists.

It should be noted that a crude model is used for plastic deformation; hence, the program is not recommended for calculations where the plastic strain is large.

The main advantage of the procedure is its capability for extension into cladding analysis where axial and bending effects are considered. Also, it is conceivable that a cracked fuel region could be handled by such a technique whereby the wedge-shaped pieces of fuel are the discrete elements.

APPENDIX A

Preparation of Input Cards

Card No. 1. Problem identification.

0–80
Alphanumeric Information
20A4

Card No. 2. Overall geometry description

1–16	17–20	21–24	25–32	33–40	41–48	49–56	57–64	65–72	73–76	77–80
Alpha-numeric Info.	No. of Matl's (≤ 10)	No. of Layers (≤ 30)	Inside Radius (Ass'y) (in.)	Inside Pressure (psi)	Inside Temp (°C)	Outside Pressure (psi)	End Time Creep (hr)	ΔT Creep (hr)	Plane Strain *	Print Interval (No. of ΔT's)
4A4	I4	I4	F8.0	F8.0	F8.0	F8.0	F8.0	F8.0	I4	I4

*Set equal to 1: Plane strain ($\epsilon_z = 0$).

Set equal to 0: No end restraint on tube (ϵ_z = constant).

Cards No. 3. Description of individual layers (One card for each individual layer; layer No. 1 starts at the outside).

1–5	6–10	11–20	21–30
Layer Number	Material No. in Layer	Outside Radius of Layer (in.)	Temp at Outside of Layer (°C)
I5	I5	F10.0	F10.0

Cards No. 4. Identification of material properties
(One card for each kind of material; see note on Cards No. 4a).

1–5	6–10	11–20	21–30	31–40	41–50
Material Number	No. of Points, Properties List (≤ 10)	Creep* Constant A	Creep* Constant N	Creep* Constant Q	Creep* Constant G
I5	I5	E10.0	E10.0	E10.0	E10.0

*Any creep law may be used by alteration of SUBRØUTINE DCREEP. Four arguments are provided here; all do not have to be used.

Cards No. 4a. Piecewise linear descriptions of material properties as functions of temperature.
(One card for each point on the properties list; an entire group of these cards follows each No. 4 card for each kind of material).

1–10	11–20	21–30	31–40	41–50	51–60
Point Number (≤ 10)	Temp at Point (°C)	Elastic Modulus (psi)	Thermal Expansion Coefficient ($°C^{-1}$)	Poisson's Ratio	Yield Stress
I10	F10.0	E10.0	E10.0	F10.0	F10.0

APPENDIX B

Program Output Description

PROGRAM OUTPUT DESCRIPTION

The first section of output describes the material properties and the mean temperature of each of the n layers. Usually, the modulus of elasticity and the yield strength will be in psi, the mean temperature in °C, the coefficient of thermal expansion in $°C^{-1}$, and the radius in inches. The layers are numbered from the outside to the inside. The MATL column identifies the material by an integer ($1 \leq MATL \leq 10$) according to the identifying number on the output.

The main section of the output gives the stress and strain information as a function of time. The columns, printed in pairs for the outside and inside of each of the layers, list the radial stress, the circumferential stress, the circumferential strain, and the axial stress. Under the heading TOTAL ELASTIC STRESSES AND DISPLACEMENTS are printed only the elastic stresses and the elastic circumferential strain. All iterations are printed; the omission of a layer indicates it is inelastic. Under the heading TOTAL STRESSES AND CREEP DISPLACEMENTS the elastoplastic solutions for stresses are given along with the circumferential strain due to creep only.

The first listed output under TOTAL STRESSES AND CREEP DISPLACEMENTS represents the stress state for zero time and the creep strain at time = $0 + \Delta t$. This is because the numerical analysis method uses the "previous" stress to compute the "new" creep strain. If the time increment Δt is reasonably small, this is not a serious limitation.

Certain control information also is contained in the output. The ELAS iterations specify the number of times subroutine DELAST was called to generate the stress and strain field which follows. The number of ELAS iterations increases according to the number of plastic layers and the number of points calculated between printouts.

APPENDIX C

Description of Subroutines

DESCRIPTION OF SUBROUTINES

The following subroutines in the program perform the functions as follows.

DELAST

Solves for elastic stresses and displacements in the multilayer cylinder as described in the section on Elastic Stress Analysis.

DCREEP

Contains the creep law and supplies the creep displacements of each element.

DØBEF

Renumbers the elastic layers in preparation for using DELAST.

DØAFT

Renumbers the elastic layers to the original numbers after the completion of DELAST.

PLAINS

Changes the elastic modulus, thermal expansion coefficient, and Poisson ratio to the values for plane strain (ends of cylinder restrained) when this condition is specified.

EXCEED

Prints a warning that all layers are stressed above the elastic limit and sets the equivalent stress in the innermost layer to some predetermined "ultimate." It is called by subroutine DCREEP.

SIMQ

Is a library subroutine for the solution of simultaneous equations using a Gaussian elimination procedure. It is called by subroutine DELAST.

APPENDIX D

Sample Problem

STAINLESS STEEL TUBE WITH INTERNAL PRESSURE AND THERMAL GRADIENT

INSIDE PRESSURE = 1163. OUTSIDE PRESSURE = 0. END TIME = 50. HRS. DELTA T = 2.00 HRS.

LAYER	MATL. NO.	RADIUS-OUT	TEMP-OUT
1	1	0.14750	685.0
2	1	0.14550	690.6
3	1	0.14350	696.1
4	1	0.14150	701.7
5	1	0.13950	707.2
		0.13750	712.8

CREEP CONSTANTS

A	N	Q	G	MATL. NO.
0.5800E 01	0.3000E 01	0.7800E 05	0.0	1

MECHANICAL PROPERTIES MATL. NO. 1

TEMP.	E	ALPHA	POISSON RATIO	FLOW STRESS
316.	0.2500E 08	0.1600E-04	0.2806	0.7657E 05
538.	0.2300E 08	0.1800E-04	0.2806	0.5000E 05
593.	0.2250E 08	0.1850E-04	0.2806	0.4500E 05
649.	0.2200E 08	0.1900E-04	0.2806	0.4000E 05
704.	0.2000E 08	0.2000E-04	0.2806	0.3200E 05

ENDS NOT RESTRAINED

TEST CASE

LAYER	E(L)	GNU(L)	ALPHA(L)	YS(L)	TMEAN	O.R.	MATL
1	0.20589E 08	0.28060E 00	0.19706E-04	0.24355E 05	0.96096E 03	0.14750E 00	1
2	0.20387E 08	0.28060E 00	0.19806E-04	0.33550E 05	0.96650E 03	0.14550E 00	1
3	0.20185E 08	0.28060E 00	0.19907E-04	0.32740E 05	0.97206E 03	0.14350E 00	1
4	0.19983E 08	0.28060E 00	0.20008E-04	0.31933E 05	0.97761E 03	0.14150E 00	1
5	0.19781E 08	0.28060E 00	0.20109E-04	0.31125E 05	0.98316E 03	0.13950E 00	1

TOTAL STRESSES AND CREEP DISPLACEMENTS TIME = 0. HRS. 1 ELAS ITERATIONS

N	SIGR-OUT	SIGR-IN	SIGT-OUT	SIGT-IN	CR ST-OUT	CR ST-IN	SIGZ-OUT	SIGZ-IN
1	0.0	-0.36611E 03	0.28030E 05	0.25238E 05	0.26853E-03	0.25928E-03	0.28030E 05	0.24872E 05
2	-0.36611E 03	-0.66827E 03	0.22702E 05	0.19917E 05	0.18962E-03	0.16954E-03	0.22336E 05	0.19249E 05
3	-0.66827E 03	-0.90361E 03	0.17427E 05	0.14534E 05	0.11515E-03	0.90113E-04	0.16758E 05	0.13630E 05
4	-0.90361E 03	-0.10695E 04	0.12112E 05	0.92207E 04	0.54010E-04	0.33436E-04	0.11208E 05	0.81512E 04
5	-0.10695E 04	-0.11630E 04	0.68574E 04	0.38545E 04	0.15305E-04	0.49137E-05	0.57879E 04	0.26915E 04

TOTAL STRESSES AND CREEP DISPLACEMENTS TIME = 50. HRS. 25 ELAS ITERATIONS

N	SIGR-OUT	SIGR-IN	SIGT-OUT	SIGT-IN	CR ST-OUT	CR ST-IN	SIGZ-OUT	SIGZ-IN
1	0.0	-0.29836E 03	0.23135E 05	0.20275E 05	0.41975E-02	0.37828E-02	0.23135E 05	0.19977E 05
2	-0.29836E 03	-0.56551E 03	0.20275E 05	0.17455E 05	0.36609E-02	0.31214E-02	0.19976E 05	0.16889E 05
3	-0.56551E 03	-0.79977E 03	0.17454E 05	0.14561E 05	0.29992E-02	0.23479E-02	0.16889E 05	0.13761E 05
4	-0.79978E 03	-0.99955E 03	0.14561E 05	0.11704E 05	0.22267E-02	0.15647E-02	0.13761E 05	0.10704E 05
5	-0.99956E 03	-0.11630E 04	0.11703E 05	0.87699E 04	0.14440E-02	0.84072E-03	0.10703E 05	0.76069E 04

APPENDIX E

FØRTRAN Listing

```
**FTN,G,L,E.
C    DISCRETE ELEMENT ANALYSIS OF FUEL AND CLADDING
      COMMON/XSHIFT/XROE(30),XRIE(30),XTOE(30),XTIE(30),XIH(30),XOH(30)
     1XIC(30),XOC(30),XI(31),XTEMP(31),XE(30),XGNU(30),XALPHA(30)
      COMMON/STRESS/SIGROE(30),SIGRIE(30),SIGTOE(30),SIGTIE(30),SIGRO(30
     1),SIGRI(30),SIGTO(30),SIGTI(30),PRESSO,UIH(30),UOH(30),UIC(30),UOC
     2(30),SIGZI(30),SIGZO(30)
      COMMON/GEOMAT/R(31),TEMP(31),E(30),GNU(30),ALPHA(30),YS(30)
      COMMON/CREEPC/CA(30),CN(30),CQ(30),CG(30),DTIME
      COMMON/CREEPS/SIGE(30),SOGE(30),DUIC(30),DUOC(30)
      DIMENSION LABEL(4),MATL(30),TEMPM(10,10),EM(10,10),ALPHAM(10,10),
     1GNUM(10,10),YSM(10,10)
      DIMENSION CAR(10),CNR(10),CQR(10),CGR(10)
      DIMENSION MAST (20)
      DIMENSION EOC(30),EIC(30)
C
C  INPUT GEOMETRY AND TEMPERATURE. INPUT MATERIALS
C
   10 READ 400, (MAST(I),I=1,20)
  400 FORMAT (20A4)
      PRINT 492,(MAST(I),I=1,20)
C
C   FOR ISPLEP = 1, PLANE STRAIN.   FOR ISPLEP = 0, NO END RESTRAINT
C
C    NOTE0  LAYERS ARE NUMBERED FROM OUTSIDE TO INSIDE
C
      READ 401,(LABEL(I),I=1,4),NOMAT,NLAY,RI,PRESSI,TEMPI,PRESSO,TIMEND
     1,DTIME,ISPLEP,IPPINT
      PRINT 450,PRESSI,PRESSO,TIMEND,DTIME
      PRINT 451
   11 READ 402,L,MATL(L),R(L),TEMP(L)
      PRINT 452,L,MATL(L),R(L),TEMP(L)
   12 IF(L.LT.NLAY) GO TO 11
      PRINT 453,RI,TEMPI
   20 READ 403,M,NOPTS,CAR(M),CNR(M),CQR(M),CGR(M)
      PRINT 454,M
      PRINT 455,CAR(M),CNR(M),CQR(M),CGR(M)
      PRINT 456,M
   21 READ 404,N,TEMPM(M,N),EM(M,N),ALPHAM(M,N),GNUM(M,N),YSM(M,N)
      PRINT 457, TEMPM(M,N),EM(M,N),ALPHAM(M,N),GNUM(M,N),YSM(M,N)
   22 IF (N.LT.NOPTS) GO TO 21
   23 IF (M.LT.NOMAT) GO TO 20
      TEMP(NLAY+1) = TEMPI
      R(NLAY+1) = RI
      IP=IPPINT
      TIME=-DTIME
      ISTEPS =0
      DO 26 I=1,NOMAT
      DO 26 J=1,NOPTS
   26 TEMPM(I,J)=TEMPM(I,J)+273.15
      DO 29 I =1,31
   29 TEMP(I) = TEMP(I) + 273.15
  401 FORMAT(4A4,2I4,6F8.0,2I4)
  402 FORMAT (2I5,2F10.0)
  403 FORMAT (2I5,4E10.0)
  404 FORMAT(I10,F10.0,2E10.0,2F10.0)
  450 FORMAT(1H0,17HINSIDE PRESSURE =,F7.0,8X,18HOUTSIDE PRESSURE =,F7.0
```

```
     1,8X,10HEND TIME =,F7.0,5H HRS.,8X,9HDELTA T =,F7.2,5H HRS. )
  451 FORMAT(6HOLAYER,12H    MATL. NO.,14H     RADIUS-OUT,11H    TEMP-OUT)
  452 FORMAT(I5,I10,F15.5,F14.1)
  453 FORMAT(15X,F15.5,F14.1)
  454 FORMAT(16HOCREEP CONSTANTS,13X,1HA,14X,1HN,14X,1HQ,14X,1HG,14X, 9H
     1MATL. NO.,I3)
  455 FORMAT(20X,4E15.4)
  456 FORMAT(22HOMECHANICAL PROPERTIES,11H  MATL. NO.,I3,5X,5HTEMP.,8X,
     11HE,9X,5HALPHA,16H    POISSON RATIO,14H    FLOW STRESS)
  457 FORMAT(40X,F6.0,2E11.4,F9.4,E18.4)
C
C  ASSIGN ELASTIC PROPERTIES TO LAYERS DEPENDING ON MEAN TEMPERATURE
C
      IF(ISPLEP.EQ.1) PRINT 440
  440 FORMAT (13H PLANE STRAIN)
      IF(ISPLEP.EQ.0) PRINT 441
  441 FORMAT (20H ENDS NOT RESTRAINED)
      PRINT 493,(LABEL(I),I=1,4)
      PRINT 494
  492 FORMAT (1H1,10X,20A4)
  493 FORMAT (1H0,4A4)
  494 FORMAT (6HOLAYER,5X,4HE(L),10X,6HGNU(L),8X,8HALPHA(L),8X,5HYS(L)
     1,10X,5HTMEAN,11X,4HO.R.,8X,4HMATL//)
   30 DO 50 L=1,NLAY
      TMEAN =  (TEMP(L+1)-TEMP(L))*(1.0/ALOG(R(L)/R(L+1))-R(L+1)/(R(L)-     912-3
     1R(L+1))) + TEMP(L)
      N=1
      M=MATL(L)
C     ASSIGN CREEP PROPERTIES TO LAYERS
      CA(L)=CAR(M)
      CN(L)=CNR(M)
      CQ(L)=CQR(M)
      CG(L)=CGR(M)
      IF(NOPTS.EQ.1) GO TO 35
      IF (TEMPM(M,N)-TMEAN) 40,35,35
   35 E(L) = EM(M,N)
      GNU(L) = GNUM(M,N)
      ALPHA(L) = ALPHAM(M,N)
      YS(L) = YSM(M,N)
      GO TO 50
   40 N=N+1
      IF(N.EQ.NOPTS) GO TO 45
      IF(TEMPM(M,N)-TMEAN) 40,45,45
   45 XT = (TMEAN-TEMPM(M,N-1))/(TEMPM(M,N)-TEMPM(M,N-1))
      E(L) = EM(M,N-1) + XT*(EM(M,N)-EM(M,N-1))
      GNU(L) = GNUM(M,N-1) + XT*(GNUM(M,N)-GNUM(M,N-1))
      ALPHA(L) = ALPHAM(M,N-1) + XT*(ALPHAM(M,N)-ALPHAM(M,N-1))
   49 YS(L) = YSM(M,N-1) + XT*(YSM(M,N)-YSM(M,N-1))
   50 PRINT 495,L,E(L),GNU(L),ALPHA(L),YS(L),TMEAN,R(L),M
  495 FORMAT(I5,6E15.5,I7)
      IF(ISPLEP.EQ.1) CALL PLAINS(NLAY)
      TMED=(TEMP(NLAY+1)-TEMP(1))*(1.0/ALOG(R(1)/R(NLAY+1))-R(NLAY+1)/
     1(R(1)-R(NLAY+1)))+TEMP(1)
C
C  STRESS ANALYSIS
C
      DO 51 I=1,30
```

```
      UIC(I)=0.0
   51 UOC(I)=0.0
   52 CALL DOBEF(1,NLAY)
      CALL DELAST(NLAY,PRESSI,PRESSO)
      CALL DOAFT(1,NLAY)
      ISTEPS=ISTEPS+1
C
C     CHECK EQUIVALENT STRESS IN INNERMOST LAYER THAT IS ELASTIC (IL)
C
C
C   ELASTOPLASTIC ANALYSIS WORKING FROM INNER AND OUTER SURFACES
C
  100 DO 105 N=1,NLAY
      IF(ISPLEP.EQ.1) SIGZI(N)=GNU(N)*(SIGRIE(N)+SIGTIE(N))-E(N)*ALPHA(N
     1)*(TEMP(N+1)-TMED)
      IF(ISPLEP.EQ.1) SIGZO(N)=GNU(N)*(SIGROE(N)+SIGTOE(N))-E(N)*ALPHA(N
     1)*(TEMP(N)-TMED)
      IF(ISPLEP.EQ.0) SIGZI(N)=SIGRIE(N)+SIGTIE(N)
      IF(ISPLEP.EQ.0) SIGZO(N)=SIGROE(N)+SIGTOE(N)
      SIGE(N)=1./SQRT(2.)*SQRT((SIGRIE(N)-SIGTIE(N))**2+(SIGTIE(N)-SIGZI
     1(N))**2+(SIGRIE(N)-SIGZI(N))**2)
      SOGE(N)=1./SQRT(2.)*SQRT((SIGROE(N)-SIGTOE(N))**2+(SIGTOE(N)-SIGZO
     1(N))**2+(SIGROE(N)-SIGZO(N))**2)
      SIGRI(N)= SIGRIE(N)
      SIGRO(N)= SIGROE(N)
      SIGTI(N)= SIGTIE(N)
  105 SIGTO(N)= SIGTOE(N)
      PN=PRESSI
      PO=PPESSO
      IL=NLAY
      LO=1
  108 IF(SIGE(IL).GT.YS(IL)) GO TO 150
      IF(SOGE(LO).GT.YS(LO)) GO TO 130
  110 CALL DCREEP(NLAY)
      TIME = TIME + DTIME
  115 DO 120 N=1,NLAY
      UOC(N)=UOC(N)+DUOC(N)
      UIC(N)=UIC(N)+DUIC(N)
      EOC(N)=UOC(N)/R(N)
  120 EIC(N)=UIC(N)/R(N+1)
      IF(IP.LT.IPRINT) GO TO 126
      IP=0
      PRINT 2100,TIME,ISTEPS
 2100 FORMAT(39HOTOTAL STRESSES AND CREEP DISPLACEMENTS ,10X,6HTIME = ,
     1F7.0,5H HRS. ,10X,I8,16H ELAS ITERATIONS )
 1000 PRINT 1001
 1001 FORMAT(5HO   N,4X,8HSIGR-OUT,8X,7HSIGR-IN,7X,8HSIGT-OUT,8X,7HSIGT-
     1IN,8X,9HCR ST-OUT,5X,8HCR ST-IN,6X,8HSIGZ-OUT,8X,7HSIGZ-IN)
      DO 125 N=1,NLAY
  125 PRINT 4,N,SIGRO(N),SIGRI(N),SIGTO(N),SIGTI(N),ECC(N),EIC(N),
     1SIGZO(N),SIGZI(N)
    4 FORMAT(I5,8E15.5)
      ISTEPS= 0
  126 IP=IP+1
      IF(TIME-TIMEND)52,52,10
  130 SOGE(LO)=YS(LO)
      SIGE(LO)=YS(LO)
```

```
      IF((LO+1).GE.IL)GO TO 110
      SIGRO(LO)=-PO
      PO=R(LO)/R(LO+1)*(PO-YS(LO))+YS(LO)
      SIGRI(LO)=-PO
      SIGRO(LO+1)=-PO
  136 TERMO=ABS(-3.*SIGRO(LO)**2-3.*SIGZO(LO)**2+6.*SIGRO(LO)*
     1SIGZO(LO)+4.*SOGE(LO)**2)
      TERMI=ABS(-3.*SIGRI(LO)**2-3.*SIGZI(LO)**2+6.*SIGRI(LO)*
     1SIGZI(LO)+4.*SIGE(LO)**2)
      SIGTO(LO)=(SIGRO(LO)+SIGZO(LO)+SQRT(TERMO))/2.
      SIGTI(LO)=(SIGRI(LO)+SIGZI(LO)+SQRT(TERMI))/2.
      LO=LO+1
      NEL=NLAY+(1-LO)-(NLAY-IL)
C
C  RENUMBER ELASTIC LAYERS
C
  140 CALL DOBEF(LO,NEL)
      CALL DELAST (NEL,PN,PO)
      CALL DOAFT(LO,NEL)
      ISTEPS=ISTEPS+1
  143 DO 146 N=LO,IL
      IF(ISPLEP.EQ.1) SIGZI(N)=GNU(N)*(SIGRIE(N)+SIGTIE(N))-E(N)*ALPHA(N
     1)*(TEMP(N+1)-TMED)
      IF(ISPLEP.EQ.1) SIGZO(N)=GNU(N)*(SIGROE(N)+SIGTOE(N))-E(N)*ALPHA(N
     1)*(TEMP(N)-TMED)
      IF(ISPLEP.EQ.0) SIGZI(N)=SIGRIE(N)+SIGTIE(N)
      IF(ISPLEP.EQ.0) SIGZO(N)=SIGROE(N)+SIGTOE(N)
      SIGE(N)=1./SQRT(2.)*SQRT((SIGRIE(N)-SIGTIE(N))**2+(SIGTIE(N)-SIGZI
     1(N))**2+(SIGRIE(N)-SIGZI(N))**2)
      SOGE(N)=1./SQRT(2.)*SQRT((SIGROE(N)-SIGTOE(N))**2+(SIGTOE(N)-SIGZO
     1(N))**2+(SIGROE(N)-SIGZO(N))**2)
  146 CONTINUE
      GO TO 108
  150 SIGE(IL)=YS(IL)
      SOGE(IL)=YS(IL)
   63 SIGRI (IL) = -PN
      PN= (PN-YS(IL))*R(IL+1)/R(IL)+YS(IL)
      SIGRI(IL-1)=-PN
   65 SIGRO (IL) = -PN
  166 TERMO=ABS(-3.*SIGRO(IL)**2-3.*SIGZO(IL)**2+6.*SIGRO(IL)*
     1SIGZO(IL)+4.*SOGE(IL)**2)
      TERMI=ABS(-3.*SIGRI(IL)**2-3.*SIGZI(IL)**2+6.*SIGRI(IL)*
     1SIGZI(IL)+4.*SIGE(IL)**2)
      SIGTO(IL)=(SIGRO(IL)+SIGZO(IL)-SQRT(TERMO))/2.
      SIGTI(IL)=(SIGRI(IL)+SIGZI(IL)-SQRT(TERMI))/2.
      IL=IL-1
  171 NEL=1-LO+IL
      IF(LO.GE.IL) GO TO 110
      IF(SOGE(LO).GT.YS(LO))GO TO 130
      GO TO 140
      END
```

```
      SUBROUTINE  DDBEF (LO,N)
      COMMON/STRESS/SIGROE(30),SIGRIE(30),SIGTOE(30),SIGTIE(30),SIGRO(30
     1),SIGRI(30),SIGTO(30),SIGTI(30),PRESSO,UIH(30),UOH(30),UIC(30),UOC
     2(30),SIGZI(30),SIGZO(30)
      COMMON/GEOMAT/R(31),TEMP(31),E(30),GNU(30),ALPHA(30),YS(30)
      COMMON/XSHIFT/XROE(30),XRIE(30),XTOE(30),XTIE(30),XIH(30),XOH(30)
     1XIC(30),XOC(30),XR(31),XTEMP(31),XE(30),XGNU(30),XALPHA(30)
      L=LO
      DO 2 I=1,N
      XROE(I)=SIGROE(L)
      XRIE(I)=SIGRIE(L)
      XTIE(I)=SIGTIE(L)
      XTOE(I)=SIGTOE(L)
      XIH(I)=UIH(L)
      XOH(I)=UOH(L)
      XIC(I)=UIC(L)
      XOC(I)=UOC(L)
      XR(I)= R(L)
      XTEMP(I)=TEMP(L)
      XE(I)=E(L)
      XGNU(I)=GNU(L)
      XALPHA(I)=ALPHA(L)
    2 L=L+1
      XR(N+1)=R(L)
      XTEMP(N+1)=TEMP(L)
      RETURN
      END
```

```
      SUBROUTINE DELAST (NOEL,PRESSI, PRESSO)
CASE WITH  TWO  CONSTANTS ON THERMAL CONDITIONS
      COMMON/XSHIFT/SIGROE(30),SIGRIE(30),SIGTOE(30),SIGTIE(30),UIH(30),
     1UOH(30),UIC(30),UOC(30),R(31),TEMP(31),E(30),GNU(30),ALPHA(30)
      DIMENSION SIGROH(30),SIGRIH(30),SIGTOH(30),SIGTIH(30),A(60,60),
     1B(60),AA(3600),BB(60)
    1 DO 5 I=1,60
    2 B(I) = 0.0
      DO 5 J=1,60
    5 A(I,J) = 0.0
      NOEQ = 2*NOEL
      DO 105 I=1,30
      SIGROH(I)=0.0
      SIGRIH(I)=0.0
      SIGTOH(I)=0.0
      SIGTIH(I)=0.0
      UIH(I)   =0.0
      UOH(I)   =0.0
  105 CONTINUE
C
COMPUTE THERMAL-ONLY DISPLACEMENTS
C
  109 DO 110 N=1,NOEL
C   EXPRESSION FOR PLANE STRAIN
      UOH(N)=ALPHA(N)*(TEMP(N+1)-TEMP(N))*(1.0+GNU(N))*R(N)*(0.5/ALOG
     1(R(N)/R(N+1))-R(N+1)**2/(R(N)**2-R(N+1)**2))+ALPHA(N)*(1+GNU(N))*
     2TEMP(N)*R(N)
      UIH(N) = UOH(N)*R(N+1)/R(N)
      UIH(N) = UIH(N) + UIC(N)
  110 UOH(N) = UOH(N) + UOC(N)
C
C SET UP ARRAY FOR THERMAL-MECHANICAL STRESSES AND DISPLACEMENTS
C
      A(1,1) = 1.0/R(1)**2
      A(1,2) = 1.0
      DO 120 N=2,NOEL
      A(2*N-2,2*N-3) = 1.0/R(N)**2
      A(2*N-2,2*N-2) = 1.0
      A(2*N-2,2*N-1) = -1.0/R(N)**2
      A(2*N-2,2*N  ) = -1.0
      A(2*N-1,2*N-3) =-1.0/E(N-1) * (1.0+GNU(N-1))/R(N)
      A(2*N-1,2*N-2) = (1.0-GNU(N-1))*R(N)/E(N-1)
      A(2*N-1,2*N-1) = 1.0/E(N) * (1.0+GNU(N))/P(N)
      A(2*N-1,2*N  ) =-(1.0-GNU(N))*R(N)/E(N)
      B(2*N-1) = UOH(N) - UIH(N-1)
  120 CONTINUE
      A(2*NOEL,2*NOEL-1) = 1.0/R(NOEL+1)**2
  130 A(2*NOEL,2*NOEL  ) = 1.0
C
CONVERT FOR SIMULTANEOUS EQUATION SOLVER 'SIMQ'
C
      K = 0
      DO 140 J=1,NOEQ
      BB(J) = B(J)
      DO 140 I=1,NOEQ
      K= K+1
```

```
  140 AA(K) = A(I,J)
      CALL SIMQ (AA,BB,NOEQ,KSIG)
C
C
C  THERMAL STRESSES AND DISPLACEMENTS BY SUPERPOSITION
C
      DO 150 N=1,NOEL
      SIGROH(N) = BB(2*N-1)/R(N)**2 + BB(2*N)
      SIGRIH(N) = BB(2*N-1)/R(N+1)**2 + BB(2*N)
      UIH(N) = UIH(N) + 1.0/E(N)*(-(1.0+GNU(N))*BB(2*N-1)/R(N+1) + BB(2*
     1N)*(1.0-GNU(N))*R(N+1) )
      UOH(N) = UOH(N) + 1.0/E(N)*(-(1.0+GNU(N))*BB(2*N-1)/R(N) + BB(2*N)
     2*(1.0-GNU(N))*R(N) )
      SIGTOH(N) = -BB(2*N-1)/R(N)**2 + BB(2*N) + ALPHA(N)*E(N)*(TEMP(N+
     11)-TEMP(N))/(1.0-GNU(N)) * (0.5/ALOG(R(N)/R(N+1)) - R(N+1)**2 /
     2(R(N)**2 - R(N+1)**2))
  150 SIGTIH(N) = -BB(2*N-1)/R(N+1)**2 + BB(2*N) + ALPHA(N)*E(N)*(TEMP
     1(N+1)-TEMP(N))/(1.0-GNU(N)) *(0.5/ALOG(R(N)/R(N+1)) - R(N)**2 /
     2(R(N)**2 - R(N+1)**2))
      DO 180 I=1,60
  178 B(I) = 0.0
      DO 180 J=1,60
  180 A(I,J) = 0.0
C
C  PRESSURE STRESSES AND DISPLACEMENTS
C
      NOEQ = 2*NOEL
      A(1,1) = 1.0/R(1)**2
      A(1,2) = 1.0
      B(1) = -PRESSO
C  EQUATE SIGMA R AND DISPLACEMENTS AT INTERFACES
      DO 210  N=2,NOEL
      A(2*N-2,2*N-3) = 1.0/R(N)**2
      A(2*N-2,2*N-2) = 1.0
      A(2*N-2,2*N-1) =-1.0/R(N)**2
      A(2*N-2,2*N  ) =-1.0
      A(2*N-1,2*N-3) =-1.0/E(N-1) * (1.0+GNU(N-1))/R(N)
      A(2*N-1,2*N-2) = 1.0/E(N-1) * (1.0-GNU(N-1))*R(N)
      A(2*N-1,2*N-1) = 1.0/E(N)   * (1.0+GNU(N)  )/R(N)
      A(2*N-1,2*N  ) =-1.0/E(N)   * (1.0-GNU(N)  )*R(N)
  210 CONTINUE
      A(2*NOEL,2*NOEL-1) = 1.0/R(NOEL+1)**2
      A(2*NOEL,2*NOEL  ) = 1.0
      B(NOEQ) = -PRESSI
C
C  LOAD SUBROUTINE SIMQ
C
      K = 0
      DO 220 J=1,NOEQ
  218 BB(J) = B(J)
      DO 220 I=1,NOEQ
      K = K+1
  220 AA(K) = A(I,J)
      CALL SIMQ (AA,BB,NOEQ,KSIG)
C
C     SUPERPOSE PPESSURE AND THERMAL STRESSES FOR ELASTIC STRESSES
C
      DO 240 N=1,NOEL
      SIGROE(N) = SIGROH(N) + BB(2*N-1)/R(N)**2 + BB(2*N)
      SIGRIE(N) = SIGRIH(N) + BB(2*N-1)/R(N+1)**2 + BB(2*N)
      SIGTOE(N) = SIGTOH(N) - BB(2*N-1)/R(N)**2 + BB(2*N)
      SIGTIE(N) = SIGTIH(N) - BB(2*N-1)/R(N+1)**2 + BB(2*N)
  240 CONTINUE
 1016 RETURN
      END
```

```
      SUBROUTINE DCREEP (NLAY)
      COMMON/GEOMAT/R(31),TEMP(31),E(30),GNU(30),ALPHA(30),YS(30)
      COMMON/CREEPC/CA(30),CN(30),CQ(30),CG(30),DTIME
      COMMON/CREEPS/SIGE(30),SOGE(30),DUIC(30),DUOC(30)
      COMMON/STRESS/SIGROE(30),SIGRIE(30),SIGTOE(30),SIGTIE(30),SIGRO(30
     1),SIGRI(30),SIGTO(30),SIGTI(30),PRESSO,UIH(30),UOH(30),UIC(30),UOC
     2(30),SIGZI(30),SIGZO(30)
      DATA CR/2./
      DATA US/76570./
      DO 25 I=1,NLAY
      IF(SOGE(I).GT.US) CALL EXCEED(SOGE(I),US,I)
      IF(SIGE(I).GT.US) CALL EXCEED(SIGE(I),US,I)
      DEPEO=CA(I)*SOGE(I)**CN(I)*EXP(-CQ(I)/CR/TEMP(I))*DTIME
      DEPEI=CA(I)*SIGE(I)**CN(I)*EXP(-CQ(I)/CR/TEMP(I+1))*DTIME
      DUIC(I)=R(I+1)*DEPEI/(2.*SIGE(I))*(2.*SIGTI(I)-SIGRI(I)-SIGZI(I))    918-1
   25 DUOC(I)=R(I)  *DEPEO/(2.*SOGE(I))*(2.*SIGTO(I)-SIGRO(I)-SIGZO(I))    918-1
      RETURN
      END
```

```
      SUBROUTINE EXCEED(S,US,I)
      S=US
      PRINT 1,I
    1 FORMAT (49H EQUIVALENT STRESS SET EQUAL TO ULTIMATE IN LAYER ,I3)
       RETURN
      END
```

```
      SUBROUTINE DOAFT(LO,N)
      COMMON/STRESS/SIGROE(30),SIGRIE(30),SIGTOE(30),SIGTIE(30),SIGRO(30
     1),SIGRI(30),SIGTO(30),SIGTI(30),PRESSO,UIH(30),UOH(30),UIC(30),UOC
     2(30),SIGZI(30),SIGZO(30)
      COMMON/GEOMAT/R(31),TEMP(31),E(30),GNU(30),ALPHA(30),YS(30)
      COMMON/XSHIFT/XROE(30),XRIE(30),XTOE(30),XTIE(30),XIH(30),XOH(30)
     1XIC(30),XOC(30),XR(31),XTEMP(31),XE(30),XGNU(30),XALPHA(30)
      L=LO
      DO 2 I=1,N
      SIGROE(L)=XROE(I)
      SIGRIE(L)=XRIE(I)
      SIGTOE(L)=XTOE(I)
      SIGTIE(L)=XTIE(I)
      UIH(L)=XIH(I)
      UOH(L)=XOH(I)
    2 L=L+1
      RETURN
      END
```

```
      SUBROUTINE PLAINS (NL)
      COMMON/GEOMAT/R(31),TEMP(31),E(30),GNU(30),ALPHA(30),YS(30)        PLAINS 2
      DO 10 L=1,NL
      E(L)=E(L)/(1.-GNU(L))                                              PLAINS 4
      ALPHA(L)=(1.+GNU(L))*ALPHA(L)                                      PLAINS 5
   10 GNU(L)=GNU(L)/(1.-GNU(L))                                          PLAINS 6
      RETURN                                                             PLAINS 7
      END                                                                PLAINS 8
```

```
C     THIS IS ORNL F04001 OF 1167                                       SIMQ0001
C     ..................................................................SIMQ 002
C                                                                       SIMQ 003
C        SUBROUTINE SIMQ                                                SIMQ 004
C                                                                       SIMQ 005
C        PURPOSE                                                        SIMQ 006
C           OBTAIN SOLUTION OF A SET OF SIMULTANEOUS LINEAR EQUATIONS,  SIMQ 007
C           AX=B                                                        SIMQ 008
C                                                                       SIMQ 009
C        USAGE                                                          SIMQ 010
C           CALL SIMQ(A,B,N,KS)                                         SIMQ 011
C                                                                       SIMQ 012
C        DESCRIPTION OF PARAMETERS                                      SIMQ 013
C           A - MATRIX OF COEFFICIENTS STORED COLUMNWISE.  THESE ARE    SIMQ 014
C               DESTROYED IN THE COMPUTATION.  THE SIZE OF MATRIX A IS  SIMQ 015
C               N BY N.                                                 SIMQ 016
C           B - VECTOR OF ORIGINAL CONSTANTS (LENGTH N). THESE ARE      SIMQ 017
C               REPLACED BY FINAL SOLUTION VALUES, VECTOR X.            SIMQ 018
C           N - NUMBER OF EQUATIONS AND VARIABLES                       SIMQ 019
C           KS - OUTPUT DIGIT                                           SIMQ 020
C                0 FOR A NORMAL SOLUTION                                SIMQ 021
C                1 FOR A SINGULAR SET OF EQUATIONS                      SIMQ 022
C                                                                       SIMQ 023
C        REMARKS                                                        SIMQ 024
C           MATRIX A MUST BE GENERAL.                                   SIMQ 025
C           IF MATRIX IS SINGULAR , SOLUTION VALUES ARE MEANINGLESS.    SIMQ 026
C           AN ALTERNATIVE SOLUTION MAY BE OBTAINED BY USING MATRIX     SIMQ 027
C           INVERSION (MINV) AND MATRIX PRODUCT (GMPRD).                SIMQ 028
C                                                                       SIMQ 029
C        SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED                  SIMQ 030
C           NONE                                                        SIMQ 031
C                                                                       SIMQ 032
C        METHOD                                                         SIMQ 033
C           METHOD OF SOLUTION IS BY ELIMINATION USING LARGEST PIVOTAL  SIMQ 034
C           DIVISOR. EACH STAGE OF ELIMINATION CONSISTS OF INTERCHANGINGSIMQ 035
C           ROWS WHEN NECESSARY TO AVOID DIVISION BY ZERO OR SMALL      SIMQ 036
C           ELEMENTS.                                                   SIMQ 037
C           THE FORWARD SOLUTION TO OBTAIN VARIABLE N IS DONE IN        SIMQ 038
C           CALCULATED BY SUCCESSIVE SUBSTITUTIONS. FINAL SOLUTION      SIMQ 040
C           VALUES ARE DEVELOPED IN VECTOR B, WITH VARIABLE 1 IN B(1),  SIMQ 041
C           VARIABLE 2 IN B(2),........, VARIABLE N IN B(N).            SIMQ 042
C           IF NO PIVOT CAN BE FOUND EXCEEDING A TOLERANCE OF 0.0,      SIMQ 043
C           THE MATRIX IS CONSIDERED SINGULAR AND KS IS SET TO 1. THIS  SIMQ 044
C           TOLERANCE CAN BE MODIFIED BY REPLACING THE FIRST STATEMENT. SIMQ 045
C                                                                       SIMQ 046
C     ..................................................................SIMQ 047
C                                                                       SIMQ 048
      SUBROUTINE SIMQ(A,B,N,KS)                                         SIMQ 049
      DIMENSION A(1),B(1)                                               SIMQ 050
C                                                                       SIMQ 051
C        FORWARD SOLUTION                                               SIMQ 052
C                                                                       SIMQ 053
      TOL=0.0                                                           SIMQ 054
      KS=0                                                              SIMQ 055
      JJ=-N                                                             SIMQ 056
      DO 65 J=1,N                                                       SIMQ 057
```

```
      JY=J+1                                                            SIMQ 058
      JJ=JJ+N+1                                                         SIMQ 059
      BIGA=0                                                            SIMQ 060
      IT=JJ-J                                                           SIMQ 061
      DO 30 I=J,N                                                       SIMQ 062
C                                                                       SIMQ 063
C        SEARCH FOR MAXIMUM COEFFICIENT IN COLUMN                       SIMQ 064
C                                                                       SIMQ 065
      IJ=IT+I                                                           SIMQ 066
      IF(ABS(BIGA)-ABS(A(IJ))) 20,30,30                                 SIMQ 067
   20 BIGA=A(IJ)                                                        SIMQ 068
      IMAX=I                                                            SIMQ 069
   30 CONTINUE                                                          SIMQ 070
C                                                                       SIMQ 071
C        TEST FOR PIVOT LESS THAN TOLERANCE (SINGULAR MATRIX)           SIMQ 072
C                                                                       SIMQ 073
      IF(ABS(BIGA)-TOL) 35,35,40                                        SIMQ 074
   35 KS=1                                                              SIMQ 075
      RETURN                                                            SIMQ 076
C                                                                       SIMQ 077
C        INTERCHANGE ROWS IF NECESSARY                                  SIMQ 078
C                                                                       SIMQ 079
   40 I1=J+N*(J-2)                                                      SIMQ 080
      IT=IMAX-J                                                         SIMQ 081
      DO 50 K=J,N                                                       SIMQ 082
      I1=I1+N                                                           SIMQ 083
      I2=I1+IT                                                          SIMQ 084
      SAVE=A(I1)                                                        SIMQ 085
      A(I1)=A(I2)                                                       SIMQ 086
      A(I2)=SAVE                                                        SIMQ 087
C                                                                       SIMQ 088
C        DIVIDE EQUATION BY LEADING COEFFICIENT                         SIMQ 089
C                                                                       SIMQ 090
   50 A(I1)=A(I1)/BIGA                                                  SIMQ 091
      SAVE=B(IMAX)                                                      SIMQ 092
      B(IMAX)=B(J)                                                      SIMQ 093
      B(J)=SAVE/BIGA                                                    SIMQ 094
C                                                                       SIMQ 095
C        ELIMINATE NEXT VARIABLE                                        SIMQ 096
C                                                                       SIMQ 097
      IF(J-N) 55,70,55                                                  SIMQ 098
   55 IQS=N*(J-1)                                                       SIMQ 099
      DO 65 IX=JY,N                                                     SIMQ 100
      IXJ=IQS+IX                                                        SIMQ 101
      IT=J-IX                                                           SIMQ 102
      DO 60 JX=JY,N                                                     SIMQ 103
      IXJX=N*(JX-1)+IX                                                  SIMQ 104
      JJX=IXJX+IT                                                       SIMQ 105
   60 A(IXJX)=A(IXJX)-(A(IXJ)*A(JJX))                                   SIMQ 106
   65 B(IX)=B(IX)-(B(J)*A(IXJ))                                         SIMQ 107
C                                                                       SIMQ 108
C        BACK SOLUTION                                                  SIMQ 109
C                                                                       SIMQ 110
   70 NY=N-1                                                            SIMQ 111
      IT=N*N                                                            SIMQ 112
      DO 80 J=1,NY                                                      SIMQ 113
      IA=IT-J                                                           SIMQ 114
      IB=N-J                                                            SIMQ 115
      IC=N                                                              SIMQ 116
      DO 80 K=1,J                                                       SIMQ 117
      B(IB)=B(IB)-A(IA)*B(IC)                                           SIMQ 118
      IA=IA-N                                                           SIMQ 119
   80 IC=IC-1                                                           SIMQ 120
      RETURN                                                            SIMQ 121
      END                                                               SIMQ 122
```

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