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FAST FLUX
TEST FACILITY
PROJECT REPORT

4-

A PROGRAM FOR CALCULATING THE
STEADY-STATE DEFORMATION RATES
FOR CYLINDRICAL FUEL ELEMENTS

K. R. Merckx

January 1968

AEC RESEARCH &
DEVELOPMENT REPORT

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A PROGRAM FOR CALCULATING THE STEADY-STATE DEFORMATION
RATES FOR CYLINDRICAL FUEL ELEMENTS

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January 1968

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A PROGRAM FOR CALCULATING THE STEADY-STATE
DEFORMATION RATES FOR CYLINDRICAL FUEL ELEMENTS

K. R. Merckx

INTRODUCTION

Despite the high irradiation exposure to which fuel pins of the Fast Test Reactor (FTR) are subjected, the integrity of the cladding material must be preserved. Irradiation of such fuel pins^(1,2) has demonstrated that the mixed oxide fuel material and the stainless steel jackets undergo radial deformations. At high burnup rates and with high smeared fuel densities, these fuel pins may deform until the cladding ruptures or until the flow of coolant in a fuel bundle is affected.

The intent of the program described in this report is to provide a means for evaluating the combined effects of steady-state reactor operation and fuel element design on the expected radial deformations of the fuel pins. The program is also to be applied in evaluating how various assumptions concerning material behavior and swelling affect the calculated radial deformations of the fuel cladding system.

PROGRAM DESCRIPTION

Several computer programs are already available at this site for evaluating fuel pin behavior. The "CYGRO" program⁽³⁾ is a general purpose program for analyzing elastic and viscous behavior in concentric cylinders which incorporates a swelling model for the fuel material and does its own temperature calculations. The "PECT" program⁽⁴⁾ is another general program for analyzing elastic, viscous, and plastic behavior in cylindrical geometries. Both "CYGRO" and "PECT" programs are based on time incremental solutions and calculate the mechanical conditions under changing thermal and boundary conditions. Simpler calculations are not easily performed in general

programs of this type because of the complicated nature of the required inputs and the generated outputs. The program described in this report performs the steady-state calculations to evaluate relative effects of operational conditions, geometries, and assumed material models prior to detailed investigations with the general purpose computer programs.

The steady-state, nonlinear viscous behavior of a cylinder can be defined by a few equations (see Appendix A). Such a model for simulating the mechanical behavior of fuel pins can readily be programmed (Appendices B and C). Because only the rates of deformation and stresses under steady-state conditions are calculated, this program cannot evaluate transient or cyclic behavior. The restriction to steady-state behavior does not act as a practical limitation to the description of fuel element behavior at this time since neither the swelling nor mechanical behavior of the fuel and cladding material can be described analytically for the transient and cyclic conditions occurring in a reactor environment.

This program attempts to evaluate major factors contributing to fuel element deformations such as creep (the viscous behavior of the fuel and cladding material), the swelling behavior of the fuel and cladding material, dimensions of the fuel rod components, and steady-state thermal conditions. All of these factors are considered in this program. The temperature input for this program is assumed to be generated by one of the existing programs for performing such thermal calculations.

Since this program for describing the steady-state mechanical behavior of a fuel pin is small and its running time is a few seconds, it could readily be combined with one of the existing thermal programs as a subroutine.

The input for the program (see Appendix B and C) has been simplified by including as part of the subroutines all the

parameters describing the material behavior. These subroutines must be recompiled to alter the models for the material behavior. A restriction on the mechanical models for the fuel and the cladding material is that the strain rate be expressed as a power function of the stress. The coefficients and power exponents for these mechanical material models can be any function of temperature and burnup rate.

The swelling behavior is assumed to depend upon the temperature, burn-up rate, and mean stress. Swelling in both the cladding and fuel material can be accounted for. The investigation of the effect of various swelling models on fuel performance is one of the intended uses for this program.

DISCUSSION

This report is written to describe the assumptions, mathematical formulation, and the computer program calculating the steady-state behavior of cylindrical fuel pins. Included in the listing (Appendix C) for the version of the program used to check its applicability are subroutines for the swelling and mechanical behavior of the fuel and cladding material. New swelling models will be added and will be incorporated into the program by the time this report is published. The models for the mechanical behavior for the fuel and cladding materials are also preliminary.

The author proposes that the program be used to evaluate the material behavior assumptions in terms of their calculated effect upon the composite fuel pin behavior. Selection of the temperature and stress ranges at which material data should be experimentally obtained to improve future fuel performance estimates should be based upon analyses provided by this program. Parameters in the material models should be adjusted not only from the conventional material test data but from fuel element irradiation results.

PLANNED DEVELOPMENTS FOR THE PROGRAM

Initial outputs from test cases indicate that certain assumptions be changed in the material models. The graph of the calculated values for the equivalent stress in a fuel rod is shown in Figure 1. This case is representative of one of the British fuel pins irradiated in the Dounreay Fast Reactor. The excessive equivalent stress at the outer surface of the fuel material suggests either that the oxide should crack, or that the creep strength of the oxide was overestimated. A radiation environment can increase creep rates⁽⁵⁾ and this effect will be included in future versions of the subroutines for estimating the creep behavior.

The swelling model for the fuel material used in the THCAL subroutine (Appendix B and C) for the sample calculations was selected because of its simplicity. A version of a Modified Greenwood-Speight⁽⁶⁾ model will be incorporated into the THCAL subroutine. This model will require that the mean stress be used in determining the swelling rate. Both of the iteration loops described in Appendix B must be used in the main program for evaluating pin deformations with such a swelling model. A model for the swelling of the cladding material will also be incorporated into future versions of the program.

FIGURE 1. *Equivalent Stress For Sample Calculation
(Representative of Dounreay fuel rod data in
Table B-I)*

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APPENDIX A

MECHANICAL MODEL FOR A HOLLOW CYLINDRICAL GEOMETRY

APPENDIX A

MECHANICAL MODEL FOR A HOLLOW CYLINDRICAL GEOMETRYINTRODUCTION

A steady-state solution for the stress and strain distributions in a hollow, mechanically incompressible cylinder undergoing viscous flow and internal dilatation can be found using existing techniques.* The assumptions of axial symmetry and plane strain are required to obtain equations that can readily be evaluated. This appendix presents the relations necessary for the computer evaluation of the mechanical conditions. The nomenclature and method of analysis follows that of Boley and Weiner.* The evaluation of this solution is based on an iteration technique where two parameters, the circumferential strain rate at the outer surface of the cylinder ($\dot{b}/b$) and the axial strain rate $\dot{\epsilon}_z$, are adjusted until all the boundary conditions are satisfied for the stress fields derived from a set of compatible displacements.

NOMENCLATURE

r, θ, a	cylindrical coordinates
$\dot{u}$	radial displacement rate
$\dot{\epsilon}_r, \dot{\epsilon}_\theta, \dot{\epsilon}_z$	strain rate components
$\dot{\epsilon} = \dot{\epsilon}_r - \dot{\epsilon}_\theta$	strain rate parameter
$\dot{\theta} = \dot{\epsilon}_r + \dot{\epsilon}_\theta + \dot{\epsilon}_z$	dilatational rate
$\sigma_r, \sigma_\theta, \sigma_z$	stress components
$s = \sigma_r - \sigma_\theta$	stress parameter
s_z	axial stress deviation

---

* B. A. Boley and J. H. Weiner. *Theory of Thermal Stresses*, John Wiley, New York, 1960. pp. 459 and 562.

$\bar{\sigma} = [(3/4) (s^2 + 3s_z^2)]^{1/2}$	equivalent stress
$\sigma = (1/3) (\sigma_r + \sigma_\theta + \sigma_z)$	mean stress
b	outer radius of the cylinder
a	inner radius of the cylinder
($\dot{}$)	time rate of change
P	net axial force
p_o	pressure on the outer surface ($r = b$)
p_i	pressure on the inner surface ($r = a$)
η	coefficient of viscosity

DISPLACEMENT CONDITIONS

The radial displacement rates within a mechanically incompressible cylindrical shell can be described by specifying the radial displacement rate at the outer surface, b , and the axial strain rate, $\dot{\epsilon}_z$. For plane strain conditions, $\dot{\epsilon}_z$ is independent of r . The volume change of a unit length of a cylindrical shell defined by outer radius b and inner radius r in the time increment Δt is:

$$\begin{aligned} & \pi(1 + \dot{\epsilon}_z \Delta t) [(b + b\dot{\epsilon}_z \Delta t)^2 - (r + r\dot{\epsilon}_z \Delta t)^2] - \pi(b^2 - r^2) \\ &= 2\pi \int_r^b \dot{\epsilon}_z \Delta t \rho d\rho \end{aligned}$$

If the left hand side of the preceding equation is expanded and the first order terms in the time increment Δt are retained, the resultant relation for the radial displacement rate, $\dot{u}$, is

$$\dot{u} = b \left(\frac{b}{r} \right) \left[\left(\frac{\dot{u}}{b} \right) + \frac{1}{2} \left(1 - \left(\frac{r}{b} \right)^2 \right) \dot{\epsilon}_z - \int_{r/b}^1 \dot{\epsilon}_z \rho d\rho \right] \quad (A-1)$$

The only other displacement quantity required for this solution is the strain parameter, $\dot{\epsilon}$, which is found with Equation (A-1) and the strain rate - displacement rate relation. The resultant equation for $\dot{\epsilon}$ is:

$$\dot{\epsilon} = \dot{\epsilon}_r - \dot{\epsilon}_\theta = \frac{rd(\dot{u}/r)}{dr} = \dot{\theta} + \left(\frac{b}{r}\right)^2 \left[2 \int_{r/b}^1 \dot{\theta}_\rho d\rho - \dot{\epsilon}_z - 2\left(\frac{\dot{b}}{b}\right) \right] \quad (A-2)$$

EQUILIBRIUM CONSIDERATIONS

The stress quantities of interest for the cylindrical analysis are:

$$\begin{aligned} s &= \sigma_r - \sigma_\theta && \text{stress parameter} \\ s_z &= \sigma_z - \sigma && \text{axial stress deviation} \\ \sigma &= \frac{1}{3} \sum \sigma_i = \sigma_r + \frac{1}{2} (s_z - s) && \text{mean stress} \\ \bar{\sigma} &= [3J_2]^{1/2} = \left[\frac{3}{4} (s^2 + 3s_z^2) \right]^{1/2} && \text{equivalent stress} \end{aligned}$$

The equilibrium of radial forces yields the following relation between the radial stress and the stress parameter:

$$\frac{d\sigma_r}{dr} = -\frac{s}{r}$$

This relation is integrated to express the radial stress in terms of the stress parameter, s ,

$$\sigma_r = -p_o + \int_{(r/b)}^1 \left(\frac{s}{\rho}\right) d\rho \quad (A-3)$$

The axial boundary condition for the net axial force, P , is satisfied when the integral of the axial stresses in the cylinder satisfies the relation

$$2\pi \int_a^b \sigma_z r dr = P + \pi a^2 p_i \quad .$$

If the axial stress is expressed as

$$\sigma_z = \left(\frac{3}{2}\right) s_z + \sigma_r - \left(\frac{1}{2}\right) s$$

and the relation

$$\begin{aligned} \int_a^b \left(\sigma_r - \frac{s}{2}\right) r dr &= \frac{1}{2} \int_a^b \left(2\sigma_r + r^2 \frac{d\sigma}{dr}\right) dr \\ &= \frac{1}{2} \int_a^b d(r^2 \sigma_r) = \frac{-b^2 p_o + a^2 p_i}{2} \end{aligned}$$

is used, the preceding equation can be expressed as:

$$\int_{(a/b)}^1 s_z \rho d\rho = \left(\frac{1}{3}\right) \left[\frac{P}{(\pi b^2)} + p_o \right] \quad (A-4)$$

STRESS-STRAIN RATE RELATIONS

For steady-state conditions [The dilatational rate (swelling) is assumed to be independent of time.], the temperatures and stresses do not change with time. For a viscous material with η as the coefficient of viscosity, the resulting constitutive equations are

$$\dot{\epsilon} = \frac{s}{2\eta} \text{ and } \dot{\epsilon}_z = \frac{\dot{\sigma}}{3} = \frac{s_z}{2\eta} \quad (A-5)$$

For a linearly viscous material, η is a function of temperature only. If the materials's behavior under steady-state tensile creep conditions ($\dot{\epsilon}$ = tensile strain rate and $\bar{\sigma}$ tensile stress) can be described by a power function

$$\frac{\dot{\epsilon}}{\bar{\sigma}} = C \bar{\sigma}^{-B}$$

then the viscous coefficient is

$$\eta = \frac{\bar{\sigma}}{3 \dot{\epsilon}} = \left(\frac{1}{3}\right) \frac{\dot{\epsilon} (1/B - 1)}{C^{1/B}} \quad (A-6)$$

where the equivalent strain rate for the cylindrical geometry is

$$\dot{\bar{\epsilon}} = \left[\frac{1}{3} \dot{\epsilon}^2 + \left(\dot{\epsilon}_z - \frac{\dot{\theta}}{3} \right)^2 \right]^{1/2} \quad (\text{A-7})$$

Since $\dot{\bar{\epsilon}}$ can be evaluated in terms of the two strain rate parameters $\dot{b}/b$ and $\dot{\epsilon}_z$ with Equations (A-2) and (A-7), η can be evaluated in terms of these strain rate parameters with Equation (A-6).

ITERATIVE EQUATIONS FOR THE STRAIN RATE PARAMETERS

A sufficient number of relations are now available to evaluate the stress and strain rate variables in terms of the two strain rate parameters $\dot{b}/b$ and $\dot{\epsilon}_z$. The relations (A-3) and (A-4) are used to obtain iterative equations for adjusting these strain rate parameters. Equation (A-3) is evaluated at the inner cylinder boundary, $r = a$, with the boundary condition on the radial stress:

$$p_o - p_i = \int_{a/b}^1 \left(\frac{s}{\rho} \right) d\rho \quad .$$

The stress parameter, s , in the preceding equation is expressed in terms of the displacement parameters with Equations (A-5) and (A-2). The resulting equation is then solved for $\dot{b}/b$:

$$(\dot{b}/b) = - \frac{1}{2} \dot{\epsilon}_z + \frac{\frac{1}{4} (p_i - p_o) + \int_{a/b}^1 \left(\frac{\eta}{\rho^3} \right) \left[\frac{1}{2} \rho^2 \dot{\theta} + \int_p^1 \dot{\theta} \xi d\xi \right] d\rho}{\int_{a/b}^1 \left(\frac{\eta}{\rho^3} \right) d\rho} \quad (\text{A-8})$$

The boundary condition on axial force, Equation (A-4), is expressed in terms of the axial strain rate with Equation (A-5). The resulting equation is then solved for $\dot{\epsilon}_z$:

$$\dot{\epsilon}_z = \frac{\left(\frac{1}{6}\right) \left[\frac{P}{\pi b^2} \right] + p_o + \left(\frac{1}{3}\right) \int_{a/b}^1 n \dot{\theta} \rho d\rho}{\int_{a/b}^1 n \rho d\rho} \quad (A-9)$$

If the material is linearly viscous (n is only a function of temperature), then Equations (A-9) and (A-8) can be solved for the strain rate parameters $\dot{\epsilon}_z$ and $(\dot{b}/b)$. If the material deforms in a non-linear viscous manner, then the viscosity, n , is evaluated using the assumed strain rate parameters, Equations (A-7) and (A-2), and the integrals in Equations (A-8) and (A-9) depend on the strain rate parameters. New values for the strain rate parameters are evaluated with Equations (A-8) and (A-9). The iteration procedure is continued until stable values are obtained for $\dot{b}/b$ and $\dot{\epsilon}_z$.

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APPENDIX B

COMPUTER PROGRAM

APPENDIX B
COMPUTER PROGRAM

INTRODUCTION

The mechanical model for a hollow cylinder described in Appendix A contains the equations necessary to evaluate the mechanical conditions encountered in cylindrical fuel elements during steady-state operation. The computer program described in this appendix is for a fuel material-clad system undergoing swelling where the displacements and radial stresses are continuous across the fuel-clad interface. Swelling models for the dilatation term $\dot{\epsilon}$ may be dependent upon the mean macroscopic stress; thus, the computer program iterates on both the strain rate parameters and mean stress. This appendix describes how to use the computer program and how the numerical operations in the computer program are related to the derivations in Appendix A.

PROGRAM INPUT

The input of this program requires only the specification of the radial dimensions of the fuel element, boundary condition, operational conditions, initial estimates for the strain rate parameters, and the temperatures at five locations in the cladding and nine locations in the fuel material. Functions are used to calculate the material parameters B and C, Equation (A-6), and the swelling rate $-\dot{\epsilon}$. Specific values of material constants are included in these functions; hence, the program user need not specify any material parameters.

The five program cards to be filled out by the program user are under the format (8F 10.0) and require the following inputs:

Card #1 -- Outer cladding radius, cladding thickness,
inner fuel radius (dimensions in inches)

- Card #2 -- Outer surface pressure, inner surface pressure,
net axial force (psi and pounds)
- Card #3 -- Burn-up rate, estimates of circumferential and
axial strain rates, parameters for swelling
models [10^{20} fission/(cc-hr) and $(\text{hr})^{-1}$]
- Card #4 -- 14 temperatures from cladding surface to fuel
& 5 center ($^{\circ}\text{F}$)

PROGRAM OUTPUT

The present program output includes the input data, the calculated strain rate parameters, the number of iterations required to perform the calculations, and a table of values that contains the radial location, temperature, $\dot{\theta}$, η , $\bar{\sigma}$, σ , s , s_z , and $\dot{u}$. A sample output is included in Table B-I.

COMPUTER PROGRAM

The computer program for the evaluation of the mechanical model described in Appendix A is based on an iteration technique. The flow diagram for this computer program is given in Figure B-1. The program iterates within an inner loop between control points "20" and "30" until stable values for the displacement parameters $\dot{b}/b$ and $\dot{\epsilon}_z$ are obtained. For all $\dot{\theta}$ models dependent upon the mean stress within the material, the program iterates between the control point 10 and the output until the mean stress values become stationary. Thus a feedback mechanism accounting for the dependence of swelling on the mean stress within the material is included in the program.

The equations derived in Appendix A did not mention the possibility of the hollow cylinder being composed of two different materials. The derived equations are applicable to a cylinder composed of two different materials if the radial stress and displacement rates are continuous across the common boundary between the two materials. Integrals and material

TABLE B-I. Sample Output

STEADY STATE SWELLING OF OXIDE FUELS

INPUT

DIMENSIONS   B= .1150+00   H= .1500-01   A= .2730-01
 EXTERNAL LOADS-PO= .0000   PI= -.0000   PA= -.0000
 BURN-UP RATE--BUR= .1140-02

NUMBER ITERATIONS   NEZ= 1   NTH= 11
 DEFORMATION RATES   ECD= .4111-07   EZD= .3378-07

RADIUS	TEMPERATURE	SWELLING RATE	ETA	EQ. STRESS	MEAN STRESS	S	SZ	UD
CLADDING								
.1150+00	.1078+04	.0000	.3175+11	.7258+04	.4828+04	-.7512+04	.2145+04	.4728-08
.1112+00	.1091+04	.0000	.2816+11	.6795+04	.4211+04	-.7121+04	.1903+04	.5016-08
.1075+00	.1107+04	.0000	.2492+11	.6366+04	.3743+04	-.6747+04	.1683+04	.5320-08
.1037+00	.1124+04	.0000	.2199+11	.5967+04	.3217+04	-.6392+04	.1485+04	.5641-08
.1000+00	.1140+04	.0000	.1934+11	.5597+04	.2738+04	-.6053+04	.1307+04	.5982-08
FUEL MATERIAL								
.1000+00	.1785+04	.7980-05	.1418+10	.2222+05	-.1576+05	.2218+05	-.7446+04	.5982-08
.9091-01	.2120+04	.7980-05	.9881+08	.1799+04	-.1268+04	.1873+04	-.5190+03	-.6976-07
.8182-01	.2465+04	.7980-05	.1204+08	.2615+03	-.1988+03	.2814+03	-.6322+02	-.1534-06
.7274-01	.2800+04	.7980-05	.2387+07	.6406+02	-.3213+02	.7071+02	-.1254+02	-.2499-06
.6365-01	.3160+04	.4902-05	.5858+06	.1644+02	-.2913+02	.1870+02	-.1875+01	-.3532-06
.5456-01	.3480+04	.1824-05	.2085+06	.6443+01	.2592+02	.7428+01	-.2394-00	-.4375-06
.4547-01	.3695+04	.1824-05	.1139+06	.5094+01	-.3299+01	.5878+01	-.1308-00	-.5465-06
.3639-01	.3840+04	.1824-05	.7835+05	.5474+01	.1555+02	.6319+01	-.8998-01	-.7015-06
.2730-01	.3925+04	.1824-05	.6366+05	.7886+01	-.1703+02	.9105+01	-.7311-01	-.9522-06

B-3

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FIGURE B-1. Flow Diagram for Computer Program

properties must account for the changes in properties across this boundary. The computer program uses five locations within the cladding material and nine locations within fuel material. The integral $\int \dot{\epsilon} \rho d\rho$, and the integrals involved in evaluating σ_r - Equation (A-3) -, $(\dot{b}/b)$ - Equation (A-8), and $\dot{\epsilon}_z$ - Equation (A-9) are numerically evaluated by using the quadrature formulae based on passing a polynomial through five equally spaced points. The quadrature formulae are not applied across the boundary between the cladding and the fuel material.

The material parameters, B and C, and dilatation rate $\dot{\epsilon}$ are evaluated in separate subroutines (BCAL, CCCAL, and THCAL). These subroutines incorporate the temperature dependence and parameters associated with the cladding and fuel material. Alteration of material properties are made by changing these subroutines. A control parameter, MET, is used to specify whether the cladding or fuel material is being considered. The dilatational subroutine will incorporate several swelling models and the swelling model used in any set of calculations is selected by setting the value of a control parameter.

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APPENDIX C

COMPUTER PROGRAM LISTING

APPENDIX C

LISTING OF THE COMPUTER PROGRAM

MAIN PROGRAM SWELL

FUEL SWELLING PROGRAM *** SWELL ***

A STEADY STATE SOLUTION FOR OXIDE FUELS IN A CLADDING. TWO REGIONS ARE USED WITH CONTINUOUS DISPLACEMENTS AND RADIAL STRAINS AT THE COMMON BOUNDARY. CREEP BEHAVIOR FOR THE FUEL AND THE CLADDING ARE GIVEN AS TEMPERATURE DEPENDENT POWER FUNCTIONS. AXIAL SYMMETRY AND PLANE STRAIN ARE ASSUMED. ONLY RATES OF DEFORMATION AND STRESSES ARE DETERMINED. AN ITERATIVE SOLUTION IS USED TO FIND THESE RATES ASSUMING THE FUEL ELEMENTS DIMENSIONS AND SWELLING BEHAVIOR CAN BE DESCRIBED AT THE EXPOSURE OF INTEREST. FIVE CLADDING AND NINE FUEL POSITIONS ARE USED IN DEFINING THE VARIOUS CONDITIONS.

*** NOMENCLATURE ***

A = CENTRAL FUEL RADIUS
B = OUTER CLAD RADIUS
BUR = BURN-UP RATE
BB = POWER IN CREEP MODEL
CC = COEFFICIENT IN CREEP MODEL
ECD = BD/B OR CIRCUMFERENTIAL STRAIN RATE AT B
ED = RADIAL - CIRCUMFERENTIAL STRAIN RATE
EZD = AXIAL STRAIN RATE
ETA = VISCOUS COEFFICIENT
H = CLAD THICKNESS
ITE = MAXIMUM NUMBER OF ITERATIONS
ITYPE = TYPE OF SWELLING MODEL
MET = MATERIAL - 1 FOR CLAD AND 2 FOR FUEL
NEZ = NUMBER OF ITERATIONS FOR EZD AND ECD
NTH = NUMBER OF ITERATIONS FOR TH
PA = NET AXIAL FORCE
PI = PRESSURE AT INNER RADIUS
PO = PRESSURE AT OUTER RADIUS
PAR = PARAMETERS USED IN SWELLING MODELS
R = RADIAL DIMENSION / B
S = RADIAL - CIRCUMFERENTIAL STRESS

```

C      SEQ = MISES STRESS
C      SIG = MEAN STRESS
C      SZ  = AXIAL STRESS DEVIATION
C      T   = TEMPERATURE
C      THD = RATE OF VOLUME EXPANSION - SWELLING -
C      THS = INTEGRAL OF THD*R
C
C      *** INPUT ***
C
C      CARD 1 - B,H,A          -DIMENSIONS          --(8F10.0)
C      CARD 2 - PO,PI,PA       -BOUNDARY CONDITIONS --(8F10.0)
C      CARD 3 - BUR,ECD,EZD,PAR -RATE CONDITIONS    --(8F10.0)
C      CARD 4,5-T              -TEMPERATURE -14-    --(8F10.0)
C
C      *** FUNCTIONS ***
C
C      BCAL - CALCULATES POWER COEFFICIENT IN CREEP MODEL
C      CCAL - CALCULATES COEFFICIENT IN CREEP MODEL
C      THCAL- CALCULATES SWELLING RATE
C      *** FORMATS ***
C
500  FORMAT(8F10.0)
505  FORMAT(1H1,41H          STEADY STATE SWELLING OF OXIDE FUELS' ///
1    6H INPUT/21H DIMENSIONS      B=,E10.4,5X, 2HH=,E10.4, 5X,2HA=,
2    E10.4 / 21H EXTERNAL LOADS-- PO=,E10.4,4X,3HPI=,E10.4,4X,3HPA=,
3    E10.4 / 21H BURN-UP RATE-- BUR=,E10.4 // 18H NUMBER ITERATIONS
4    ,4X, 4HNEZ=,I3,4X,4HNTH=,I3/18H DEFORMATION RATES , 4X, 4HECD=,
5    E10.4,4X,4HEZD=,E10.4 /// 2X, 6HRADIUS,4X, 11HTEMPERATURE,
6    2X, 13HSWELLING RATE,6X , 3HETA, 7X,24HEQ. STRESS MEAN SIRESS,
7    5X, 1HS , 11X , 2HSZ, 11X , 2HUD // 20X, 14H***CLADDING*** / )
510  FORMAT(1H , 9(E10.4,3X) )
515  FORMAT(1H0, 20X , 19H***FUEL MATERIAL*** / )
C
C      *** DIMENSIONS AND DATA ***
C
C      DIMENSION T(14) , R(14) , THD(14) , THS(14) , BB(14) , CC(14)
1      , ED(14) , ETA(14) , S(14) , SZ(14) , UD(14) , SIG(14)
2      , SEQ(14) , CLDS(4,5) , FULS(8,9) , SSIG(14) , PAR(5)
C
C      DATA TECD, TEZD / 2*1.0E-09 / , ITE / 40 / , ITYPE/ 1 /
C      DATA ((CLDS(L,K),K=1,5) , L=1,4 ) /
1      .348611, .897222, -.366666, .147222, -.026389 ,
2      .322222,1.377778, .266667, .044444, -.011111 ,
3      .3375 , 1.275 , .9 , .525 , -.0375 ,
4      .311111,1.422222, .533334 ,1.422222 , .311111 /
C      DATA ((FULS(L,K),K=1,9),L=1,8) /
1      .348611, .897222, -.366666, .147222, -.026389, 4*0.0 ,
2      .322222,1.377778, .266667 ,.044444, -.011111, 4*0.0 ,
3      .3375 , 1.275 , .9 , .525 , -.0375 , 4*0.0 ,
4      .311111,1.422222,.533334, 1.42222 , .311111 , 4*0.0,
5      .348611,1.208333,1.055556, .680556,1.395833, .311111, 3*0.0,

```

```

6 .322222,1.377778,.577778,1.466666,.522223,1.42222,.311111, 2*0.0,
7.3375,1.275,.9 ,.836111,1.384722,.533334,1.42222,.311111,0.0,
8.311111,1.422222,.533334, 1.422222,.622222,1.422222,.533334 ,
9 1.422222,.311111 /

```

```

C
C   *** INPUT VALUES ***
C

```

```

1 READ(5,500) B,H,A
  READ(5,500) PO,PI,PA
  READ(5,500) BUR,ECD,EZD , (PAR(K),K=1,5)
  READ(5,500) ( T(K),K=1,14 )

```

```

C   INITIAL VALUES

```

```

  DEL1 = H / ( 4.*B)
  DEL2 = (B - H - A ) / (8.*B)
  PBDZ = ( PA /(3.14159*B**2) + PO ) / 6.
  MET = 1
  DO 5 K=1,14
    SIG(K) = 0.0
    IF(K.GT.5) GO TO 2
    R(K) = 1. - DEL1 * FLOAT(K-1)
    GO TO 3
  2 CONTINUE
    MET = 2
    R(K) = R(5) - DEL2 * FLOAT(K-6)
  3 CONTINUE
    BB(K) = BCAL(MET,T(K))
    CC(K) = CCAL(MET,T(K))
  5 CONTINUE
    DO 6 K=6,14
      ETA(K) = .3333333 * 10.**(-CC(K) )
  6 CONTINUE

```

```

C
C   *** SWELLING ***
C

```

```

  NTH = 0
10 CONTINUE
  NTH = NTH + 1
  DO 11 K=1,14
    MET = 1
    IF(K.GT.5) MET = 2
    THD(K) = THCAL(MET,T(K),SIG(K),BUR, PAR , ITYPE )
  11 CONTINUE
    THS(1) = 0.0
    DO 15 K=2,14
      IF(K.GT.5) GO TO 13
      THS(K) = 0.0
      DO 12 L=1,5
        THS(K) = THS(K) + THD(L) * R(L) * CLDS( K-1 , L ) * DEL1
      12 CONTINUE
      GO TO 15
    13 CONTINUE

```

```

      THS(K) = THS(5)
      IF(K.EQ.6) GO TO 15
      DO 14 L=6,14
      THS(K) = THS(K) + THD(L) * R(L) * FULS( K-6 , L-5 ) * DEL2
14  CONTINUE
15  CONTINUE

```

```

C      *** CALCULATION ECD AND EZD BY ITERATION ***
C
C

```

```

      NEZ = 0
20  CONTINUE
      IF(NEZ.GT.ITE) GO TO 99
      NEZ = NEZ + 1
      EECD = ECD
      EEZD = EZD
C      CALCULATION ED AND ETA
      DO 25 K=1,14
      ED(K) = THD(K) + ( 2.*THS(K) - EZD - 2.*ECD ) / R(K)**2
      IF( K.GT.5 ) GO TO 25
      EEQ = .5*ALOG10( ED(K)**2/3. + (EZD-THD(K)/3. )**2 )
      ETA(K) = 10.** ( EEQ*(1./BB(K)-1.) - .47712 - CC(K)/BB(K) )
25  CONTINUE

```

```

C      CALCULATION OF INTEGRALS
      SS1 = 0.0
      SS2 = 0.0
      SS3 = 0.0
      SS4 = 0.0
      DO 26 K=1,14
      IF(K.LT.6) FAC = CLDS(4,K) * DEL1
      IF(K.GT.5) FAC = FULS(8, K-5 ) * DEL2
      RE3 =(ETA(K)/R(K)**3)*FAC
      RE1 = ETA(K)*R(K)*FAC
      SS1 = SS1 + RE3 * ( .5*THD(K)*R(K)**2 + THS(K) )
      SS2 = SS2 + RE3
      SS3 = SS3 + RE1 * THD(K)
      SS4 = SS4 + RE1
26  CONTINUE

```

```

C      CALCULATION ECD AND EZD
      ECD = -.5*EZD + (SS1 + 0.25*(PI-PO) ) / SS2
      EZD = (.333333*SS3 + PBDZ ) / SS4

```

```

C      CHECK CONVERGENCE
      IF(TECD.LT. ABS(ECD - EECD)) GO TO 20
      IF(TEZD.LT. ABS(EZD - EEZD)) GO TO 20

```

```

C      *** CALCULATION OF STRESS VALUES ***
C
C

```

```

30  CONTINUE
      DO 35 K=1,14
      SSIG(K) = SIG(K)
      S(K) = 2.*ETA(K)*ED(K)
      SZ(K) = 2.*ETA(K)*(EZD - THD(K)/3. )

```

```

      SEQ(K) = SQRT( .75*S(K)**2 + 2.25*SZ(K)**2 )
      UD(K) = B * ( ECD + (.5-.5*R(K)**2)*EZD - THS(K) ) / R(K)
      SIG(K) = .5*(SZ(K) - S(K)) - PO
      IF(K.EQ.1) GO TO 35
      IF(K.GT.5) GO TO 32
      DO 31 L=1,5
      SIG(K) = SIG(K) + (S(L)*CLDS(K-1,L) / R(L)) * DEL1
31  CONTINUE
      GO TO 35
32  CONTINUE
      SIG(K) = SIG(K) + SIG(5) - .5*(SZ(5)-S(5)) + PO
      IF(K.EQ.6) GO TO 35
      DO 33 L=6,14
      SIG(K) = SIG(K) + (S(L)*FULS( K-6 , L-5 ) / R(L)) * DEL2
33  CONTINUE
35  CONTINUE
C
C    *** OUTPUT ***
C
40  CONTINUE
      WRITE(6,505) B,H,A,PO,PI,PA,BUR,NTH,NEZ,ECD,EZD
      DO 41 K=1,14
      R(K) = B*R(K)
      IF(K.EQ.6) WRITE(6,515)
      WRITE(6,510) R(K),T(K),THD(K),ETA(K),SEQ(K),SIG(K),S(K),SZ(K),
1      UD(K)
41  CONTINUE
C
      GO TO 1
C    FAILURE TO CONVERGE
99  CONTINUE
      WRITE(6,505) B,H,A,PO,PI,PA,BUR,NTH,NEZ,ECD,EZD
      WRITE(6,2000)
2000 FORMAT(1H0,30HNO CONVERGENCE ON STRAIN RATES )
      GO TO 1
      END

```

SUBROUTINES

C FUNCTION TO CALCULATE EXPONENT IN CREEP MODEL

```

C FUNCTION BCAL(MET,T)
C CALCULATES POWER COEFFICIENT B IN CREEP MODEL
C IF(MET.GT.1) GO TO 10
C *** CLADDING ***

```



```

C      REF.  BNWL-603 PAGE 3.86
      IF(T.GT.1000.)GO TO 2
      BCAL = 18.8 - 0.0134*T
      RETURN
2 BCAL = 5.4
      RETURN
C      *** FUEL ***
C      REF.  WAPD-TM-587  GRAPH ON PAGE 61
10 CONTINUE
      BCAL = 1.
      RETURN
      END

```

C FUNCTION TO CALCULATE ALOG10 OF COEFFICIENT IN CREEP MODEL

```

      FUNCTION CCAL(MET,T)
C      CALCULATES ALOG10 OF C
      IF(MET.GT.1) GO TO 10
C      *** CLADDING ***
C      REF.  BNWL-603 PAGE 3.86
      IF(T.GT.1000.) GO TO 2
      CCAL =      (-96.7 + 0.0679*T )
      RETURN
2 CCAL =      (-39.8 + 0.011*T )
      RETURN
C      *** FUEL ***
C      REF.  WAPD-TM-587  GRAPH ON PAGE 61
10 CONTINUE
      CCAL =      ( -.72 - 20000. / (T+460.) )
      RETURN
      END

```

C FUNCTION TO CALCULATE SWELLING

```

      FUNCTION THCAL( MET, T, SIG, BUR, PAR, ITYPE)
C
C      A FUNCTION TO CALCULATE THE SWELLING RATE.  BOTH THE CLADDING AND
C      THE FUEL MATERIAL ARE CONSIDERED.
C      MET - 1 CLADDING AND 2 FUEL
C      T    -TEMPERATURE (F)
C      SIG -MEAN STRESS (PSI)
C      BUR -BURNUP RATE (10**20 FISSIONS/ (CC*HR) )
C      PAR - PARAMETERS
C      ITYPE-DEFINES THE SWELLING MODEL BEING USED
C      1 FOR GE/APO MODEL

```

```
C      DIMENSION  PAR(5)
C
C      IF( MET.EQ.2) GO TO 99
C      *** CLAD ***
C      THCAL = 0.0
C      RETURN
C      *** SELECTION OF FUEL SWELLING MODEL ***
99  IF(IITYPE.EQ.1) GO TO 100
C
C      *** GE/APO SWELLING MODEL ***
C      REFERENCE BNWL-CC-1340 PAGE III.2
C      INCLUDES .0016*BUR FOR SOLID FISSION PRODUCTS
100 CONTINUE
    IF(T.GT.2910.) GO TO 110
    THCAL = 0.0070 * BUR
    RETURN
110 IF(T.GT.3270.) GO TO 120
    THCAL = 0.0043 * BUR
    RETURN
120 CONTINUE
    THCAL = 0.0016 * BUR
    RETURN
    END
```


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