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VISCOELASTIC ANALYSIS OF GRAPHITE UNDER NEUTRON IRRADIATION AND TEMPERATURE DISTRIBUTION

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Reactor Division

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IRRADIATION AND TEMPERATURE DISTRIBUTION

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OCTOBER 1969

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Nomenclature

σ, τ	Stress
ϵ, γ	Strain
D	Accumulated neutron exposure
J_x	Creep function in the transverse plane
J_z	Creep function in the axial direction
J_{zx}	Creep function in shear
μ	Poisson's ratio
J_p	Primary creep
J_s	Secondary creep
G	Relaxation function
E	Young's modulus
K	Creep coefficient
A_o	Material property constant
ϕ	Stress function
T_x	Boundary traction, x-component
T_y	Boundary traction, y-component
ψ	Dimensional change function
α	Coefficient of thermal expansion
T	Temperature
$T_{a,b}$	Surface temperatures
Z	Coordinate in the axial direction
L	Length of the cylinder
κ_a	Thermal conductivity
H	Heat transfer coefficient
R	Hydraulic radius
ϕ	Neutron flux

VISCOELASTIC ANALYSIS OF GRAPHITE UNDER NEUTRON IRRADIATION AND TEMPERATURE DISTRIBUTION

Shih-Jung Chang*

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Abstract

This report is concerned with the adaptation and application of linear viscoelasticity to the stress analysis of irradiated graphite under temperature gradients and dimensional changes. Under the assumptions of uniform neutron distribution throughout the body and of a temperature-independent creep function, the generalized plane-strain viscoelastic solution for an arbitrary two-dimensional cross section is represented by the sum of four associated elastic solutions when multiplied by appropriate functions of the neutron dose. From this plane-strain formulation, solutions are obtained for various thick-walled circular cylinders which represent graphite core components in a Molten-Salt Breeder Reactor (MSBR) design study. These cylinders are subjected to radial temperature distributions and to a temperature-dependent neutron-induced dimensional change which has a quadratic dependence upon the accumulated neutron exposure. The creep function used is based upon available experimental test results. The stress and strain components are determined as functions of the accumulated dose. An analytical expression is developed for the rate of change of the axial stress for large values of accumulated neutron dose where this stress component has a linear dependence on the dose. Design lifetimes for the graphite core components are developed in accordance with both a volumetric distortion and an axial strain criterion. The methods presented can be extended to the three-dimensional axisymmetrical case.

Keywords: stress analysis, graphite, neutron irradiation, dimensional change, temperature, viscoelasticity, lifetime, MSBR.

Introduction

The purpose of this report is to develop and apply a linear viscoelastic creep analysis to the description of the mechanical behavior of

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irradiated graphites. Constitutive equations for transversely isotropic graphites subject to neutron-induced dimensional changes, temperature gradients, and arbitrary mechanical loadings are developed and shown to be of the same form as those of classical linear viscoelasticity with time being replaced by the accumulated neutron exposure (fluence). Through the use of these relations, the generalized plane-strain conditions are formulated for an isotropic graphite. It is then shown that the viscoelastic solution for an arbitrary two-dimensional cross section subject to boundary tractions, temperature distribution, and neutron-induced dimensional change can be determined from elastic solutions which correspond to the same conditions.

This formulation is then applied to the analysis of a series of thick-walled circular cylinders subjected to radial temperature distributions and to temperature-dependent neutron-induced dimensional changes. These cylinders are representations of graphite elements in the core of a single fluid MSBR. The restrictions made are that the neutron flux is uniform throughout the cross section and the creep function is temperature independent. A computer code was developed which converts the elastic solution to the viscoelastic solution corresponding to these conditions. The stresses and strains are calculated and plotted for these cylinders as functions of accumulated neutron exposure. A graphical method is also presented for determining crucial stresses for neutron exposures greater than 10^{22} nvt ($E > 50$ kev). Design lifetimes for these graphite cylinders are computed using both a volumetric distortion criterion and an axial strain criterion. The lifetimes are graphically expressed in terms of both time (months) and accumulated neutron exposure (dose).

Constitutive Equations

As shown in the various experiments conducted by Kennedy,^{1*} the uniaxial creep curve for irradiated graphite approximates the linear superposition principle, e.g., the creep strain shown in Fig. 1 at neutron dose

*Numerical superscripts refer to similarly numbered items in the list of References.

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Fig. 1. Linear Superposition for a Viscoelastic Material.

D_2 can be represented by a linear combination of the creep due to the stress σ_1 at zero dose and that due to an additional stress $-\sigma_2$ at D_1 as given by the following relation:

$$\epsilon(D_2) = \sigma_1 J(D_2) - \sigma_2 J(D_2 - D_1) , \quad (1)$$

where $J(D)$ is a dose-dependent creep function. Hence, for a continuously changing stress, σ , the strain, ϵ , for an arbitrary accumulated dose D can be represented by the integral relation

$$\epsilon(D) = \int_0^D J(D - D') \frac{d\sigma}{dD'} dD' , \quad (2)$$

where D' is an integration variable ranging over the history of the loading program. This equation, analogous to that of classical viscoelasticity,² provides a basic constitutive equation, in which the stress and the strain are linearly related. The merit of this linearity will be made clear in the calculations shown later.

As many graphites are transversely isotropic in structure, it is convenient to generalize Eq. (2) to the following multiaxial constitutive equations which are valid for that type of material symmetry:

$$\epsilon_x = J_x * (d\sigma_x - \mu_x d\sigma_y) - \mu_z J_z * d\sigma_z + \alpha_x T + \psi_x(T, D) , \quad (3)$$

$$\epsilon_y = J_x * (d\sigma_y - \mu_x d\sigma_x) - \mu_z J_z * d\sigma_z + \alpha_x T + \psi_x(T, D) , \quad (4)$$

$$\epsilon_z = J_z * (d\sigma_z - \mu_z d\sigma_x - \mu_z d\sigma_y) + \alpha_z T + \psi_z(T, D) , \quad (5)$$

$$\gamma_{xy} = 2(1 + \mu_x) J_x * d\tau_{xy} , \quad (6)$$

$$\gamma_{yz} = J_{zx} * d\tau_{yz} , \quad (7)$$

$$\gamma_{zx} = J_{zx} * d\tau_{zx} , \quad (8)$$

where the z axis is assumed to be the axis of material symmetry and both Poisson ratios, μ_x and μ_z , to be constants. The Poisson ratio μ_x is

defined as the ratio of induced lateral strain to longitudinal strain for a uniaxial test when both directions lie in the plane of isotropy (x,y). Whereas, μ_z is the ratio of the lateral strain induced in a direction in the plane of isotropy to the longitudinal strain in the direction normal to the isotropic plane. When these Poisson ratios are dose-dependent, two creep functions, in addition to J_x , J_z , and J_{zx} , are required for the stress-strain representation. The notation (*) is used in accordance with the convention for representing a convolution integral,

$$J * d\sigma = \int_0^D J(D - D') \frac{\partial \sigma}{\partial D'} dD' . \quad (9)$$

The terms αT and $\psi(T,D)$ represent the strains due to thermal expansion and dimensional changes resulting from neutron irradiation, respectively.

The generalized plane-strain conditions are defined by the case when the normal strain in a given direction, say the z direction, assumes a constant value ϵ_0 , all derivatives with respect to z vanish, and the net resultant force in the z direction vanishes. Under these conditions, Eqs. (7) and (8) identically vanish and Eq. (5) reduces to:

$$J_z * d\sigma_z = \mu_z J_z * (d\sigma_x + d\sigma_y) - \alpha_z T - \psi_z(T,D) + \epsilon_0 . \quad (10)$$

Through the use of Eq. (10), the two-dimensional constitutive equations which characterize these generalized plane-strain conditions can be expressed by Eqs. (3), (4), and (6) in the form

$$\begin{aligned} \epsilon_x = & (J_x - \mu_z^2 J_z) * d\sigma_x - (\mu_x J_x + \mu_z^2 J_z) * d\sigma_y \\ & + (\alpha_x + \mu_z \alpha_z) T + \psi_x + \mu_z \psi_z - \mu_z \epsilon_0 , \end{aligned} \quad (11)$$

$$\begin{aligned} \epsilon_y = & (J_x - \mu_z^2 J_z) * d\sigma_y - (\mu_x J_x + \mu_z^2 J_z) * d\sigma_x \\ & + (\alpha_x + \mu_z \alpha_z) T + \psi_x + \mu_z \psi_z - \mu_z \epsilon_0 , \end{aligned} \quad (12)$$

$$\gamma_{xy} = 2(1 + \mu_x) J_x * d\tau_{xy} . \quad (13)$$

Thus, for a transversely isotropic material, two creep functions, J_x and J_z , along with two Poisson ratios, μ_x and μ_z , are required for the viscoelastic stress analysis under generalized plane-strain conditions when the isotropic plane coincides with the cross section of the specimen.

For an isotropic graphite, the following simplifications can be made in the generalized plane-strain formulation:

$$\mu_z = \mu_x = \mu ,$$

$$J_x = J_z = J ,$$

$$\alpha_x = \alpha_z = \alpha ,$$

$$\psi_x = \psi_z = \psi ,$$

and it follows that

$$\epsilon_x = (1 - \mu^2)J * \left(d\sigma_x - \frac{\mu}{1 - \mu} d\sigma_y \right) + (1 + \mu)(\alpha T + \psi) - \mu \epsilon_o , \quad (14)$$

$$\epsilon_y = (1 - \mu^2)J * \left(d\sigma_y - \frac{\mu}{1 - \mu} d\sigma_x \right) + (1 + \mu)(\alpha T + \psi) - \mu \epsilon_o , \quad (15)$$

$$\gamma_{xy} = 2(1 + \mu)J * d\tau_{xy} . \quad (16)$$

It is seen from Eqs. (14), (15), and (16) that the viscoelastic stress analysis of an isotropic graphite under these conditions requires the determination of only one creep function, $J(D)$, and one Poisson ratio, μ .

The creep function used in the present analysis is based on the experimental results reported by Kennedy.¹ These experimental results show that the creep function can be considered as the sum of an elastic contribution, a primary creep term, and a secondary creep part. The primary creep is expressed in terms of the accumulated neutron exposure by

$$J_p(D) = \frac{1}{2E} \left(1 - e^{-A_o D} \right) , \quad (17)$$

and the secondary creep is linearly dependent upon the dose and given by

$$J_s(D) = K(T)D . \quad (18)$$

The secondary creep coefficient $K(T)$ is dependent upon the temperature,¹ whereas A_0 and E in the primary creep term are constants. The overall creep function, including the elastic part, is then

$$J(D) = \frac{1}{E} + K(T)D + \frac{1}{2E} \left(1 - e^{-\frac{A_0 D}{E}} \right) , \quad (19)$$

where A_0 is large in the sense that the second term in $J_p(D)$, Eq. (17), becomes negligible for a low neutron exposure as compared with a design dose. In the subsequent analysis, we shall assume $K(T)$ to be a constant value which in practice would correspond to some mean temperature. This assumption is necessary to obtain the governing Eq. (24), given in the next section.

This form of the creep function for graphite under irradiation can be represented analogously by a model of springs and dashpots with the spring constants and viscous coefficients shown in Fig. 2. It is seen that, if A_0 is large, the right dashpot can be removed, leaving two springs and a dashpot connected in series.

Formulation and Solution

In this section the intent is to illustrate the relation between the thermal stress problem in an elastic material and that in a viscoelastic material. Consider an arbitrary two-dimensional cross section where the neutron flux is assumed to be uniform over the entire section and the creep function is independent of temperature. As discussed by Sokolnikoff,³ the equations of equilibrium for a continuum are expressed only in terms of the stress components and not influenced by the constitutive equations; it will be convenient, therefore, to introduce the Airy stress function, ϕ , such that

$$\sigma_x = \frac{\partial^2 \phi}{\partial y^2} , \quad (20)$$

Fig. 2. Viscoelastic Model Representation for Irradiated Graphite.

$$\sigma_y = \frac{\partial^2 \phi}{\partial x^2}, \quad (21)$$

$$\tau_{xy} = -\frac{\partial^2 \phi}{\partial x \partial y}. \quad (22)$$

Hence, if there are no body forces, the equations of equilibrium for the generalized plane-strain formulation will be identically satisfied by Eqs. (20), (21), and (22). After substituting Eqs. (20), (21), and (22) into the equation of compatibility, which is stated by Timoshenko⁴ for plane-strain conditions as

$$\frac{\partial^2 \epsilon_y}{\partial x^2} + \frac{\partial^2 \epsilon_x}{\partial y^2} = \frac{\partial^2 \gamma_{xy}}{\partial x \partial y}, \quad (23)$$

the governing equation of ϕ for an isotropic graphite is

$$\int_0^D J(D - D') \frac{\partial}{\partial D'} \nabla^4 \phi \, dD' = -\frac{1}{1 - \mu} \nabla^2 [\psi(D, T) + \alpha T]. \quad (24)$$

After inversion, ϕ satisfies

$$\nabla^4 \phi = -\frac{1}{1 - \mu} \int_0^D G(D - D') \frac{\partial}{\partial D'} \left\{ \nabla^2 [\psi(D, T) + \alpha T] \right\} dD', \quad (25)$$

where the relaxation function G is related to the creep function J by

$$\int_0^D G(D - D') \frac{\partial}{\partial D'} J(D') \, dD' = H(D), \quad (26)$$

and $H(D)$ is the unit step function. Specifically, the relaxation function which corresponds to the creep function given by Eq. (19) is

$$G(D) = \frac{E}{\sqrt{(EK + 1.5A_0)^2 - 4EKA_0}} \left[(k_1 + A_0) e^{k_1 D} - (k_2 + A_0) e^{k_2 D} \right], \quad (27)$$

where

$$k_1 = -0.5(EK + 1.5A_0) + 0.5 \sqrt{(EK + 1.5A_0)^2 - 4EKA_0}, \quad (28)$$

$$k_2 = -0.5(EK + 1.5A_0) - 0.5\sqrt{(EK + 1.5A_0)^2 - 4EKA_0}, \quad (29)$$

and where both k_1 and k_2 are seen to be negative. For prescribed boundary traction, the boundary conditions are

$$\frac{\partial \phi}{\partial y} = \int_C T_x \, ds \quad (30)$$

and

$$\frac{\partial \phi}{\partial x} = - \int_C T_y \, ds, \quad (31)$$

where T_x and T_y are the x- and y-components of the boundary traction acting on the boundary, C , of the cross section of the body.

It will be established that if the temperature field is independent of time and if the temperature-dependent neutron-induced dimensional change is given by

$$\psi(D, T) = A_2(T)D^2 + A_1(T)D, \quad (32)$$

then the stress function ϕ is expressed by

$$\begin{aligned} \phi(x, y, D) = & \phi^a(x, y) + \phi^b(x, y) \frac{G(D)}{G(0)} \\ & + \phi^c(x, y) F_1(D) + \phi^d(x, y) F_2(D), \end{aligned} \quad (33)$$

where ϕ^a , ϕ^b , ϕ^c , and ϕ^d are elastic solutions, corresponding to boundary tractions, thermal expansion, dimensional change $A_1(T)$, and dimensional change $A_2(T)$, respectively, and

$$F_1(D) = \frac{1}{G(0)} \int_0^D G(D - D') \, dD' \quad (34)$$

and

$$F_2(D) = \frac{1}{G(0)} \int_0^D G(D - D') 2D' \, dD'. \quad (35)$$

In the elastic solutions for the ϕ 's, $E = G(0)$. From this consideration, therefore, the viscoelastic solution for an arbitrary plane-strain problem can be found immediately, provided a nonhomogeneous biharmonic computer code is available for the calculation of the elastic plane-strain problems with the indicated loadings.

The above correspondence can be seen from an examination of the solution of Eq. (25) and the boundary conditions, Eqs. (30) and (31). The solution for ϕ can be divided into two parts, say ϕ_h and ϕ_p , where the particular solution

$$\phi_p(x, y, D) = -\frac{1}{2\pi(1-\mu)} \int_0^D G(D-D') \frac{\partial}{\partial D'} \left\{ \iint [\psi(D, T) + \alpha T] \log r' d\xi d\eta \right\} dD', \quad (36)$$

in which

$$r' = [(x - \xi)^2 + (y - \eta)^2]^{1/2}$$

and where ξ and η are integration variables ranging over the cross section of the body. Consequently, ϕ_h satisfies

$$\nabla^4 \phi_h = 0 \quad (37)$$

subject to the boundary conditions

$$\frac{\partial \phi_h}{\partial y} = \int T_x ds - \frac{\partial \phi_p}{\partial y} \quad (38)$$

and

$$\frac{\partial \phi_h}{\partial x} = - \int T_y ds - \frac{\partial \phi_p}{\partial x}. \quad (39)$$

By substituting the expression given in Eq. (32) for $\psi(D, T)$ into Eq. (36), ϕ_p can be separated as

$$\phi_p(x, y, D) = \frac{G(D)}{G(0)} \phi_p^b(x, y) + F_1(D) \phi_p^c(x, y) + F_2(D) \phi_p^d(x, y), \quad (40)$$

where

$$\phi_p^b(x,y) = -\frac{G(o)}{2\pi(1-\mu)} \iint \alpha T \log r' d\xi d\eta, \quad (41)$$

$$\phi_p^c(x,y) = -\frac{G(o)}{2\pi(1-\mu)} \iint A_1(T) \log r' d\xi d\eta, \quad (42)$$

$$\phi_p^d(x,y) = -\frac{G(o)}{2\pi(1-\mu)} \iint A_2(T) \log r' d\xi d\eta. \quad (43)$$

Moreover, the homogeneous solution ϕ_h is obtained from Eq. (37) and the boundary conditions, Eqs. (38) and (39), which are of the same form as for the elastic problem.

The stress function is related to the boundary traction by Eqs. (38) and (39). Hence, the homogeneous solution can be written as

$$\begin{aligned} \phi_h(x,y,D) = & \phi_h^a(x,y) + \frac{G(D)}{G(o)} \phi_h^b(x,y) \\ & + F_1(D) \phi_h^c(x,y) + F_2(D) \phi_h^d(x,y), \end{aligned} \quad (44)$$

where $\phi_h^a(x,y)$ is due to the boundary traction; and $F_1(D)$ and $F_2(D)$ are the same functions used in Eq. (40). Therefore, after the combination of Eqs. (40) and (44), we obtain

$$\begin{aligned} \phi(x,y,D) = & \phi^a(x,y) + \frac{G(D)}{G(o)} \phi^b(x,y) \\ & + F_1(D) \phi^c(x,y) + F_2(D) \phi^d(x,y), \end{aligned} \quad (45)$$

where $\phi(x,y) = \phi_h(x,y) + \phi_p(x,y)$. Thus, four elastic solutions, ϕ^a , ϕ^b , ϕ^c , and ϕ^d , will be enough to describe the thermo-viscoelastic solution for a plane-strain problem with boundary tractions, thermal gradients, and neutron-induced dimensional changes of the form given by Eq. (32).

Application to MSBR Core Design Studies

When exposed to a fast neutron flux such as could be experienced by a structural member in the core of a nuclear reactor, graphite tends to

change dimensions as a function of the accumulated neutron exposure (fluence) and the irradiation temperature. At current reactor design temperature levels (500 to 1000°C), the graphite initially contracts,⁵ reaches a minimum volume, and then expands. The original volume is regained and the expansion continues at an increasing rate above about 3×10^{22} nvt ($E > 50$ kev) until the structural integrity is destroyed.

A reasonable design criterion would be to limit the operating lifetime of graphite structural elements in the core of a nuclear reactor such as the Molten Salt Breeder Reactor by the fluence, or time, required for the graphite to return to its original volume, provided the stresses induced by differential dimensional changes within the structure remain low.

As a specific example for application of the viscoelastic representation of graphite behavior under fast neutron exposure, consider the analysis of graphite elements in the core of a single fluid MSBR.⁵ Typically, these elements are long rods with a central hole. The exact shape of the cross section has not been finalized, but can be represented as circular for purposes of preliminary studies. Molten salt passes through the central hole and along the outer surface. The thickness of the wall is minimal so that any given cross section of the element will experience a nearly uniform fast neutron flux. The flux distribution along the length of the rod varies approximately according to $\sin(\pi Z/L)$, where L is the length of the rod. The internal heat generation within the graphite is roughly uniform and is conducted radially to the molten salt. The analysis of these elements considers the graphite to be isotropic.

The specific problems solved are concentric circular cylinders with inner radius, a , outer radius, b , length, L , and b/a ratio of 6.667. To illustrate the influence of the geometric size of the elements on their lifetimes, several values of b ranging from 4 cm to 6 cm were chosen. As defined by Refs. 5 and 6, these cylinders are surrounded by molten salt whose temperature is

$$T_s (^\circ\text{C}) = 625 - 75 \cos \left(\pi \frac{Z}{L} \right). \quad (46)$$

The temperature-dependent thermal conductivity of the graphite is given by

$$\kappa_a = 0.358 \left[\frac{T(^{\circ}\text{K})}{773} \right]^{-0.7} \text{ watts/cm-}^{\circ}\text{C} , \quad (47)$$

and plotted in Fig. 3. The heat transfer coefficient of the hydraulic film is of the form

$$H = a^{-0.2} [1.444 \times 10^{-3} T(^{\circ}\text{C}) - 0.228] \text{ watts-cm}^{0.2}/\text{cm}^2\text{-}^{\circ}\text{C} . \quad (48)$$

The internal heat generation rate which results from both prompt and delayed γ rays is given by

$$Q = 1.2 + 9.0 \sin \left(\pi \frac{Z}{L} \right) \text{ watts/cm}^3 . \quad (49)$$

The axial distribution of the fast neutron flux is

$$\Phi(E > 50 \text{ kev}) = \Phi_{\text{max}} \sin \left(\pi \frac{Z}{L} \right) = 4.5 \times 10^{14} \sin \left(\pi \frac{Z}{L} \right) . \quad (50)$$

Following the development of Carslaw and Jaeger,⁷ the temperature distribution within a cross section of the cylinder is determined to be

$$T(^{\circ}\text{C}) = T_a - C \log \frac{r}{a} - \frac{Qa^2}{4\kappa_a} \left[\left(\frac{r}{a} \right)^2 - 1 \right] , \quad (51)$$

where

$$C = \left\{ T_a - T_b - \frac{Qa^2}{4\kappa_a} \left[\left(\frac{b}{a} \right)^2 - 1 \right] \right\} / \log \frac{b}{a} . \quad (52)$$

The surface temperatures, T_a and T_b , of the graphite at the graphite-salt interfaces are evaluated through the use of the boundary conditions:

$$H(T_a - T_s) = \kappa_a \left. \frac{dT}{dr} \right|_{r=a} \quad (53)$$

and

$$H(T_b - T_s) = \kappa_a \left. \frac{dT}{dr} \right|_{r=b} , \quad (54)$$

where κ_a is the thermal conductivity evaluated at the inner surface

Fig. 3. Thermal Conductivity as a Function of Temperature.

($r = a$). The radial temperature distribution in the cross section defined by $Z/L = 0.60$ for a cylinder with $b = 5$ cm and $b/a = 6.667$ is shown in Fig. 4.

The coefficient of thermal expansion and all the mechanical properties appearing in Eqs. (14) through (19), except the steady-state creep coefficient $K(T)$, are taken to be independent of the temperature level.

$$\begin{aligned}
 E &= 1.7 \times 10^6 \text{ psi} \\
 A_0 &= 2.0 \times 10^{-22} \text{ neut}^{-1}\text{-cm}^2 \\
 \mu &= 0.27 \\
 K(T) &= (5.3 - 1.45 \times 10^{-2}T + 1.4 \times 10^{-5}T^2) \times 10^{-5} \\
 &\quad \text{for } 550^\circ\text{C} < T < 800^\circ\text{C} \\
 \alpha &= 6.20 \times 10^{-6} \text{ }^\circ\text{C}^{-1}
 \end{aligned} \tag{55}$$

The value of the steady-state creep coefficient to be used in subsequent calculations was determined from Eq. (55) by using the temperature of the inner surface. The temperature-dependent neutron-induced dimensional change has a quadratic dependence⁵ on the neutron dose as expressed by

$$\psi(D, T) = A(T) [(10^{-22}D)^2 + B(T)(10^{-22}D)] , \tag{56}$$

where

$$A(T) = \frac{1}{3} (0.11 - 7.0 \times 10^{-5}T) / (5.7 - 6.0 \times 10^{-3}T)^2 \tag{57}$$

and

$$B(T) = 2 \times (6.0 \times 10^{-3}T - 5.7) . \tag{58}$$

T is in $^\circ\text{C}$ and D is in nvt ($E > 50$ kev). This dimensional change is represented by the curves in Fig. 5 for temperatures ranging from 400 to 750°C and for an accumulated neutron exposure ranging up to 3×10^{22} nvt ($E > 50$ kev).

According to the previous discussion, the combination of three associated elastic solutions due to thermal expansion, dimensional change $A_1 = A(T) \cdot B(T)$ and dimensional change $A_2 = A(T)$, describe the viscoelastic

Fig. 4. Radial Temperature Profile at the Axial Position $Z/L = 0.60$.

Fig. 5. Neutron-Induced Dimensional Changes in Graphite at Various Temperatures.

solution for the boundary traction free problem, since in this case $\phi^a(x, y) = 0$.

The generalized plane-strain elastic solution for the thermal stresses in a cylinder having a radial temperature distribution is given by Timoshenko⁴ as

$$\sigma_r^b(r) = \frac{E}{1 - \mu} \left[\frac{1}{b^2 - a^2} \left(1 - \frac{a^2}{r^2} \right) \int_a^b \alpha T(\xi) \xi d\xi - \frac{1}{r^2} \int_a^r \alpha T(\xi) \xi d\xi \right], \quad (59)$$

$$\sigma_\theta^b(r) = \frac{E}{1 - \mu} \left[\frac{1}{b^2 - a^2} \left(1 + \frac{a^2}{r^2} \right) \int_a^b \alpha T(\xi) \xi d\xi + \frac{1}{r^2} \int_a^r \alpha T(\xi) \xi d\xi - \alpha T \right], \quad (60)$$

$$\sigma_z^b(r) = \frac{E}{1 - \mu} \left[\frac{2}{b^2 - a^2} \int_a^b \alpha T(\xi) \xi d\xi - \alpha T \right], \quad (61)$$

where the superscript b is used to denote the elastic thermal stress as used before. Similarly, superscripts c and d are used, as defined in the preceding section, to designate the stresses due to dimensional change $A_1(T)$ and those due to $A_2(T)$, respectively.

$$\sigma_r^c(r) = \frac{E}{1 - \mu} \left[\frac{1}{b^2 - a^2} \left(1 - \frac{a^2}{r^2} \right) \int_a^b A(T)B(T) \xi d\xi - \frac{1}{r^2} \int_a^r A(T)B(T) \xi d\xi \right], \quad (62)$$

$$\sigma_\theta^c(r) = \frac{E}{1 - \mu} \left[\frac{1}{b^2 - a^2} \left(1 + \frac{a^2}{r^2} \right) \int_a^b A(T)B(T) \xi d\xi + \frac{1}{r^2} \int_a^r A(T)B(T) \xi d\xi - A(T)B(T) \right], \quad (63)$$

$$\sigma_z^c(r) = \frac{E}{1 - \mu} \left[\frac{2}{b^2 - a^2} \int_a^b A(T)B(T) \xi d\xi - A(T)B(T) \right], \quad (64)$$

and

$$\sigma_r^d(r) = \frac{E}{1-\mu} \left[\frac{1}{b^2 - a^2} \left(1 - \frac{a^2}{r^2} \right) \int_a^b A(T) \xi d\xi - \frac{1}{r^2} \int_a^r A(T) \xi d\xi \right], \quad (65)$$

$$\begin{aligned} \sigma_\theta^d(r) = \frac{E}{1-\mu} \left[\frac{1}{b^2 - a^2} \left(1 + \frac{a^2}{r^2} \right) \int_a^b A(T) \xi d\xi \right. \\ \left. + \frac{1}{r^2} \int_a^r A(T) \xi d\xi - A(T) \right], \quad (66) \end{aligned}$$

$$\sigma_z^d(r) = \frac{E}{1-\mu} \left[\frac{2}{b^2 - a^2} \int_a^b A(T) \xi d\xi - A(T) \right]. \quad (67)$$

Therefore, the complete viscoelastic solution for the stresses in a cylinder under these conditions is:

$$\sigma_r = \frac{G(D)}{G(O)} \sigma_r^b + F_1(D) \sigma_r^c + F_2(D) \sigma_r^d, \quad (68)$$

$$\sigma_\theta = \frac{G(D)}{G(O)} \sigma_\theta^b + F_1(D) \sigma_\theta^c + F_2(D) \sigma_\theta^d, \quad (69)$$

$$\sigma_z = \frac{G(D)}{G(O)} \sigma_z^b + F_1(D) \sigma_z^c + F_2(D) \sigma_z^d, \quad (70)$$

where $F_1(D)$ and $F_2(D)$ are defined by Eqs. (34) and (35). Since the displacements in an elastic material are independent of the elastic modulus, the viscoelastic radial displacement is the same as that given by the elastic solution, that is,⁴

$$\begin{aligned} u_r(r, D) = \frac{1+\mu}{1-\mu} \left\{ \frac{1}{r} \int_a^r [\psi(D, T) + \alpha T] \xi d\xi \right. \\ \left. + \left[\frac{1-3\mu}{1+\mu} \frac{r}{b^2 - a^2} + \frac{1}{b^2 - a^2} \frac{a^2}{r} \right] \int_a^b [\psi(D, T) + \alpha T] \xi d\xi \right\}. \quad (71) \end{aligned}$$

Stress Solution for Large Dose

It can be shown that, for small EK/A_0 , as the neutron dose becomes large

$$F_1(D) \rightarrow \text{constant} , \quad (72)$$

and

$$F_2(D) \rightarrow \frac{2}{EK \left(1 + \frac{1}{3} \frac{EK}{1.5A_0}\right)} D . \quad (73)$$

Then by using Eqs. (72) and (73) with Eq. (70), the rate of change of σ_z is seen to approach a constant value as D becomes large. This asymptotic value is given by

$$\frac{\partial \sigma_z}{\partial D} \approx \frac{2}{EK \left(1 + \frac{1}{3} \frac{EK}{1.5A_0}\right)} \frac{E}{1 - \mu} \left[\frac{2}{b^2 - a^2} \int_a^b A(T) \xi d\xi - A(T) \right] . \quad (74)$$

These results can be shown by observing from Eqs. (27) and (34) that $F_1(D)$ tends to a constant as D goes to ∞ , and by using the following integral in Eq. (35),

$$\int_0^D e^{k_1(D-D')} D' dD' = -\frac{1}{k_1} \left[D - \int_0^D e^{k_1(D-D')} dD' \right] . \quad (75)$$

The second term on the right-hand side of Eq. (75) tends to a constant as $D \rightarrow \infty$ by the same reasoning as used for $F_1(D)$. Therefore we obtain, for large D ,

$$F_2(D) \approx \frac{2}{\sqrt{(EK + 1.5A_0)^2 - 4EKA_0}} \left[-\left(1 + \frac{A_0}{k_1}\right) + \left(1 + \frac{A_0}{k_2}\right) \right] D ,$$

which is simplified by using Eqs. (28) and (29) to give

$$F_2(D) = \frac{2A_0}{k_1 k_2} D . \quad (76)$$

But for small EK/A_0 , expanding the square root,

$$k_1 = -0.5 \times 1.5A_0 \left\{ 1 + \frac{EK}{1.5A_0} + \left[\left(1 + \frac{EK}{1.5A_0} \right)^2 - \frac{4EK}{(1.5)^2 A_0} \right]^{1/2} \right\}$$

$$\approx -0.5 \times 1.5A_0 \left[1 + \frac{EK}{1.5A_0} - \left(1 - \frac{1}{2} \frac{EK}{(1.5)^2 A_0} \right) \right],$$

or

$$k_1 = -0.5 \times 1.5A_0 \left(\frac{4}{3} \frac{EK}{1.5A_0} \right) \quad (77)$$

and

$$k_2 = -0.5 \times 1.5A_0 \times 2 \left(1 + \frac{1}{3} \frac{EK}{1.5A_0} \right). \quad (78)$$

Therefore the result, Eq. (73), follows.

Numerical Results

The stresses and strains were determined from the generalized plane-strain solutions for cylinders subject to the conditions which exist on the cross sections defined by Z/L ranging from 0.20 to 0.80 in increments of 0.10. As will be shown later, the conditions which exist on cross sections near $Z/L = 0.60$ give rise to the minimum lifetime in the cylinder. Therefore, many of the numerical results displayed subsequently in this report correspond to the conditions which exist on the cross section defined by $Z/L = 0.60$.

The strains in each cylinder are identical to those of the elastic solution which corresponds to the prescribed temperature distribution and neutron-induced dimensional changes. Figure 6 shows the distribution of circumferential strain ϵ_θ with radial position in the $Z/L = 0.60$ cross section of a cylinder with $b = 5$ cm and $b/a = 6.667$. The value of the circumferential strain ϵ_θ at the outer boundary is the same as that of the longitudinal strain ϵ_z , and the variation of this value with accumulated dose up to 3×10^{22} nvt ($E > 50$ kev) is shown in Fig. 7.

Fig. 6. Circumferential Strain as a Function of Radial Position.

Fig. 7. Circumferential Strain at Outside Surface as a Function of Fluence Level.

The stresses were calculated with the aid of a computer code developed to evaluate Eqs. (68) through (70). For the conditions investigated, the axial stress, σ_z , at the surface $r = b$ initially changes very rapidly, but before a dose of 10^{22} nvt is reached (about 3×10^{21} nvt) this stress has developed a linear dependence on dose. Figure 8 shows a typical plot of σ_z as a function of dose and specifically corresponds to $r = b = 5.0$ cm, $Z/L = 0.60$, and $b/a = 6.667$. Figure 9 is a plot of the stress σ_z existing at the outer surface of the cylinders studied as a function of Z/L when $D = 10^{22}$ nvt. The constant stress rate, $d\sigma_z/dD$, which exists for $D > 10^{22}$ nvt, is shown in Fig. 10 for these cylinders, also as a function of axial position. Thus, the axial stress present for a dose greater than 10^{22} nvt can be calculated from Figs. 9 and 10 by using the following equation:

$$\sigma_z = \sigma_z \Big|_{D=10^{22}} + \frac{d\sigma_z}{dD} (D - 10^{22}) . \quad (79)$$

This procedure also gives the corresponding value of σ_θ , since $\sigma_\theta = \sigma_z$ on the surface $r = b$.

Lifetime Conditions

The design lifetimes of the cylinders studied were evaluated in two manners. The first criterion, called the volumetric distortion criterion, was used to determine the dose and consequently the time required for the volumetric dilatation, $\epsilon_r + \epsilon_\theta + \epsilon_z$, when integrated over the cross section, to return to zero. The second criterion, called the axial strain criterion, closely approximates the first by determining the dose required for the axial strain ϵ_z to return to zero on the surface $r = b$. The second criterion has additional physical significance when a thin layer of coating is applied to the outer surface of the cylinder, since small cracks will develop in these layers when ϵ_z , or ϵ_θ which equals ϵ_z at the surface, becomes greater than zero. Since the neutron flux varies with axial position, each criterion gives lifetime predictions which also vary with axial position.

Fig. 8. Axial Stress at the Outer Surface as a Function of Fluence Level.

Fig. 9. Axial Stress at Outer Surface of MSBR Graphite Core Cylinders as a Function of Axial Position for a Fluence Level of $D = 10^{22} \text{ nvt}$ ($E > 50 \text{ kev}$).

Fig. 10. Constant Axial Stress Rate for MSBR Graphite Core Cylinders as a Function of Axial Position for Fluence Levels Beyond $D = 10^{22} \text{ nvt}$ ($E > 50 \text{ kev}$).

Figure 11 shows the lifetimes, in months, at various axial positions calculated on the basis of the volumetric distortion criterion for cylinders of outer radii 4, 5, and 6 cm and a (b/a) ratio of 6.667. In all cases, the minimum lifetime occurs near $Z/L = 0.60$. Figure 12 shows the lifetimes of these same cylinders as determined by the axial strain criterion which is based upon ϵ_z vanishing on the outer surface, where $\epsilon_z = \epsilon_\theta$. Since the neutron flux given by Eq. (50) is not uniform along the length of the cylinder, different cross sections will have experienced different total fluences during a given time interval. On this basis, the lifetime curves given by Figs. 11 and 12 are represented by Figs. 13 and 14, respectively, in terms of the total dose experienced on the given cross section.

Summary and Conclusions

The theory of linear viscoelasticity was applied in the study of stresses and strains in graphite bodies exposed to fast neutron-induced dimensional changes and creep. A theoretical solution was obtained for generalized plane-strain conditions including the effects of boundary tractions, thermal stresses, temperature-dependent dimensional changes resulting from neutron irradiation, and a temperature-independent creep function.

When the fast neutron flux is constant over the cross section of the body, an important consequence of the present formulation is that the solution for any two-dimensional problem, subject to the above conditions, can be obtained from the sum of four associated elastic solutions which are multiplied by appropriate functions of the neutron dose. The elastic solutions require, at most, the use of a nonhomogeneous biharmonic computer code for calculating elastic thermal stresses.

The generalized plane-strain formulation was applied to the study of long thick-walled cylindrical rods, which represent graphite core components in a Molten-Salt Breeder Reactor design study. The stresses and strains were evaluated as functions of position and accumulated neutron exposure. The maximum axial stress σ_z , which equals the circumferential stress σ_θ at the outside radius $r = b$, was seen to have a linear dependence

Fig. 11. Lifetime of MSBR Graphite Core Cylinders as a Function of Axial Position According to the Volumetric Distortion Criterion.

Fig. 12. Lifetime of MSBR Graphite Core Cylinders as a Function of Axial Position According to the Axial Strain Criterion.

Fig. 13. Lifetime of MSBR Graphite Core Cylinders as a Function of Axial Position According to the Volumetric Distortion Criterion.

Fig. 14. Lifetime of MSBR Graphite Core Cylinders as a Function of Axial Position According to the Axial Strain Criterion.

upon the accumulated neutron exposure for fluence levels above $D = 10^{22}$ nvt ($E > 50$ kev) for all cases investigated. The asymptotic value of the stress rate, $d\sigma_z/dD$, and the value of the axial stress corresponding to an accumulated dose of 10^{22} nvt were plotted as functions of axial position. Hence, the axial stress present at the boundary of any cross section for a dose greater than 10^{22} nvt can be evaluated directly from these plots.

The expected design life of these elements was determined according to both a volumetric distortion criterion and an axial strain criterion. Curves showing the expected lifetimes, as functions of axial position, are presented for three different sized cylinders. These lifetimes are expressed both in terms of time and accumulated neutron exposure.

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