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Thermal Stress Analysis of HTGR Fuel and Control Rod Fuel Blocks in the HTGR In-Block Carbonization and Annealing Furnace

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THERMAL STRESS ANALYSIS OF HTGR FUEL AND CONTROL ROD FUEL BLOCKS
IN THE HTGR IN-BLOCK CARBONIZATION AND ANNEALING FURNACE

R. C. Gwaltney W. J. McAfee

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R. C. Gwaltney W. J. McAfee

ABSTRACT

A new approach that utilizes the equivalent solid plate method has been applied to the thermal stress analysis of HTGR fuel and control rod fuel blocks. Cases were considered where these blocks, loaded with reprocessed HTGR fuel pellets, were being cured at temperatures up to 1800°C. A two-dimensional segment of a fuel block cross section including fuel, coolant holes, and graphite matrix was analyzed using the ORNL HEATING3 heat transfer code to determine the temperature-dependent effective thermal conductivity for the perforated region of the block. Using this equivalent conductivity to calculate the temperature distributions through different cross sections of the blocks, two-dimensional thermal-stress analyses were performed through application of the equivalent solid plate method. In this approach, the perforated material is replaced by solid homogeneous material of the same external dimensions but whose material properties have been modified to account for the perforations. The peak stresses are determined from the calculated nominal stress distribution using stress concentration factors from detailed analyses of a typical hole-to-hole ligament. These analyses were used to assess the potential for crack generation in the blocks during the curing process.

Key words: stress analysis, thermal stress, heat transfer, HTGR fuel, control rod fuel blocks.

1. INTRODUCTION

The Metals and Ceramics Division of the Oak Ridge National Laboratory (ORNL) has completed design details and installation studies for an in-block carbonization and annealing furnace to process HTGR fuel elements.¹ This development model furnace is a forerunner of a cold prototypic furnace for the HTGR Demonstration Facility. The fabrication scheme involves in-situ carbonization and annealing of the "green" fuel rods in the fuel holes of HTGR fuel and control rod fuel blocks. This is a continuous process in which the blocks are inserted into the furnace at essentially ambient conditions, pass vertically downward through the hot zone of the furnace at a

rate designed to introduce the desired block heatup rate, are cooled, and are removed from the bottom of the furnace once again essentially at ambient conditions.

The purpose of this study was to provide, through scoping type calculations, estimates of the general magnitudes of the internal stresses and strains induced by the temperatures and thermal gradients imposed on the blocks as they pass through the furnace. Additionally, the results were to be used to assess the potential for crack generation in the graphite matrix of the blocks.

A new method for performing thermal stress analyses in structures with multiple penetrations was applied to the analysis of the HTGR fuel and control rod fuel blocks. This method is based on the development of an effective thermal conductivity for the matrix of penetrations. This technique has been used extensively for modeling the thermal characteristics of reactor cores.² In the subsequent thermal analyses, the region of the structure containing the matrix of penetrations is replaced by a homogeneous region having the same dimensions and this effective thermal conductivity. The stress analyses were performed using this effective thermal conductivity in conjunction with the equivalent solid plate method.³ In the equivalent solid plate method, the region of penetrations being modeled is replaced by a pseudo material having the same dimensions but whose material properties have been adjusted to account for the penetrations. The peak stresses and strains are determined by applying stress and strain intensification factors to the calculated distributions through the pseudo material. These intensification factors are developed by detailed thermal stress analyses of a typical hole-to-hole ligament.

The remainder of this report is a discussion of these calculations. Chapter 2 covers the details of the thermal analyses required to develop the effective thermal conductivity and temperature boundary conditions for the thermal stress analyses. Chapter 3 discusses the techniques employed and the general results of the analyses. Chapter 4 presents the overall results and conclusions of this study.

2. THERMAL ANALYSES

2.1 Problem Statement and Basic Assumptions

Thermal analyses of the HTGR standard fuel and control rod fuel blocks in the cure-in-place furnace¹ were necessary to establish the temperature boundary conditions for the thermal stress analyses. The computer code HEATING3,⁴ which is stored on the ORNL IBM 360 system, was chosen to perform the required thermal analyses since it has the capability for considering conduction, convection, and radiation heat transfer in structures composed of multiple solids, liquids, and/or gases. The use of this latter feature was necessary to accurately model the thermal behavior of the composite blocks.

The standard fuel and control rod fuel blocks are hexagonal graphite prisms, 0.360 m (14.172 in.) across flats, of H-451 graphite manufactured by the Great Lakes Carbon Company. The fuel blocks contain 210 fuel holes [12.7 mm (0.500 in.) in diameter], 6 burnable poison holes [12.7 mm (0.500 in.) in diameter], 102 coolant holes [15.875 mm (0.625 in.) in diameter], and 6 coolant holes [12.7 mm (0.500 in.) in diameter]. The overall configuration is shown in Fig. 1. The control rod fuel blocks contain 120 fuel holes [12.7 mm (0.500 in.) in diameter], 4 burnable poison holes [12.7 mm (0.500 in.) in diameter], 52 coolant holes [15.875 mm (0.625 in.) in diameter], 5 coolant holes [12.7 mm (0.500 in.) in diameter], 2 control rod channels [0.102 m (4.000 in.) in diameter], and one reserve shutdown hole [0.095 m (3.750 in.) in diameter]. An overall view of the control rod fuel block is shown in Fig. 2.

The fuel holes in the blocks are filled with fuel rods fabricated from coated uranium and thorium-bearing particles held together by a mixture composed mainly of petroleum pitch. This mixture is carbonized as the blocks pass through the furnace.

The furnace, which is described in detail in Ref. 1, maintains an argon purge while providing the desired thermal environment for the carbonization process. As the blocks pass through the furnace, they are subjected to an outside surface temperature as shown in Fig. 3. This temperature profile

Fig. 1. Typical HTGR fuel element (1 in. = 25.4 mm).

Fig. 2. Typical HTGR control rod fuel element (1 in. = 25.4 mm).

FUEL BLOCKS FABRICATED FROM H-327 GRAPHITE

Fig. 3. Axial surface temperature distribution in fuel and control rod fuel blocks vs furnace height (1 in. = 25.4 mm).

introduces both axial and radial temperature gradients within the blocks which are considered to be essentially in thermal equilibrium at any instant due to low block velocity through the furnace.

The situation investigated was that of a block located near the center of the furnace. In this position, it had been determined that the temperatures at selected points on the surface of a block were as shown in Fig. 4 (Ref. 5). These temperatures were used as boundary conditions for

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Fig. 4. Specified temperatures at locations around the surface of the fuel and control rod fuel blocks positioned near furnace midheight.

the thermal analysis. Five specific two-dimensional cases were analyzed: plane analyses of each end of a standard fuel block (two cases), plane analyses of each end of a control rod fuel block (two cases), and an analysis of a fuel block treated as an axisymmetric cylinder.

Since these thermal stress analyses were to be scoping calculations, certain simplifying assumptions, which were compatible with the analysis techniques being used, were made for the problem description. These assumptions were:

1. The thermal properties of the H-451 graphite were isotropic in cross-sectional planes of the blocks.
2. The fuel rods were in perfect thermal contact with the walls of the fuel holes in the graphite blocks.
3. The temperature of the argon purge gas would closely follow the temperature of the graphite.
4. The argon purge gas, which is introduced at the rate of $7079 \text{ cm}^3/\text{sec}$ ($15 \text{ ft}^3/\text{min}$), would be distributed equally among the coolant holes.
5. The temperature distribution within the blocks could be adequately described using an effective thermal conductivity representative of the combined matrix of H-451 graphite, fuel, and coolant holes filled with argon. This effective thermal conductivity will be discussed in detail later.

These assumptions and simplifications were basic to all the analyses. Other assumptions which relate to specific cases will be pointed out in context.

2.2 Determination of an Effective Thermal Conductivity

The matrix of fuel and coolant holes in the fuel and control rod fuel blocks presents a complex geometric array that alone requires large computer space capability to model in detail. An alternate approach which has been used successfully in modeling the thermal response of HTGR cores² is to calculate an effective thermal conductivity such that the blocks can be treated as essentially a homogeneous material. Note that since these are steady-state calculations, only thermal conductivity must be modeled.

To calculate an effective thermal conductivity, a model was used that was representative of the repetitive arrangement of fuel and coolant holes. The fuel holes form a hexagon with a coolant hole as the center, see Fig. 5, and symmetry considerations required modeling only the cell shown.

The procedure used in calculating the effective thermal conductivity was as follows. A temperature differential was imposed across the length of the cell model where the top and bottom edges (Fig. 5) were insulated. One-dimensional surface-to-surface radiation across the coolant hole, combined with individual cases of convection to the argon and conduction

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Fig. 5. Layout of fuel and coolant holes showing region used to develop model for effective thermal conductivity (1 in. = 25.4 mm).

through the argon, was considered. Modeling of surface-to-surface radiation using the HEATING3 code was accomplished by specifying a radiation heat transfer coefficient which is defined by

$$h_r = F \epsilon_g \sigma ,$$

where

F = shape factor (a value of 0.6 was used⁶),

ϵ_g = emissivity of graphite (0.8),

σ = Planck's constant = $5.676 \times 10^{-8} \text{ W/m}^2\text{-}^\circ\text{C}^4 = 1.714 \times 10^{-9} \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}^4$.

For the cases that considered convection, a convective heat transfer coefficient h_c was also required input. Here it was necessary to assume some temperature for the argon and, using standard techniques,⁷ to evaluate a value of h_c for the conditions assumed. From the detailed thermal analysis, the net heat flux q was calculated. A straightforward calculation using

$$\kappa_{\text{eff}} = \frac{L}{\Delta T} \left(\frac{q}{A} \right)_{\text{net}} ,$$

where

κ_{eff} = the effective thermal conductivity of an equivalent homogeneous material,

L = the length of the cell,

ΔT = the imposed temperature differential across the cell,

$\left(\frac{q}{A} \right)_{\text{net}}$ = the net calculated heat flux across the cooler face of the cell.

The temperature dependency of κ_{eff} could be ascertained by varying T_1 and T_2 and maintaining the same ΔT . The cell model developed for analysis using the HEATING3 code is shown in Fig. 6.

Thermal conductivity values for H-451 graphite, which were required input to the HEATING3 analysis, are listed in Table 1 and shown graphically in Fig. 7. Data from Ref. 8 were available for temperatures up to 800°C (1472°F). Supplementary data and trend curves from Ref. 9 were used to extrapolate the properties to the required maximum temperature of 1800°C (3272°F). Although not needed for the steady-state calculations, the density and specific heat are also included in Table 1 and shown graphically

Fig. 6. Model used for evaluating effective radial thermal conductivity in HTGR fuel block.

Table 1. Thermal properties of H-451 graphite

Temperature [°C (°F)]	Density, ρ [kg/m ³ (lb _m /ft ³)]	Thermal conductivity, k [W/m-°C (Btu/hr-ft-°F)]	Specific heat, C_p [J/kg-°C (Btu/lb _m -°F)]
22 (72)	1717 (107.2) ^a	123.68 (71.455) ^a	753.6 (0.180) ^a
200 (392)	1713 (106.9) ^b	108.22 (62.523) ^a	1172.2 (0.280) ^b
400 (752)	1709 (106.7) ^b	90.25 (52.143) ^a	1507.1 (0.360) ^b
600 (1112)	1704 (106.4) ^b	73.54 (42.487) ^a	1674.6 (0.400) ^b
800 (1472)	1701 (106.2) ^b	63.51 (36.693) ^a	1779.3 (0.425) ^b
1000 (1832)	1696 (105.9) ^b	56.43 (32.6) ^b	1863.0 (0.445) ^b
1200 (2192)	1692 (105.6) ^b	51.41 (29.7) ^b	1967.7 (0.463) ^b
1400 (2552)	1687 (105.3) ^b	48.12 (27.8) ^b	2009.5 (0.480) ^b
1600 (2912)	1682 (105.0) ^b	45.87 (26.5) ^b	2051.4 (0.490) ^b
1800 (3272)	1677 (104.7) ^b	34.79 (25.8) ^b	2114.3 (0.505) ^b

^aData from Ref. 8.^bExtrapolated values using trend curves from Ref. 9.

Fig. 7. Thermal conductivity of H-451 graphite.

in Figs. 8 and 9. The thermal conductivity of unirradiated fuel rods (shown in Fig. 10) was taken from Ref. 10 and is representative of the average rod in a large HTGR core (approximately 23 vol % shim particles). The required properties of argon, taken from Ref. 11, are shown in Table 2 and in Figs. 11 to 13. The values of viscosity and Prandtl number shown in Table 2 were required for cases where convection was considered.

To determine the temperature dependency of κ_{eff} , several different cases were run with the average cell temperature varied from 1079°C (1975°F) to 1635°C (2975°F). The temperature distribution in the cell for a typical case is shown in Fig. 14. It was found that, although κ_{eff} was much less than the thermal conductivity of graphite alone, it was relatively insensitive to temperature. Although it was assumed that the argon would closely follow the block temperature, which means that, with the low flow rates involved, conduction would be the dominant heat transfer process through the

Fig. 8. Density of H-451 graphite.

Fig. 9. Specific heat of H-451 graphite.

argon, several cases of forced convection were also analyzed. The temperature distribution within the cell for the case of an average cell temperature of 1468°C (2675°F) and a free stream argon temperature of 538°C (1000°F) is shown in Fig. 15. Note that convection to the argon does not cause severe temperature gradients or temperature spikes, which would be the source of high thermal stresses.

The results of the effective thermal conductivity cases are summarized in Table 3 and shown graphically in Fig. 16. The final selection of the κ_{eff} values to be used was based on the assumption that convection to the argon purge gas would only slightly affect thermal conductance and that the argon purge gas temperature would slightly lag the block temperature at each end by approximately 56°C (100°F), being cooler at the top and hotter at the bottom. These results are shown in Fig. 16 by the two curves parallel

Table 2. Properties of argon

Temperature [°C (°F)]	Viscosity, $\mu \times 10^5$ [kg/m-sec (lb _m /ft-sec)]	Density, ρ [kg/m ³ (lb _m /ft ³)]	Thermal conductivity, k [W/m-°C (Btu/hr-ft-°F)]	Specific heat, C_p [J/kg-°C (Btu/lb _m -°F)]	Prandtl No.
21 (70)	2.257 (1.517)	1.6512 (0.10311)	0.0174 (0.0101)	521.6 (0.1246)	0.677
93 (200)	2.680 (1.801)	1.3263 (0.08283)	0.0208 (0.0120)	521.3 (0.1245)	0.672
204 (400)	3.262 (2.192)	1.0179 (0.06357)	0.0255 (0.0148)	520.9 (0.1244)	0.666
315 (600)	3.784 (2.543)	0.8260 (0.05158)	0.0298 (0.0172)	520.8 (0.1244)	0.663
427 (800)	4.267 (2.867)	0.6940 (0.04334)	0.0336 (0.0194)	520.6 (0.1243)	0.661
538 (1000)	4.713 (3.167)	0.5995 (0.03744)	0.0372 (0.0215)	520.5 (0.1243)	0.660
649 (1200)	5.137 (3.452)	0.5275 (0.03294)	0.0405 (0.0234)	520.5 (0.1243)	0.661
760 (1400)	5.539 (3.723)	0.4707 (0.02940)	0.0436 (0.0252)	520.5 (0.1243)	0.661
871 (1600)	5.982 (3.982)	0.4250 (0.02654)	0.0465 (0.0269)	520.4 (0.1243)	0.663
982 (1800)	6.297 (4.232)	0.3874 (0.02419)	0.0493 (0.0285)	520.4 (0.1243)	0.666
1093 (2000)	6.644 (4.478)	0.3560 (0.02223)	0.0519 (0.0300)	520.4 (0.1243)	0.668
1205 (2200)	7.013 (4.712)	0.3290 (0.02055)	0.0545 (0.0315)	520.4 (0.1243)	0.673
1316 (2400)	7.367 (4.950)	0.3075 (0.01921)	0.0570 (0.0329)	520.4 (0.1243)	0.675
1427 (2600)	7.720 (5.188)	0.2860 (0.01786)	0.0594 (0.0343)	520.4 (0.1243)	0.678
1538 (2800)	8.074 (5.426)	0.2685 (0.01677)	0.0619 (0.0358)	520.4 (0.1243)	
1649 (3000)	8.428 (5.663)	0.2486 (0.01581)	0.0644 (0.0372)	520.4 (0.1243)	0.679
1760 (3200)	8.782 (5.901)	0.2351 (0.01495)	0.0669 (0.0386)	520.4 (0.1243)	0.682

Fig. 10. Thermal conductivity of unirradiated HTGR fuel rods with 23 vol % shim.

Fig. 11. Thermal conductivity of argon.

Fig. 12. Density of argon.

Fig. 13. Specific heat of argon.

Fig. 14. Temperature distribution within the effective thermal conductivity cell for the case of conduction through argon [average cell temperature of 1635°C (2975°F)].

Fig. 15. Temperature distribution within the effective thermal conductivity cell for the case of convection to argon [argon-graphite temperature differential of 930°C (1675°F)].

Fig. 16. Effective thermal conductivity for HTGR fuel block.

Table 3. Summary of effective thermal conductivity results

Case	ΔT^a [°C (°F)]	T^b [°C (°F)]	κ_{eff} [W/m-°C (Btu/hr-in.-°F)]
1	-930 (-1675)	1468 (2675)	12.150 (0.585)
2	-375 (-675)	1468 (2675)	17.233 (0.830)
3	0 0	1468 (2675)	23.682 (1.140)
4		1468 (2675)	23.663 (1.139)
5		1635 (2975)	23.755 (1.144)
6		1079 (1975)	24.241 (1.167)
7	-97 (-175)	1468 (2675)	21.804 (1.050)
8	+125 (+225)	1468 (2675)	25.557 (1.231)
9		1302 (2375)	23.962 (1.154)

^aTemperature differential between the argon and graphite for cases considering convection.

^bAverage cell temperature.

to the base conduction-radiation curve. The final values of κ_{eff} used in the subsequent thermal analyses are given in Table 4.

2.3 Thermal Analysis of HTGR Fuel Block Ends

The thermal analysis of the top and bottom ends of the HTGR fuel block considered the section of geometric symmetry shown in Fig. 17 to also be a section of thermal symmetry. The surface of the center hole was assumed to be at a uniform temperature of 1443°C (2630°F) at the top end and 1599°C (2910°F) at the bottom end, with the hexagonal flats uniformly at 1521°C (2770°F). The plane of symmetry was taken as an insulated boundary. The model was set up such that conduction and surface-to-surface radiation were considered across the dowel socket holes. Since the HEATING3 code requires the description of a plane geometry using either rectangular or polar elements, the geometric boundaries shown in Fig. 17 cannot all be exactly described. However, using a sufficient number of rectangular elements permitted satisfactory description of the cross section.

Table 4. Values of effective thermal conductivity used in thermal stress analyses of HTGR fuel and control rod fuel blocks

Temperature [°C (°F)]	Average [W/m-°C (Btu/hr-in.-°F)]	Top end [W/m-°C (Btu/hr-in.-°F)]	Bottom end [W/m-°C (Btu/hr-in.-°F)]
1100 (2012)	24.10 (1.160)	23.20 (1.117)	25.00 (1.204)
1200 (2192)	23.90 (1.151)	23.01 (1.108)	24.79 (1.194)
1300 (2372)	23.73 (1.143)	22.86 (1.101)	24.60 (1.184)
1400 (2552)	23.61 (1.137)	22.75 (1.095)	24.47 (1.178)
1500 (2732)	23.55 (1.134)	22.70 (1.093)	24.40 (1.175)
1600 (2912)	23.57 (1.135)	22.71 (1.093)	24.42 (1.176)
1700 (3092)	23.68 (1.140)	22.80 (1.098)	24.55 (1.182)
1800 (3272)	23.90 (1.151)	23.03 (1.109)	24.77 (1.193)

Fig. 17. Section used as basis for thermal model of top and bottom ends of HTGR fuel block.

The analyses indicated a very symmetric radial temperature distribution for both the top and bottom ends of the fuel block as shown in Figs. 18 and 19, respectively. Additionally, the dowel socket holes had little effect on the temperature distribution.

2.4 Thermal Analysis of HTGR Control Rod Fuel Block Ends

The model development for the thermal analysis of the control rod block was essentially the same as for the fuel block. Due to the relatively large areas of graphite without penetrations (see Fig. 2), it was necessary to develop the thermal model using three materials: H-451 graphite, the composite (graphite-fuel-argon cell), and argon. The basic model used, showing the general areas of each material, is shown in Fig. 20.

Fig. 18. Plot of isotherms for top end of HTGR fuel block (1 in. = 25.4 mm).

Fig. 19. Plot of isotherms for bottom end of HTGR fuel block (1 in. = 25.4 mm).

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Fig. 20. Section used as basis for thermal model of top and bottom ends of HTGR control rod fuel block.

The results of the thermal analyses for the top and bottom ends of the control rod block are shown in Figs. 21 and 22, respectively. The temperatures are symmetric radially, with little disturbance caused by the dowel socket and control rod holes.

2.5 Thermal Analysis of the HTGR Fuel Block Treated as an Axisymmetric Cylinder

The last case analyzed was that of the HTGR fuel block modeled as an axisymmetric cylinder. The purpose of this analysis was to investigate the axial distribution of thermal stresses in the fuel block. The temperature distribution across each end of the block was taken from the results of the analysis of each respective end. The axial surface temperature distribution was based on that shown in Fig. 3. However, it was found that the given profile needed to be shifted slightly to satisfy the end conditions [1521°C (2770°F)]. The results were that the peak surface temperature did not occur at the exact axial midplane of the block and that the peak temperature to satisfy the specified axial gradient was 1818°C (3305°F) rather than 1802°C (3275°F). Both of these factors would yield conservative predictions of thermal stresses.

In setting up the thermal model, the cylinder was assumed to consist of a homogeneous material with the same thermal conductivity as the effective value previously calculated. Also, the radius of the right-circular cylinder was taken as the mean of the maximum and minimum radial dimensions of the block, as shown in Fig. 23, which is the basis used for the thermal model.

The results of the thermal analysis are shown in Fig. 24. Note that the end of the block being heated has the more severe thermal gradients. Also, the maximum temperature of the radial center of the block is not as high as that on the axial surface of the block.

The thermal analyses described above were used to establish the thermal boundary conditions for the stress analyses, which are discussed in the next chapter.

Fig. 21. Plot of isotherms for top end of HTGR control rod fuel block (1 in. = 25.4 mm).

Fig. 22. Plot of isotherms for bottom end of HTGR control rod fuel block (1 in. = 25.4 mm).

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Fig. 23. Section used as basis for thermal model of axisymmetric cylinder representation of HTGR fuel block (1 in. = 25.4 mm).

Fig. 24. Plot of isotherms for axisymmetric cylinder model of HTGR fuel block (1 in. = 25.4 mm).

3. THERMAL-STRESS ANALYSIS

3.1 Methods of Analysis

The matrix of fuel and coolant holes in the fuel and control rod fuel blocks forms a complex geometric array which would be very expensive and time consuming to analyze by three-dimensional methods. Since these analyses were to be scoping calculations, it was assumed that two-dimensional analyses could be used. As with the thermal analyses, five specific cases were analyzed: plane analyses of each end of a fuel block (two cases), plane analyses of each end of a control rod block (two cases), and a two-dimensional axisymmetric analysis of the fuel block treated as a right-circular cylinder. Both plane strain and plane stress analyses were done for each plane analysis case.

The plane analyses were done using the equivalent solid plate concept.³ In this approach,¹²⁻¹⁴ the perforated material is replaced by solid material of the same exterior dimensions but whose material properties have been adjusted to account for the penetrations. Both the coolant and fuel holes were simulated in this manner since the fuel in the fuel holes was assumed to be unable to carry a load. This procedure has been successfully applied in the past to thermal-stress analysis of tubesheets in heat exchangers.

The other assumptions made in the analysis are (1) elastic deformations and (2) transversely isotropic material constants. These assumptions were used in all the analyses. To perform the required thermal stress analysis, ORNL's version of the FEATS^{15,16} code was used.

3.2 Materials Constants

The temperature variation of modulus of elasticity used in these analyses is shown in Fig. 25. Data from Ref. 8 were used to establish the room-temperature properties, and supplementary data and trend curves from Ref. 9 were used to extrapolate the properties to the required temperatures [1800°C (3272°F)].

Fig. 25. Modulus of elasticity of H-451 graphite.

The temperature variation of the mean coefficient of thermal expansion is shown in Fig. 26. Data from Ref. 8 were used to establish base temperature-dependent properties, and an extrapolation method developed in Ref. 17 was used to extrapolate the properties to the required temperatures.

For values of Poisson's ratio, room-temperature data were used because no data for higher temperature could be found. Data from Ref. 8 are tabulated below.

Poisson's ratio — H-541

Direction of stress	Direction of strain	ν_{13}	ν_{12}	ν_{31}
Radial	Axial	0.110		
Radial	Radial		0.108	
Axial	Axial			0.125

As discussed above, the plane thermal stress analyses of the blocks were accomplished through the application of the equivalent solid plate concept.³ In this approach, the perforated material is replaced by solid plate material whose material properties have been adjusted to account for the penetrations. The elastic modulus E and Poisson's ratio ν were replaced by the effective elastic modulus E^* and effective Poisson's ratio ν^* of the perforated material, and conventional elastic analysis methods were used to calculate the deformations and stresses for the equivalent solid material. The effective elastic constants for the perforated plane were calculated by the methods of Ref. 18. The fuel blocks have a triangular penetration pattern (see Fig. 1) with a ligament efficiency of 0.24. The calculated effective elastic constants are $E^* = 0.21E$ and $\nu^* = 0.4$.

The fracture criteria of graphite against which the calculated results are compared are usually the mean value minus 2 multiplied by a standard deviation or the minimum measured value of fracture stress or strain. The fracture strains for type H-451 graphite were obtained from Ref. 8. The means and standard deviations of fracture strains for this graphite were

Fig. 26. Coefficient of thermal expansion of H-451 graphite.

calculated using data from specimens taken from the midlength center (MLC) position of commercial H-451 graphite logs. The calculated means and standard deviations for the fracture stress at position MLC for type H-451 graphite was taken directly from Ref. 8. The tabulated means are listed in Table 5. Because the analyses were not exact, a safety factor of 2 was assumed in establishing fracture criteria. Our criteria, which were used in making the final comparison, are listed in Table 6.

Table 5. Stress and strain at fracture

	Axial orientation			Radial orientation		
	Mean	Standard deviation	Minimum value	Mean	Standard deviation	Minimum value
Strain, $\text{m/m} \times 10^{-6}$	2410	480	1300	2190	540	930
Stress, MPa (psi)	13.85 (2009)	1.64 (238)		11.31 (1640)	2.27 (329)	

Table 6. Limiting values of stress and strain from established criteria

	Axial orientation	Radial orientation
Strain, $\text{m/m} \times 10^{-6}$	650	465
Stress, MPa (psi)	5.31 (770)	3.38 (490)

3.3 Plane Analyses

In order to verify the equivalent solid plate concept, some analyses were done to calculate the stress and strain concentration factors caused by the holes under thermal loading. The analyses were based on the model used to calculate the effective radial thermal conductivity (Fig. 6).

The temperatures calculated in the thermal analysis were used in symmetric finite-element models, one with holes and one without holes, as shown in Figs. 27 and 28. The temperature distributions in both models are shown in Figs. 29 and 30. A plane stress and plane strain analysis of each model was completed. Both models were fixed in the Z direction and allowed to freely move in the r direction along the boundaries at $Z = 0.0$

Fig. 27. Model with holes to calculate the stress and strain concentration factors.

Fig. 28. Model without holes to calculate the stress and strain concentration factors.

Fig. 29. Temperature distribution in the model with holes.

TEMPERATURE IN °F

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2987.2
2986
2985.6
2984.8
2984.0
2983.2
2982.4
2981.6
2980.8
2980.0
2979.2
2978.4
2977.6
2976.8
2976.0
2975.2

Fig. 30. Temperature distribution in the model without holes.

and $Z = 0.370$ in. (9.398 mm). The other boundaries were free. Figures 31 through 34 show the maximum principal stress and shear stress distributions for the model with holes. Figures 35 through 38 show the same distributions for the model without holes. As may be seen, the distributions in the model with holes is much more complex than those in the model without holes; however, the maximum calculated values of stress and strain are the same or lower in the model with holes. The stress and strain concentration factors are listed in Table 7. These analyses have shown that essentially no stress or strain concentrations occurred because of the holes.

Table 7. Stress and strain concentration factors

Factors	Plane stress	Plane strain
Maximum stress	0.79	0.79
Maximum shear stress	1.02	1.02
Maximum strain	0.68	0.68
Maximum shear strain	1.02	1.03

The finite-element model used for the thermal stress analyses of the top and bottom surfaces of the fuel block is shown in Fig. 39. Plane stress and plane strain analyses (one each) of both the top and bottom surfaces were done by using the temperature boundary conditions calculated previously and shown in Figs. 18 and 19. The model was assumed to be fixed in the r direction (see Fig. 39) and free to move in the Z direction along the boundary $r = 0.0$. The other outside boundaries were assumed to be free to move. The distributions for the maximum principal stress for the top surface of the fuel block are shown in Figs. 40 and 41, while the distributions for the bottom surface are shown in Figs. 42 and 43. These figures show that the calculated maximum principal stress decreased from the center hole to the outer hexagonal surface on the top surface of the

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Fig. 31. Maximum principal stress distribution in the model with holes for a plane stress solution ($1 \text{ psi} = 6.895 \times 10^{-3} \text{ MPa}$).

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Fig. 32. Maximum principal shearing stress distribution in the model with holes for a plane stress solution ($1 \text{ psi} = 6.895 \times 10^{-3} \text{ MPa}$).

Fig. 33. Maximum principal stress distribution in the model with the holes for a plane strain solution ($1 \text{ psi} = 6.895 \times 10^{-3} \text{ MPa}$).

Fig. 34. Maximum principal shear stress distribution in the model with holes for a plane strain solution ($1 \text{ psi} = 6.895 \times 10^{-3} \text{ MPa}$).

Fig. 35. Maximum principal stress distribution in the model without holes for a plane stress solution ($1 \text{ psi} = 6.895 \times 10^{-3} \text{ MPa}$).

Fig. 36. Maximum principal shear stress distribution in the model without holes for a plane stress solution ($1 \text{ psi} = 6.895 \times 10^{-3} \text{ MPa}$).

Fig. 37. Maximum principal stress distribution in the model without holes for a plane strain solution ($1 \text{ psi} = 6.895 \times 10^{-3} \text{ MPa}$).

Fig. 38. Maximum principal shear stress distribution in the model without holes for a plane strain solution ($1 \text{ psi} = 6.895 \times 10^{-3} \text{ MPa}$).

Fig. 39. Finite-element layout of the top and bottom surfaces of the fuel block.

Fig. 40. Maximum principal stress distribution for the top surface of the fuel block for a plane stress solution ($1 \text{ psi} = 6.895 \times 10^{-3} \text{ MPa}$).

Fig. 41. Maximum principal stress distribution for the top surface of the fuel block for a plane strain solution ($1 \text{ psi} = 6.895 \times 10^{-3} \text{ MPa}$).

Fig. 42. Maximum principal stress distribution for the bottom surface of the fuel block for a plane stress solution ($1 \text{ psi} = 6.895 \times 10^{-3} \text{ MPa}$).

Fig. 43. Maximum principal stress distribution for the bottom surface of the fuel block for a plane strain solution ($1 \text{ psi} = 6.895 \times 10^{-3} \text{ MPa}$).

fuel block and increased from the center hole to the outer hexagonal surface on the bottom surface. All the maximum calculated values have been tabulated and are presented later in the report.

The finite-element model used for the analysis of the top and bottom surfaces of the control rod fuel block is shown in Fig. 44. Due to the relatively large areas of graphite without penetrations, it was necessary to use a model made of two materials. The shaded elements in Fig. 44 are H-451 graphite and the unshaded elements are assumed to be the equivalent solid graphite material. Plane stress and plane strain analyses of both the top and bottom surfaces were done using the temperature calculated previously and shown in Figs. 21 and 22. The model was assumed to be fixed in the r direction (see Fig. 44) and free to move in the Z direction along the boundary $r = 0.0$. The other outside boundaries were assumed to be free to move. The distributions of the maximum principal stress for the top surface of the control rod fuel block are shown in Figs. 45 and 46. These figures show that stresses are concentrated around the center hole, the reserve shutdown hole, and the control rod channel hole. The maximum stress occurred at the center hole in the plane stress analysis and at one side of the control rod channel hole in the plane strain analysis. The stress distributions for the bottom surface are shown in Figs. 47 and 48; the maximum principal stresses increase from the center hole to the outer hexagonal surface. The reserve shutdown hole and the control rod channel hole cause some concentration of the stresses even though the maximum stresses occur on the outside surface. In all the plane analyses, the maximum stresses were calculated in the plane strain solutions.

3.4 Thermal Stress Analysis of the Fuel Block as an Axisymmetric Cylinder

The finite-element model used to analyze the fuel block as a right-circular cylinder is shown in Fig. 49. A two-dimensional axisymmetric analysis was done using this model. As stated earlier, the radius of the right-circular cylinder was taken as the mean of the maximum and minimum radial dimensions of the block as shown in Fig. 23. The temperature boundary conditions used in the analysis were previously calculated and are

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Fig. 44. Finite-element layout of the top and bottom surfaces of the control rod block for a plane stress solution ($1 \text{ psi} = 6.895 \times 10^{-3} \text{ MPa}$).

Fig. 45. Maximum principal stress distribution for the top surface of the control rod block for a plane stress solution ($1 \text{ psi} = 6.895 \times 10^{-3} \text{ MPa}$).

Fig. 46. Maximum principal stress distribution for the top surface of the control rod block for a plane strain solution ($1 \text{ psi} = 6.895 \times 10^{-3} \text{ MPa}$).

Fig. 47. Maximum principal stress distribution for the bottom surface of control rod block for a plane stress solution ($1 \text{ psi} = 6.895 \times 10^{-3} \text{ MPa}$).

Fig. 48. Maximum principal stress distribution for the bottom surface of control block for a plane strain solution ($1 \text{ psi} = 6.895 \times 10^{-3} \text{ MPa}$).

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Fig. 49. Finite-element layout of the fuel block as an axisymmetric cylinder.

shown in Fig. 24. The model was assumed to be fixed in the Z direction and free to move in the r direction along the boundary $Z = 0$ and $r = 17.46 \text{ mm}$ (0.6875 in.) to $r = 193.91 \text{ mm}$ (7.6341 in.) and fixed in the r direction and free to move in the Z direction along the boundary $r = 0$ and $Z = 50.8 \text{ mm}$ (2.0 in.) to $Z = 422.15 \text{ mm}$ (16.62 in.) (see Fig. 49). The other outside boundaries were assumed to be free to move. Figures 50 and 51 show the distributions of the circumferential and maximum principal stresses. The calculations indicate that the stresses and strains increase greatly from the center toward each end.

Fig. 50. Distribution of circumferential stress in the fuel block as an axisymmetric cylinder.

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Fig. 51. Maximum principal stress distribution in the fuel block as an axisymmetric cylinder.

4. SUMMARY AND CONCLUSIONS

The plane stress and strain analyses of the ends of the fuel block and control rod fuel block did not take the effect of the axial temperature gradient into account. A plane strain analysis and a plane stress analysis of the hot end of the fuel block as an axisymmetric cylinder were done for a radial temperature gradient only. Comparison between the radial and circumferential stresses of the axisymmetric analysis to those of the plane analyses indicated that the maximum radial stresses of the plane analyses were somewhat larger than the radial stresses of the axisymmetric analysis. However, the circumferential stresses did not compare very well and the plane analyses were not conservative for these stresses. The differences between the analyses for the circumferential stresses can be attributed to neglecting the axial gradient in the plane analyses.

The plane analyses were used because of the complex geometry of the cross sections of the fuel blocks (see Figs. 1 and 2). The equivalent solid plate concept could be used in the analysis of the fuel blocks to model the hole penetration pattern of the fuel and coolant holes. The plane analyses were used to analyze the control rod fuel blocks to ascertain the effects of the reserve shutdown holes and control rod channel holes. Our assumed safety factor of 2.0 on the failure criteria should account for the neglected axial temperature gradient in the plane analyses.

The results for the plane and the axisymmetric analyses are given in Table 8. As may be seen, the maximum calculated tensile stress values are smaller than the criteria values (listed in Table 6) except for the plane strain analysis of the control rod fuel block end surfaces and the axisymmetric analysis of the fuel block as a circular cylinder. However, most of the maximum calculated strain values are greater than the criteria values.

The analysis of the fuel block as an axisymmetric cylinder indicated that the maximum stresses and strains occur at the two ends of the block. Figure 24 shows the temperature distribution in the block. As may be seen, the axial and radial temperature gradients increase greatly at the ends of the fuel block; this in turn caused the stresses and strains to increase greatly toward the ends of the block as shown in Figs. 50 and 51. Based

Table 8. Maximum stresses and strains

Cases	Axial or circumferential stress [MPa (psi)]	Maximum principal stress [MPa (psi)]	Minimum principal stress [MPa (psi)]	Maximum principal shearing stress [MPa (psi)]	Axial or circumferential strain (m/m $\times 10^{-6}$)	Maximum principal strain (m/m $\times 10^{-6}$)	Minimum principal strain (m/m $\times 10^{-6}$)	Shear strain (m/m $\times 10^{-6}$)
Fuel block as a right-circular cylinder	7.47 (1084) (top center)	6.84 (992) (bottom center)	-9.26 (-1343)	5.20 (754)	648 (top center)	583 (bottom center)	-918	535
Control rod-top surface (plane strain)	0	3.72 (540)	-4.37 (-634)	2.45 (355)	-1007	1001	-956	778
Control rod-top surface (plane stress)	0	2.14 (310)	-2.48 (-360)	1.38 (200)	-421	830	-534	523
Control rod-bottom surface (plane strain)	0	3.65 (530)	-3.99 (-579)	2.42 (351)	973	641	-1125	883
Control rod-bottom surface (plane stress)	0	2.48 (359)	-2.22 (-322)	1.37 (199)	423	520	-830	524
Fuel element block- top surface (plane strain)	0	3.02 (438)	1.25 (181)	1.07 (155)	-978	916	-441	671
Fuel element block- top surface (plane stress)	0	1.78 (258)	0.74 (107)	0.65 (94)	-405	709	-313	405
Fuel element block- bottom surface (plane strain)	0	1.18 (171)	-3.08 (-448)	1.09 (158)	976	441	-914	670
Fuel element block- bottom surface (plane stress)	0	0.07 (101)	-1.82 (-264)	0.66 (98)	405	313	-709	405

on the established criteria, we concluded that the stresses are too large on the ends of the fuel block and any cracking that occurs will likely be on the ends.

In summary, the analyses show that there is the potential for the fuel and control rod fuel blocks to fracture on the end surfaces. However, even without the safety factor of 2.0 the calculated results are marginal; therefore, we cannot say that the thermal stresses and strains developed in the fuel and control rod fuel blocks will or will not cause fracture. A more refined analysis or a better material description of the graphite may lead to a more exact answer. However, for this complex geometry, a more refined analysis would be very expensive. A better answer would be to reduce the thermal gradients in the ends of the blocks in some manner; this would reduce the thermal stresses in the block ends because the thermal stresses depend on the thermal gradients rather than the temperature.

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