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GRAPHITE DESIGN HANDBOOK

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GRAPHITE DESIGN HANDBOOK

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SYMBOLS, ACRONYMS, AND ABBREVIATIONS

A	axial direction
b	percent graphite burnoff
b	inverse of the crystallite boundary spacing (Eq. 4-6)
CR	central reflector
C_p	specific heat at constant pressure
CTE	coefficient of thermal expansion
D_{H_2O}	effective diffusion coefficient of steam in graphite
D_{CO}	effective diffusion coefficient of carbon monoxide in graphite
D_{H_2}	effective diffusion coefficient of hydrogen in graphite
D_{O_2}	effective diffusion coefficient of oxygen in graphite
d	irradiation damage parameter (Eq. 4-6)
E	elastic modulus (see sections on mechanical properties), may have subscript x, z, 1, or 3
E_j , $j = 1, 2, 3$	Activation energy (see sections on oxidation rates)
E	energy level (of neutron)
F	fractional increase in thermal resistivity due to neutron irradiation
F_b , F_c	modifying factors for effects of burnoffs and catalysts on oxidation rates
G	shear modulus (see sections on mechanical properties), may have subscript x, z, 1, or 3
GA	General Atomics

K	thermal conductivity
K_b	effect of the grain boundary scattering (Eq. 4-6)
K_d	effect of the irradiation damage (Eq. 4-6)
K_U	crystallite conductivity with Umklapp processing dominating
K_{IC}	fracture toughness
$K_j, j = 1, 2, 3$	chemical rate constant (see sections on oxidation rates)
$k_j, j = 1, 2, 3$	Arrhenius frequency factor (see sections on oxidation rates)
M_s	steady-state mobility coefficient, also called steady-state creep coefficient
n	exponent in the oxidation rate equation
ORNL	Oak Ridge National Laboratory
P	pressure
P_{H_2}, P_{H_2O}	local partial pressures of hydrogen and steam, respectively
PSR	permanent side reflector
QA	quality assurance
R	radial direction
R	$\sigma_{max}/\sigma_{min}$
RT	room temperature
r	radial distance from the axis of a billet
S	mean strength
STP	standard temperature and pressure
S_u	specified minimum ultimate strength
S_{uc}	compressive S_u
S_{ut}	tensile S_u

T	temperature
T_ϕ	irradiation temperature
UCS	ultimate compressive strength
UTS	ultimate tensile strength
x	fractional weight loss from oxidation (burnoff)
Z	axial distance from midlength of a billet
α	thermal expansivity
ϵ	strain, may have subscript x , y , or z
ϵ^c	irradiation-induced creep strain
ϵ^e	elastic strain
ϵ^I	irradiation-induced dimensional change (stress-free)
ϵ^s	steady state part of ϵ^c
ϵ^T	transient part of ϵ^c
ϵ^θ	thermal strain
γ	shear strain, may have subscript xy , yz , or zx
ζ	internal damping factor (see Section 3.3.4.6)
ν	Poisson's ratio (see sections on mechanical properties), may have subscript 12 or 13
σ	applied normal stress, may have subscript x , y , or z
$\sigma_{\max}, \sigma_{\min}$	maximum and minimum applied stresses, respectively, during a cycle in fatigue tests
τ	exponential relaxation time in units of neutron fluence
τ	shear stress, may have subscript xy , yz , or zx
Φ	fast neutron fluence expressed as equivalent HTGS fast fluence, $E > 29$ fJ or equivalently $E > 0.18$ MeV
Φ_R	relaxation time (Eq. 4-32)

1. INTRODUCTION

1.1. OBJECTIVE

The objectives of the Graphite Design Handbook (GDH) are (1) to provide and maintain a single source of graphite properties and phenomenological model of mechanical behavior to be used for design of MHTGR graphite components of the Reactor System, namely, core support, permanent side reflector, hexagonal reflector elements, and prismatic fuel elements; (2) to provide a single source of data and material models for use in MHTGR graphite component design, performance, and safety analyses; (3) to present properties and equations representing material models in a form which can be directly used by the designer or analyst without the need for interpretation and is compatible with analytical methods and structural criteria used in the MHTGR project; and (4) to control the properties and material models used in the MHTGR design and analysis to proper Quality Assurance standards and project requirements.

1.2. SCOPE

The Reactor System includes graphite parts in the reactor core, reflector, and internals (Ref. 1-1). The reference graphite in the reactor core and replaceable hexagonal reflector components is grade H-451. These components are to be designed to meet the structural criteria for core graphite (Ref. 1-2).

The reference graphite in the reactor internals components is the nuclear grade 2020. There are two subgrades of interest, the cylinder nuclear grade and the large rectangular nuclear grade. The large rectangular nuclear grade is molded in large rectangular blocks. It is the

reference material for the permanent side reflector and the central column support structure. The cylindrical nuclear grade is isostatically pressed and is intended for use as the core support component. This nuclear grade is provided as cylindrical logs. Both components are designed to meet the structural criteria for graphite core supports (Ref. 1-3). Since the material properties of graphite are dependent on both process and size, the properties of these two subgrades are defined separately.

This report gives the design properties for both H-451 and 2020 graphite as they apply to their respective criteria. The properties are presented in a form for design, performance, and safety calculations that define or validate the component design.

1.3. APPLICABILITY

The properties presented in this handbook are the reference properties that are approved for use in MHTGR design, performance, and safety calculations.

1.4. ORGANIZATION OF THIS HANDBOOK

(Later)

1.5. DEFINITION OF SYMBOLS AND ACRONYMS

(Later)

1.6. REFERENCES

- 1-1. "Reactor System Design Description," DOE-HTGR-86035, Rev. 2 (GA Document 908438/3), April 1988.

- 1-2. "Structural Design Criteria for Replaceable Graphite Core Elements," DOE-HTGR-88150, Rev. 0 (GA Document 909729/0), August 1988.
- 1-3. "Proposed Section III, Division 2, ASME Boiler and Pressure Vessel Code, Subsection CE, Design Requirements for Graphite Core Supports," April 1984.

2. RESPONSIBILITY AND AUTHORITY

2.1. RESPONSIBILITY

Responsibility for maintaining this document is vested in General Atomics.

2.2. QUALITY ASSURANCE

All structures and components that are designated as "safety-related" shall come under a Quality Assurance Program which fully complies with the requirements of Title 10 of the Code of Federal Regulations Part 50 (10CFR50), Appendix B. The basic requirements and supplements of ANSI/ASME NQA-1 (as endorsed by USNRC Regulatory Guide 1.28, Revision 3) shall be implemented for activities that affect the quality of such items. The core supports, permanent side reflectors, hexagonal reflector elements, and prismatic fuel elements are "safety-related" structures and components (Ref. 2-1). Therefore, the graphite used in these structures and components is "safety-related."

2.3. REFERENCE

- 2-1. "Equipment Classification List for the Modular High Temperature Gas-Cooled Reactor," DOE-HTGR-86032, Rev. 2 (GA Document 908792/2), July 1987.

3. NUCLEAR GRADE 2020 GRAPHITE

3.1. DESCRIPTION OF GRADE

There are two subgrades of nuclear grade 2020 graphite used for the reactor internals components, the large rectangular nuclear grade and the cylindrical nuclear grade. The large rectangular grade 2020 graphite is a fine-grained, molded artificial graphite produced in large rectangular blocks. It is the reference material for permanent side reflectors and central reflector column support blocks. To date, the largest log fabricated and tested was 1.067 m (42 in.) long x 0.914 m (36 in.) wide x 0.457 m (18 in.) thick. The log intended for use as central reflector column support blocks and permanent side reflector column supports at the entrance of the hot duct will be slightly larger than the above. For preliminary design analysis, the properties of the log tested are assumed to apply to the larger size (until such time as the experimental data are available).

The cylindrical nuclear grade 2020 graphite is a fine-grained, isostatically molded artificial graphite produced in cylindrical logs. The nuclear grade differs from the off-the-shelf commercial grade only in that the raw material has been carefully controlled in impurity content, hence its oxidation characteristics improved. All other material properties are nearly identical to those of a commercial grade of the same size log. Nuclear grade is the reference material for the core support structure, including the post block, post and lower plenum floor block. The log tested (except oxidation rate) was a commercial grade of 1.98 m (78 in.) long x 0.254 m (10 in.) in diameter. The properties of the cylindrical log varied somewhat with axial position along the log because one end has a higher density than the other.

For the present, unless otherwise noted, design data given hereafter were derived from a 0.254 m (10 in.) diameter log.

3.2. APPLICATION

Application of 2020 grade graphite to the reactor internals components is summarized below:

1. Large rectangular nuclear grade: permanent side reflector (PSR), PSR support block at the entrance of the hot duct and central reflector column support structure.
2. Cylindrical nuclear grade: post block, T-post, and lower plenum floor block.

3.3. CYLINDRICAL NUCLEAR GRADE 2020 GRAPHITE

3.3.1. Introduction

The nuclear 2020 graphite properties are consistent with the structural criteria for graphite core supports (Ref. 3.3-1). Unless otherwise noted, the material properties given below for the nuclear grade 2020 are mean values.

The maximum predicted fast neutron fluence to the graphite core support structure is 2×10^{23} n/m² (E > 29 fJ, HTGR), which is less than 1% of the maximum fluence accumulated by fuel element graphite. Experience with fuel element graphite has shown that only elastic modulus and thermal conductivity will be noticeably affected by a total fast neutron fluence of 5×10^{23} n/m². Therefore, irradiation effects on other properties described below are insignificant and not discussed.

3.3.2. Physical and Chemical Properties

3.3.2.1. Density. The bulk density of 2020 graphite is 1.78 Mg/m³ averaged over the log (Refs. 3.3-2 and 3.3-3).

3.3.2.2. Transport and Reaction Rates.

3.3.2.2.1. Steam-Graphite Oxidation Rates. The Langmuir-Hinshelwood equation, Eq. 3.3-1, is used to predict steam-graphite oxidation rates for nuclear grade 2020 graphite (Ref. 3.3-4):

$$\text{Rate} = \frac{K_1 P_{\text{H}_2\text{O}} F_b}{1 + K_2 (P_{\text{H}_2})^n + K_3 P_{\text{H}_2\text{O}}} \quad (3.3-1)$$

where Rate = local graphite mass fraction reacting per second,

P_{H_2} , $P_{\text{H}_2\text{O}}$ = local partial pressures of hydrogen and steam, respectively,

F_b = modifier for effects of burnoff,

n = exponent,

$K_j = k_j \exp(E_j/RT)$,

where $j = 1, 2, \text{ or } 3$,

k_j = Arrhenius frequency factor,

E_j = activation energy,

$R = 8.314 \text{ J/mole}\cdot\text{K}$.

The values of K_1 , K_2 , K_3 , and n given in Table 3.3-1 are based on data for the temperatures indicated. Until data at other temperatures are available, it is assumed that k_j in Table 3.3-1 can be extrapolated to other temperatures.

For preliminary design, F_b is the same as that used to predict burnoff effects for steam oxidation of H-451 graphite (until such time

TABLE 3.3-1
SUMMARY OF OXIDATION KINETIC CONSTANTS FOR
NUCLEAR 2020 GRAPHITE

Temperature (°C)	n	High Water >100 Pa H ₂ O			Low Water <100 Pa H ₂ O		
		K_1 (s·Pa) ⁻¹	K_2 Pa ^{-1.3}	K_3 Pa ⁻¹	K_1 (s·Pa) ⁻¹	K_2 Pa ^{-1.3}	K_3 Pa ⁻¹
980	1.3	8.7E-10	1.1E-3	2.6 - 8.7E-4	7.2E-9	9.0E-3	8.1E-2
930	1.3	3.8E-10	1.6E-3	3.8 - 16E-4	2.3E-9	9.5E-3	1.7E-1
900	1.3	2.0E-10	2.0E-3	2.0 - 4.0E-4			

as additional 2020 graphite oxidation data are available). The oxidation rate of the nuclear grade 2020 graphite is about one-fifth that of H-451 graphite.

3.3.2.2.2. Air-Graphite Reaction Rates. The rate of oxidation of graphite by air is given by Eq. 3.3-2 (Ref. 3.3-8):

$$\text{Rate} = K \exp(-E/RT) P_{O_2} \quad , \quad (3.3-2)$$

where Rate = local graphite mass fraction reacting per second (SI) or
local graphite mass fraction reacting per hour (units
normally used in OXIDE code calculations),

P_{O_2} = local partial pressure of oxygen.

Table 3.3-2 gives the system of units derived from H-327 experimental data. It is assumed that the air-graphite reaction rate of H-451 is identical to that of H-327.

Since there are no experimental data on air-graphite reaction rate reported for the grade 2020 graphite, Eq. 3.3-2, together with Table 3.3-2, shall be used. The value of K given in Table 3.3-2 needs to be modified by a factor equal to the ratio of the steam-graphite oxidation rate of nuclear grade 2020 graphite to that of H-451 graphite at the environmental conditions of interest.

3.3.2.2.3. Radiolytic Effect on Oxidation Rate. The available experimental data show that there is a small and negligible radiolytic effect on oxidation rate in air (see discussion in Section 4.3.2.3).

TABLE 3.3-2
AIR-GRAPHITE REACTION RATE COEFFICIENTS^(a)

Systems of Units	K	E	T	R
SI	0.79 (s·Pa) ⁻¹	1.7 x 10 ⁵ J/mol·K	K	8.314 J/mol·K
OXIDE code	2.88 x 10 ¹⁰ (% h·atm) ⁻¹	4.06 x 10 ⁴ cal/mol	K	1.986 cal/mol·K

^(a)See text for the appropriate values to be used in Eq. 3.3-2 for nuclear grade 2020 graphite.

3.3.2.2.4. Transport of Steam in Helium by Diffusion. The effective diffusion coefficient of steam in graphite is given by Eq. 3.3-3 (Refs. 3.3-5 through 3.3-7):

$$D_{H_2O} = \frac{1.0 \times 10^{-10} \times T^{1.58} \times P}{P_{total}} \text{ (m}^2\text{/s)} \quad , \quad (3.3-3)$$

where D_{H_2O} = effective diffusion coefficient through graphite,
 T = temperature (K),
 P = pressure at STP* (Pa),
 P_{total} = total pressure (Pa).

A parameter such as diffusion through graphite is recognized to vary by as much as a factor of three from sample to sample or from position to position in the graphite block. Equation 3.3-3 describes the present best estimate for H_2O diffusion in graphite having 1% average oxidation burnoff.

Equation 3.3-3 was obtained by pooling all available experimental data on steam diffusion through graphite in helium. No corrections were made for the differences in porosity and pore structure. Equation 3.3-3 is assumed to be applicable to all reference HTGR graphites.

The effective diffusion coefficients recommended for carbon monoxide, oxygen, and hydrogen are as follows (until such time as experimental data are available):

$$\begin{aligned} D_{CO} &= D_{H_2O} \quad , \\ D_{O_2} &= D_{H_2O} \quad , \\ D_{H_2} &= 2D_{H_2O} \quad . \end{aligned} \quad (3.3-4)$$

*STP - standard temperature and pressure.

3.3.2.2.5. Transport of Steam in Helium by Convection. The transport of steam by convection involves the permeation of graphite. The permeability coefficients of graphite (Ref. 3.3-29) are:

$$K_I = 1.55E-13 \text{ m}^2 \quad ,$$

$$K_P = 9.20E-14 \text{ m}^2 \quad ,$$

where the subscripts represent the following regions of the hexagonal graphite blocks:

I = interior region consisting of a hexagonal block having an area in the plane of the hexagon one-seventh of the corresponding area of the entire block,

P = periphery region consisting of the entire hexagonal block minus the interior region.

The values of K_I and K_P are derived from data on H-327 graphite; they are assumed to apply to 2020 graphite (until such time as experimental data are available).

3.3.3. Thermal Properties

3.3.3.1. Specific Heat. The specific heat of graphite over the temperature range 250 to 3000 K is given by Eq. 3.3-5 (Ref. 3.3-9):

$$\begin{aligned} C_p = & (0.54212 - 2.42667 \times 10^{-6} T - 90.2725 T^{-1} \\ & - 4.34493 \times 10^4 T^{-2} + 1.59309 \times 10^7 T^{-3} \\ & - 1.43688 \times 10^9 T^{-4}) \times 4184 \quad , \end{aligned} \quad (3.3-5)$$

where C_p = specific heat at constant pressure (J/kg-K),
T = temperature (K).

Equation 3.3-5 is also presented graphically in Fig. 3.3-1.

Fig. 3.3-1 Specific Heat of Graphite as a Function of Temperature

3.3.3.2. Thermal Expansivity. The thermal expansivity of 2020 graphite is given below (Ref. 3.3-10):

$$\alpha = A + B (\Delta T) \quad , \quad (3.3-6)$$

where α = CTE ($1/^{\circ}\text{C}$),

ΔT = temperature increase above room temperature ($^{\circ}\text{C}$),

$A = 0.3075 \times 10^{-5}$ in the radial direction,

$= 0.3225 \times 10^{-5}$ in the axial direction,

$B = 1.078 \times 10^{-9}$ in the radial direction,

$= 1.167 \times 10^{-9}$ in the axial direction.

3.3.3.3. Thermal Conductivity. The thermal conductivity of unirradiated 2020 graphite is given in Table 3.3-3 as a function of measurement temperature (Ref. 3.3-3). The change in thermal conductivity of irradiated 2020 graphite at irradiation temperature is given in Eq. 3.3-6 (Ref. 3.3-11).

$$\frac{1}{K_i(T)} = \frac{1}{K_o(T)} + \frac{F}{K_o(295 \text{ K})} \quad , \quad (3.3-7)$$

where $K_i(T)$ = thermal conductivity of irradiated graphite at temperature T (K),

$K_o(T)$ = thermal conductivity of unirradiated graphite at temperature T (K) (derived from Table 3.3-3),

$K_o(295 \text{ K})$ = thermal conductivity of unirradiated graphite at room temperature,

F = fractional increase in thermal resistivity due to neutron irradiation (fluence dependence is given in Table 3.3-4 and Fig. 3.3-2).

TABLE 3.3-3
THERMAL CONDUCTIVITY OF 2020 GRAPHITE

Orientation	Conductivity at Measurement Temperature (W/m·K)				
	295 K	473 K	673 K	873 K	1073 K
Radial	62.4	67.2	57.2	49.8	43.9
Axial	63.0	63.7	53.7	45.2	40.8

TABLE 3.3-4
THERMAL RESISTIVITY CONSTANT F, USED IN EQ. 3.3-7

Fast Neutron Fluence (10^{22} n/m ²)	Irradiation Temperature (K)		
	673	873	1073
0.4	0.075	0.0885	0.0215
1	0.125	0.063	0.036
4	0.27	0.138	0.078
10	0.445	0.225	0.124
20	0.665	0.33	0.185

Fig. 3.3-2. Design curves for change in room temperature thermal resistivity of 2020 graphite as a function of irradiation conditions

The tabulated data on F were established from analysis of experimental data measured on miscellaneous graphites. Until such time as 2020 graphite thermal conductivity data under low irradiation level are available, it is assumed that Table 3.3-4 is applicable to 2020 graphite.

For other fast fluences, a linear relationship may be used between logarithms of F and fast fluence. An approximately linear relationship also exists between T and logarithm of F .

Thermal annealing on thermal conductivity appears to begin at 1273 K and is completed by 1573 K (Refs. 3.3-12 and 3.3-13). In this temperature range the fractional change in conductivity is close to linearly proportional to temperature. The fractional increase in thermal resistivity, F , in Eq. 3.3-7 is assumed to linearly decrease to zero over the above temperature range.

3.3.3.4. Emissivity. The emissivity of 2020 graphite for machined surface is 0.85 (Refs. 3.3-14 through 3.3-16).

3.3.4. Mechanical Properties

3.3.4.1. Transversely Isotropic Linear Elastic Constants. The mechanical properties of 2020 graphite can be modeled as transversely isotropic. The isotropic plane is in the across grain direction of an isostatically molded cylindrical graphite log. The with-grain direction is the axial direction, and is labelled as the 3-axis. The five independent parameters in the transversely isotropic linear elastic material are two elastic moduli, E_1 and E_3 ; shear modulus, G_1 ; and two Poisson's ratios, ν_{12} and ν_{13} .

The properties given below are the average of the combined tensile and compressive moduli at room temperature. The difference between two moduli is less than 10% (Refs. 3.3-2, 3.3-3 and 3.3-17 through 3.3-19):

$$\begin{aligned} E_1 &= 9.5 \text{ GPa}, \\ E_3 &= 8.9 \text{ GPa}, \\ G_1 &= 4.1 \text{ GPa}, \\ \nu_{12} &= \nu_{13} = 0.15. \end{aligned}$$

The elastic moduli given above are the secant moduli of the second loading curve between 0 and 6.9 MPa.

The following modulus/temperature relationship applies to E_1 , E_3 , and G_1 , but not ν_{12} and ν_{13} (Ref. 3.3-20):

$$\begin{aligned} C(T) &= C_{RT} - 9.94 \times 10^{-4} (T - 21) \\ &\quad + 3.09 \times 10^{-6} (T - 21)^2, \end{aligned} \quad (3.3-8)$$

where $C_{RT} = E_1, E_3$, or G_1 at room temperature (GPa),

$T = \text{temperature } (^{\circ}\text{C})$,

$C(T) = E_1, E_3$, or G_1 at temperature T (GPa).

The relationship is valid up to 1100°C.

The moduli increase with fast neutron irradiation. The percent increase (P) is given in Table 3.3-5 as well as plotted in Fig. 3.3-3 as a function of neutron fluence and irradiation temperature (Ref. 3.3-21). To calculate modulus (E_i) at any point during neutron irradiation, the following equation applies:

$$E_i = E_o (1 + P/100) \quad , \quad (3.3-9)$$

TABLE 3.3-5
 PERCENT INCREASE (P) IN ELASTIC MODULUS AS
 A FUNCTION OF FLUENCE AND TEMPERATURE

Fast Neutron Fluence (10^{22} n/m ²)	Irradiation Temperature (K)		
	673	873	1173
1	4.3	3.1	2.3
4	13.3	9.8	7.4
10	24.0	18.3	13.9

Fig. 3.3-3. Design curves for change in elastic modulus of 2020 graphite as a function of irradiation conditions

where E_o = elastic modulus of unirradiated graphite at room temperature,

$$P = \left(\frac{E_o}{E_i} - 1 \right) \times 100,$$

E_i = elastic modulus of irradiated graphite measured at room temperature.

For P at irradiation temperature and fast neutron fluence other than that given in Table 3.3-5, the following relationship applies:

1. Logarithm of P is a quadratic function of logarithm of ϕ .
2. Logarithm of P is a quadratic function of temperature ($^{\circ}\text{C}$).

3.3.4.2. Stress-Strain Curve. Typical room temperature (RT) tensile and compressive stress-strain curves for 2020 graphite are shown in Figs. 3.3-4 and 3.3-5, respectively (Refs. 3.4-2, 3.4-3, and 3.4-22). The curves are applicable to a nonlinear design analysis.

Typical RT tensile and compressive stress strain curves when compared in the stress range below the specified minimum ultimate tensile strength (S_{ut} in Section 3.3.4.3) are slightly deviated from each other by less than one "within log" standard deviation. For practical purpose in the design analysis, the typical RT compressive stress strain curve can be considered as the same as the tensile curve when the maximum stress is expected to be lower than S_{ut} . The above assumption is not valid for test evaluation on component failure.

Fig. 3.3-4 Tensile stress-strain curve for 2020 graphite

Fig. 3.3-5 Compressive stress-strain curve for 2020 graphite

3.3.4.3. Strength.

Specified Minimum Ultimate Strength (S_u). Specified minimum ultimate strength is the uniaxial strength along a principal stress direction which is used in design analysis to measure the structural integrity of a given core support graphite component against the design and accident condition stresses. Per ASME Code Subsection CE (Ref. 3.3-1), specified minimum strength is established from statistical treatment of graphite strength data such that the survival probability is 99% with a confidence level of 95%.

For unirradiated 2020 graphite at room temperature along the material axes the specified minimum tensile strength (S_{ut}) (Refs. 3.3-2, 3.3-3, and 3.3-17 through 3.3-19):

$$\begin{aligned} S_{ut} &= 14.7 \text{ MPa in the axial direction} \quad , \\ &\quad 16.1 \text{ MPa in the radial direction} \quad . \end{aligned}$$

The specified minimum compressive strength (S_{uc}) is

$$\begin{aligned} S_{uc} &= 51.0 \text{ MPa in the axial direction} \quad , \\ &\quad 52.5 \text{ MPa in the radial direction} \quad . \end{aligned}$$

In the off-axis case, the following Hankinson's formula is recommended for use:

$$S_{ut}(\theta) = \frac{14.7 \times 16.1}{14.7 \times \sin^2 \theta + 16.1 \times \cos^2 \theta} \text{ MPa} \quad , \quad (3.3-10)$$

where θ is the angle between the direction of the principal stress and the axial (material) axis.

Both S_{ut} and S_{uc} may be assumed to increase with temperature and neutron fluence identical to that for UTS (until such time as the

experimental data are available). The relationship is (Refs. 3.3-20 and 3.3-21)

$$S_u(T) = [(S_u)_{RT} + 0.00392 (T - 294)] (E_i/E_o)^{1/2} , \quad (3.3-11)$$

where $(S_u)_{RT}$ = room temperature unirradiated S_{ut} (MPa),

T = temperature (K),

E_i = modulus of irradiated graphite at room temperature (GPa),

E_o = modulus of unirradiated graphite at room temperature (GPa),

$S_u(T)$ = S_u of unirradiated 2020 at temperature T (MPa).

Specified Minimum Biaxial Strength. In the biaxial stress state, the Coulomb-Mohr theory, modified to include a maximum tensile strength cutoff, is the failure theory currently recommended for graphite (Ref. 3.3-23). This theory defines that the maximum principal stress governs failure in the first and third stress quadrants. In the second and fourth quadrants, the maximum principal stress or the Coulomb-Mohr theory, whichever is more restrictive, is applied.

The specified minimum biaxial strength surface is established similar to that of the above failure surface. The surface is given in Fig. 3.3-6. Caution is required when using the biaxial strength in the third quadrant. Early failure may occur in other modes prior to biaxial compressive failure. Minimum values are determined by the ASME rules of Ref. 3.3-1.

Fatigue Strength. The normalized fatigue strength (normalized with respect to mean strength) is defined in Table 3.3-6 (Ref. 3.3-24) as a

Fig. 3.3-6 Specified Minimum Biaxial Strength Surface for 2020 Graphite

TABLE 3.3-6
UNIAXIAL FATIGUE STRENGTH LIMITS FOR 2020 GRAPHITE

Orientation	Fatigue Strength Limits, Peak Stress/Mean Strength			
	R ($\sigma_{\min}/\sigma_{\max}$)	Number of Cycles	50% Survival	99/95 Lower Tolerance Limit
Axial	0	100	0.87	0.69
		1,000	0.83	0.66
		10,000	0.80	0.63
		100,000	0.76	0.60
	-1	100	0.84	0.66
		1,000	0.79	0.62
		10,000	0.74	0.58
		100,000	0.70	0.54
	-2	100	0.85	0.66
		1,000	0.80	0.62
		10,000	0.75	0.58
		100,000	0.71	0.55
Radial	0	100	0.86	0.71
		1,000	0.81	0.67
		10,000	0.77	0.64
		100,000	0.73	0.60
	-1	100	0.79	0.61
		1,000	0.73	0.56
		10,000	0.68	0.52
		100,000	0.63	0.48
	-2	100	0.81	0.66
		1,000	0.76	0.61
		10,000	0.71	0.57
		100,000	0.66	0.53

function of stress ratio (R) and number of cycles. Survival is shown up to 10^5 cycles under uniaxial cyclic loading in air at ambient temperature. Mean strength of graphite, as well as fatigue strength, increases with fast fluence and temperature in the range of interest. However, it is assumed that normalized fatigue strength remains constant for the design use.

The design fatigue diagram can be used to interpolate the fatigue strength at other R ratios (Fig. 3.3-7).

3.3.4.4. Fracture Toughness and the Critical Defect Size. Fracture toughness of unirradiated 2020 graphite at room temperature is (Ref. 3.3-25):

$$K_{IC} = 1.25 \text{ MPa } \sqrt{\text{m}} \quad .$$

The calculated critical defect size is 0.6 mm.

The reduction of K_{IC} with oxidation follows the relationship

$$K_{IC}/(K_{IC})_o = \exp (-7x) \quad , \quad (3.3-12)$$

where x = fractional weight loss due to oxidation and the subscript "o" represents the unoxidized state. The calculated critical defect size remains unchanged with oxidation.

3.3.4.5. Effect of Oxidation on Mechanical Properties. The reduction in tensile strength (S) and elastic modulus (E) is assumed to be the same for the commercial and the nuclear 2020 grades, which may be represented by the following relationship (Refs. 3.3-26 and 3.3-27):

$$\frac{S}{S_o} = \frac{E}{E_o} = \exp (-10x) \quad , \quad (3.3-13)$$

(Later)

Fig. 3.3-7. Design fatigue diagram of nuclear grade 2020 graphite at 99% survival probability with 95% confidence level

where x = fractional weight loss due to oxidation and the subscript "o" represents the unoxidized state.

For the preliminary calculation on the component subjected to external loads, it may be conservatively assumed that any portion of graphite that oxidized to $\geq 0.1\%$ loses its entire strength.

3.3.4.6. Material Internal Damping Factor. The internal damping factor ζ , defined as the ratio of actual damping to critical damping is dependent on the stress amplitude. At a stress amplitude of 7.35 MPa, ζ is equal to 0.596% (Ref. 3.3-28). This is for $0.5 S_{ut}$, approximately the 99/95 endurance limit. When the stress amplitude is reduced to half, ζ decreases only by 12%.

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3.4. LARGE RECTANGULAR NUCLEAR GRADE 2020 GRAPHITE

3.4.1. Introduction

The large rectangular nuclear grade 2020 graphite is referenced for the permanent side reflector (PSR) and central reflector (CR) column support structure. The properties given in this section are presented to be consistent with the structural criteria for graphite core supports (Ref. 3.4-1). Unless otherwise noted, the material properties given below for this nuclear grade 2020 graphite are mean values.

The maximum predicted fast neutron fluence to the PSR and the CR column support structure is 1.2×10^{24} n/m² (E > 29 fJ, HTGR), which is only 3% of the maximum fluence accumulated by fuel element graphite. Experience with fuel element graphite has shown that only elastic modulus and thermal conductivity will be noticeably affected by a total fast neutron fluence of 2×10^{24} n/m². Therefore, irradiation effects on other properties described below are insignificant and not discussed.

3.4.2. Physical and Chemical Properties

3.4.2.1. Density. The bulk density of 2020 graphite is 1.78 Mg/m³ averaged over the log (Refs. 3.4-2 and 3.4-3).

3.4.2.2. Transport and Reaction Rates.

3.4.2.2.1. Steam-Graphite Oxidation Rates. The Langmuir-Hinshelwood equation, Eq. 3.4-1, is used to predict steam-graphite oxidation rates for nuclear grade 2020 graphite (Ref. 3.4-4):

$$\text{Rate} = \frac{K_1 P_{\text{H}_2\text{O}} F_b}{1 + K_2 (P_{\text{H}_2})^n + K_3 P_{\text{H}_2\text{O}}} \quad (3.4-1)$$

where Rate = local graphite mass fraction reacting per second,

P_{H_2} , P_{H_2O} = local partial pressures of hydrogen and steam,
respectively,

F_b = modifier for effects of burnoff,

n = exponent,

$K_j = k_j \exp(E_j/RT)$,

where $j = 1, 2, \text{ or } 3$,

k_j = Arrhenius frequency factor,

E_j = activation energy,

$R = 8.314 \text{ J/mole}\cdot\text{K}$.

The values of K_1 , K_2 , K_3 , and n given in Table 3.4-1 are based on data for the temperatures indicated. Before additional data at other temperatures will be generated to allow K_j to be determined, it is assumed that k_j in Table 3.4-1 can be extrapolated to other temperatures.

For preliminary design, F_b is the same as that used to predict burnoff effects for steam oxidation of H-451 graphite (until such time as additional 2020 graphite oxidation data are available). The oxidation rates of the nuclear grade 2020 graphite is about one-fifth that of H-451 graphite.

3.4.2.2.2. Air-Graphite Reaction Rates. The rate of oxidation of graphite by air is given by Eq. 3.4-2 (Ref. 3.4-8):

$$\text{Rate} = K \exp(-E/RT) P_{O_2} \quad , \quad (3.4-2)$$

where Rate = local graphite mass fraction reacting per second (SI) or
local graphite mass fraction reacting per hour (units
normally used in OXIDE code calculations),

P_{O_2} = local partial pressure of oxygen.

TABLE 3.4-1
SUMMARY OF OXIDATION KINETIC CONSTANTS FOR
NUCLEAR 2020 GRAPHITE

Temperature (°C)	n	High Water >100 Pa H ₂ O			Low Water <100 Pa H ₂ O		
		K_1 (s·Pa) ⁻¹	K_2 Pa ^{-1.3}	K_3 Pa ⁻¹	K_1 (s·Pa) ⁻¹	K_2 Pa ^{-1.3}	K_3 Pa ⁻¹
980	1.3	8.7E-10	1.1E-3	2.6 - 8.7E-4	7.2E-9	9.0E-3	8.1E-2
930	1.3	3.8E-10	1.6E-3	3.8 - 16E-4	2.3E-9	9.5E-3	1.7E-1
900	1.3	2.0E-10	2.0E-3	2.0 - 4.0E-4			

Table 3.4-2 gives the system of units derived from H-327 experimental data. It is assumed that the air-graphite reaction rate of H-451 is identical to that of H-327.

Since there are no experimental data on air-graphite reaction rate reported for the grade 2020 graphite, Eq. 3.4-2, together with Table 3.4-2, shall be used. With the exception that the K appeared in Eq. 3.4-2 and value given in Table 3.4-2 needs to be modified by a factor equal to the ratio of the oxidation rate of nuclear grade 2020 graphite to that of H-451 graphite at the environmental conditions of interest.

3.4.2.2.3. Radiolytic Effect on Oxidation Rate. The available experimental data show that there is a small and negligible radiolytic effect on oxidation rate in air (see discussion in Section 4.3.2.3).

3.4.2.2.4. Transport of Steam in Helium by Diffusion. The effective diffusion coefficient of steam in graphite is given by Eq. 3.4-3 (Refs. 3.4-5 through 3.4-7):

$$D_{H_2O} = \frac{1.0 \times 10^{-10} \times T^{1.58} \times P}{P_{total}} \text{ (m}^2\text{/s)} \quad , \quad (3.4-3)$$

where D_{H_2O} = effective diffusion coefficient through graphite,

T = temperature (K),

P = pressure at STP* (Pa),

P_{total} = total pressure (Pa).

A parameter such as diffusion through graphite is recognized to vary by as much as a factor of three from sample to sample or from position to position in the graphite block. Equation 3.4-3 describes the present best estimate for H_2O diffusion in graphite having 1% average oxidation burnoff.

*STP - standard temperature and pressure.

TABLE 3.4-2
AIR-GRAPHITE REACTION RATE COEFFICIENTS(a)

Systems of Units	K	E	T	R
SI	0.79 (s·Pa) ⁻¹	1.7 x 10 ⁵ J/mol·K	K	8.314 J/mol·K
OXIDE code	2.88 x 10 ¹⁰ (% h·atm) ⁻¹	4.06 x 10 ⁴ cal/mol	K	1.986 cal/mol·K

(a) See text for the appropriate values to be used in Eq. 3.3-2 for nuclear grade 2020 graphite.

Equation 3.4-3 was obtained by pooling all available experimental data on steam diffusion through graphite in helium. No corrections were made for the differences in porosity and pore structure. Equation 3.4-3 is assumed to be applicable to all reference HTGR graphites.

The effective diffusion coefficients recommended for carbon monoxide, oxygen, and hydrogen are as follows (until such time as experimental data are available):

$$\begin{aligned} D_{CO} &= D_{H_2O} \quad , \\ D_{O_2} &= D_{H_2O} \quad , \\ D_{H_2} &= 2D_{H_2O} \quad . \end{aligned} \quad (3.4-4)$$

3.4.2.2.5. Transport of Steam in Helium by Convection. The transport of steam by convection involves the permeation of graphite. The permeability coefficients of graphite Ref. 3.4-29 are:

$$\begin{aligned} K_I &= 1.55E-13 \text{ m}^2 \quad , \\ K_P &= 9.20E-14 \text{ m}^2 \quad , \end{aligned}$$

where the subscripts represent the following regions of the hexagonal graphite blocks:

I = interior region consisting of a hexagonal block having an area in the plane of the hexagon one-seventh of the corresponding area of the entire block,

P = periphery region consisting of the entire hexagonal block minus the interior region.

The values of K_F and K_P are derived from data on H-327 graphite; they are assumed to apply to 2020 graphite (until such time as experimental data are available).

3.4.3. Thermal Properties

3.4.3.1. Specific Heat. The specific heat of graphite over the temperature range 250 to 3000 K is given by Eq. 3.4-6 (Ref. 3.4-9):

$$\begin{aligned} C_p = & (0.54212 - 2.42667 \times 10^{-6} T - 90.2725 T^{-1} \\ & - 4.34493 \times 10^4 T^{-2} + 1.59309 \times 10^7 T^{-3} \\ & - 1.43688 \times 10^9 T^{-4}) \times 4184 \quad , \end{aligned} \quad (3.4-6)$$

where C_p = specific heat at constant pressure (J/kg-K),
 T = temperature (K).

Equation 3.4-6 is also presented graphically in Fig. 3.4-1.

3.4.3.2. Thermal Expansivity. The thermal expansivity of 2020 graphite is given below (Ref. 3.4-10):

$$\alpha = A + B (\Delta T) \quad , \quad (3.4-7)$$

where α = CTE (1/°C),
 ΔT = temperature increase above room temperature (°C),
 $A = 0.3075 \times 10^{-5}$ in the radial direction,
 0.3225×10^{-5} in the axial direction,
 $B = 1.078 \times 10^{-9}$ in the radial direction,
 1.167×10^{-9} in the axial direction.

3.4.3.3. Thermal Conductivity. The thermal conductivity of unirradiated 2020 graphite is given in Table 3.4-3 as a function of measurement temperature (Ref. 3.4-3). The change in thermal conductivity of irradiated 2020 graphite at irradiation temperature is given in Eq. 3.4-8 (Ref. 3.4-11).

Fig. 3.4-1 Specific Heat of Graphite as a Function of Temperature

TABLE 3.4-3
THERMAL CONDUCTIVITY OF 2020 GRAPHITE

Orientation	Conductivity at Measurement Temperature (W/m·K)				
	295 K	473 K	673 K	873 K	1073 K
Radial	62.4	67.2	57.2	49.8	43.9
Axial	63.0	63.7	53.7	45.2	40.8

$$\frac{1}{K_I(T)} = \frac{1}{K_O(T)} + \frac{F}{K_O(295 \text{ K})} \quad , \quad (3.4-8)$$

where $K_I(T)$ = thermal conductivity of irradiated graphite at temperature T (K),

$K_O(T)$ = thermal conductivity of unirradiated graphite at temperature T (K) (derived from Table 3.4-3),

$K_O(295 \text{ K})$ = thermal conductivity of unirradiated graphite at room temperature,

F = fractional increase in thermal resistivity due to neutron irradiation (fluence dependence is given in Table 3.4-4 and Fig. 3.4-2).

The tabulated data on F were established from analysis of experimental data measured on miscellaneous graphites. Until such time as 2020 graphite thermal conductivity data under low irradiation level are available, it is assumed that Table 3.4-4 is applicable to 2020 graphite.

For other fast fluences, a linear relationship may be used between logarithms of F and fast fluence. An approximately linear relationship also exists between T and logarithm of F.

Thermal annealing on thermal conductivity appears to begin at 1273 K and is completed by 1573 K (Refs. 3.4-12 and 3.4-13). In this temperature range the fractional change in conductivity is close to linearly proportional to temperature. The fractional increase in thermal resistivity, F, in Eq. 3.4-8 is assumed to linearly decrease to zero over the above temperature range.

TABLE 3.4-4
THERMAL RESISTIVITY CONSTANT F, USED IN EQ. 3.4-8

Fast Neutron Fluence (10^{22} n/m ²)	Irradiation Temperature (K)		
	673	873	1073
0.4	0.075	0.0885	0.0215
1	0.125	0.063	0.036
4	0.27	0.138	0.078
10	0.445	0.225	0.124
20	0.665	0.33	0.185

Fig. 3.4-2. Design curves for change in room temperature thermal resistivity of 2020 graphite as a function of irradiation conditions

3.4.3.4. Emissivity. The emissivity of 2020 graphite for machined surface is 0.85 (Refs. 3.4-14 through 3.4-16).

3.4.4. Mechanical Properties

3.4.4.1. Transversely Isotropic Linear Elastic Constants. The mechanical properties of commercial 2020 graphite can be modeled as transversely isotropic. The isotropic plane is in the direction perpendicular to molding pressure (with-grain) for rectangular graphite logs. The axes in this plane are designated 1-axis and 2-axis. The across-grain direction is the axial direction, and is labelled as the 3-axis. The five independent unknowns in the transversely isotropic linear elastic material are two elastic moduli, E_1 and E_3 ; shear modulus, G_1 ; and two Poisson's ratios, ν_{12} and ν_{13} .

The properties given below are the average of the combined tensile and compressive moduli at room temperature. The difference between two moduli is less than 10% (Refs. 3.4-17 through 3.4-19):

$$\begin{aligned} E_1 &= [\text{later}] \text{ GPa,} \\ E_3 &= [\text{later}] \text{ GPa,} \\ G_1 &= [\text{later}] \text{ GPa,} \\ \nu_{12} &= \nu_{13} = 0.15. \end{aligned}$$

The elastic modulus given above is the tangent elastic modulus at the origin of the stress-strain curve.

The following modulus/temperature relationship applies to all E_1 , E_3 , and G_1 , but not ν_{12} and ν_{13} (Ref. 3.4-20):

$$\begin{aligned} C(T) &= C_{RT} - 9.94 \times 10^{-4} (T - 21) \\ &\quad + 3.09 \times 10^{-6} (T - 21)^2, \end{aligned} \quad (3.4-9)$$

where $C_{RT} = E_1, E_3, \text{ or } G_1$ at room temperature (GPa),

$T = \text{temperature } (^{\circ}\text{C}),$

$C(T) = E_1, E_3, \text{ or } G_1$ at temperature T (GPa).

The relationship is valid up to $1100^{\circ}\text{C}.$

The moduli increase with fast neutron irradiation. The percent increase (P) is given in Table 3.4-5, as well as plotted in Fig. 3.4-3, as a function of neutron fluence and irradiation temperature (Ref. 3.4-21). To calculate modulus (E_1) at any point during neutron irradiation, the following equation applies:

$$E_1 = E_0 (1 + P/100) \quad , \quad (3.4-10)$$

where $E_0 = \text{elastic modulus of unirradiated graphite at room temperature,}$

$$P = \left(\frac{E_0}{E_1} - 1 \right) \times 100,$$

$E_1 = \text{elastic modulus of irradiated graphite measured at room temperature.}$

For P at irradiation temperature and fast neutron fluence other than that given in Table 3.4-5, the following relationship shall be used:

1. Logarithm of P is a quadratic function of logarithm of ϕ .
2. Logarithm of P is a quadratic function of temperature ($^{\circ}\text{C}$).

3.4.4.2. Stress-Strain Curve. Typical room temperature (RT) tensile and compressive stress-strain curves for 2020 graphite are shown in Figs. 3.4-4 and 3.4-5, respectively (Ref. 3.4-22). The curves are applicable to a nonlinear design analysis when nonlinear analysis.

(Later)

Fig. 3.4-3. Design curves for change in elastic modulus of 2020 graphite as a function of irradiation conditions

TABLE 3.4-5
 PERCENT INCREASE (P) IN ELASTIC MODULUS AS
 A FUNCTION OF FLUENCE AND TEMPERATURE

Fast Neutron Fluence (10^{22} n/m ²)	Irradiation Temperature (K)		
	673	873	1173
1	4.3	3.1	2.3
4	13.3	9.8	7.4
10	24.0	18.3	13.9

Fig. 3.4-4. Tensile stress-strain curve for 2020 graphite

Fig. 3.4-5. Comprehensive stress-strain curve for 2020 graphite

Typical RT tensile and compressive stress strain curves when compared in the stress range below the specified minimum ultimate tensile strength (S_{ut} in Section 3.4.4.3) are slightly deviated from each other by less than one "within-log" standard deviation. For practical purpose in the design analysis, the typical RT compressive stress strain curve can be considered as the same as the tensile curve when the maximum stress is expected to be lower than S_{ut} . The above assumption is not valid for test evaluation on component failure.

3.4.4.3. Strength.

Specified Minimum Ultimate Strength (S_u). Specified minimum ultimate strength is the uniaxial strength along a principal stress direction which is used in design analysis to measure the structural integrity of a given core support graphite component against the design and accident condition stresses. Per ASME Code Subsection CE (Ref. 3.4-1), specified minimum strength is established from statistical treatment of graphite strength data such that the survival probability is 99% with a confidence level of 95%.

Since the specified minimum compressive strength (S_{uc}) of 2020 graphite is about three to four times its specified minimum tensile strength (S_{ut}), only S_{ut} is needed in the uniaxial stress analysis.

For unirradiated 2020 graphite at room temperature along the material axes, the specified minimum tensile strength (S_{ut}) is (Refs. [LATER]):

$$\begin{aligned} S_{ut}(z) &= [\text{LATER}] \text{ MPa in the axial direction} \quad , \\ S_{ut}(r) &= [\text{LATER}] \text{ MPa in the radial direction} \quad . \end{aligned}$$

The specified minimum compressive strength (S_{uc}) is

$$\begin{aligned} S_{uc}(z) &= [\text{LATER}] \text{ MPa in the axial direction} , \\ S_{uc}(r) &= [\text{LATER}] \text{ MPa in the radial direction} . \end{aligned}$$

In the off-axis case, the following Hankinson's formula is recommended for use:

$$S_{ut}(\theta) = \frac{S_{ut}(z) S_{ut}(r)}{S_{ut}(z) \times \sin^2 \theta + S_{ut}(r) \times \cos^2 \theta} \text{ MPa} , \quad (3.4-11)$$

where θ is the angle between the direction of the principal stress and the axial (material) axis.

Both S_{ut} and S_{uc} may be assumed to increase with temperature and neutron fluence identical to that for UTS (until such time as the experimental data are available). The relationship is (Refs. 3.4-20 and 3.4-21)

$$S_u(T) = [(S_u)_{RT} + 0.00392 (T - 294)] (E_1/E_0)^{1/2} , \quad (3.4-12)$$

where $(S_u)_{RT}$ = room temperature unirradiated S_u (MPa),

T = temperature (K),

E_1 = modulus of irradiated graphite at room temperature (GPa),

E_0 = modulus of unirradiated graphite at room temperature (GPa),

$S_u(T)$ = S_u of unirradiated 2020 at temperature T (MPa).

Specified Minimum Biaxial Strength. In the biaxial stress state, the Coulomb-Mohr theory, modified to include a maximum tensile strength

cutoff, is the failure theory currently recommended for graphite (Ref. 3.4-23). This theory defines that the maximum principal stress governs failure in the first and third stress quadrants. In the second and fourth quadrants, the maximum principal stress or the Coulomb-Mohr theory, whichever is more restrictive, is applied.

The specified minimum biaxial strength surface is established similar to that of the above failure surface. The surface is given in Fig. 3.4-6. Caution is required when using the biaxial strength in the third quadrant. Early failure may occur in other modes prior to biaxial compressive failure. Minimum values are determined by the ASME rules of Ref. 3.4-1.

Fatigue Strength. The normalized fatigue strength (normalized with respect to mean strength) is defined in Table 3.4-6 (Ref. 3.4-24) as a function of stress ratio (R) and number of cycles. Mean strength of graphite, as well as fatigue strength, increases with fast fluence and temperature in the range of interest. However, it is assumed that normalized fatigue strength remains constant for the design use.

The design fatigue diagram can be used to interpolate the fatigue strength at other R ratios (Fig. 3.4-7).

3.4.4.4. Fracture Toughness and the Critical Defect Size. Fracture toughness of unirradiated 2020 graphite at room temperature is (Ref. 3.4-25):

$$K_{IC} = 1.25 \text{ MPa } \sqrt{\text{m}} \quad .$$

The calculated critical defect size is 0.6 mm.

The reduction of K_{IC} with oxidation follows the relationship

$$K_{IC}/(K_{IC})_0 = \exp (-7x) \quad , \quad (3.4-13)$$

(Later)

Fig. 3.4-6. Specified minimum biaxial strength surface for
2020 graphite

TABLE 3.4-6
UNIAXIAL FATIGUE STRENGTH LIMITS FOR 2020 GRAPHITE

Orientation	Fatigue Strength Limits, Peak Stress/Mean Strength			
	R ($\sigma_{\min}/\sigma_{\max}$)	Number of Cycles	50% Survival	99/95 Lower Tolerance Limit
Axial	0	100	0.87	0.69
		1,000	0.83	0.66
		10,000	0.80	0.63
		100,000	0.76	0.60
	-1	100	0.84	0.66
		1,000	0.79	0.62
		10,000	0.74	0.58
		100,000	0.70	0.54
	-2	100	0.85	0.66
		1,000	0.80	0.62
		10,000	0.75	0.58
		100,000	0.71	0.55
Radial	0	100	0.86	0.71
		1,000	0.81	0.67
		10,000	0.77	0.64
		100,000	0.73	0.60
	-1	100	0.79	0.61
		1,000	0.73	0.56
		10,000	0.68	0.52
		100,000	0.63	0.48
	-2	100	0.81	0.66
		1,000	0.76	0.61
		10,000	0.71	0.57
		100,000	0.66	0.53

(Later)

Fig. 3.4-7. Design fatigue diagram of nuclear grade 2020 graphite at 99% survival probability with 95% confidence level

where x = fractional weight loss due to oxidation and the subscript o represent the unoxidized state. The calculated critical defect size remains unchanged with oxidation.

3.4.4.5. Effect of Oxidation on Mechanical Properties. The reduction in tensile strength (S) and elastic modulus (E) is assumed to be the same for the commercial and the nuclear 2020 grades which may be represented by the following relationship (Refs. 3.4-26 and 3.4-27):

$$\frac{S}{S_o} = \frac{E}{E_o} = \exp(-10x) \quad , \quad (3.4-14)$$

where x = fractional weight loss due to oxidation, and the subscript "o" represents the unoxidized state.

For the preliminary calculation on the component subjected to external loads, it may be conservatively assumed that any portion of graphite that oxidized to $\geq 0.1\%$ and beyond loses its entire strength.

3.4.4.6. Material Internal Damping Factor. The internal damping factor ζ , defined as the ratio of actual damping to critical damping, is dependent on the stress amplitude. At a stress amplitude of 7.35 MPa, ζ is equal to 0.596% (Ref. 3.4-28). This is for $0.5 S_{ut}$, approximately the 99/95 endurance limit). When the stress amplitude is reduced to half, ζ decreases only by 12%.

3.4.5. References

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4. GRADE H-451 GRAPHITE

4.1. DESCRIPTION OF GRADE

Grade H-451 graphite is a near-isotopic, petroleum-coke-based, artificial graphite developed specifically for HTGR fuel element and reflector application by Great Lakes Carbon Company. The graphite is extruded into right-circular or oblong cylinders. The logs used for HTGR application are 0.863 m (34 in.) long by 0.457 m (18 in.) in diameter.

The design data presented herein have been derived from characterization tests of H-451 preproduction lot 426 and from strength testing of production lot No. 440, 472, 478, and 482. Several hundred preproduction logs of H-451 graphite were produced for qualification tests. Three production grade lots, totaling over 300 logs, have been produced for use in FSV reload segments.

4.2. APPLICATION

Grade H-451 graphite is the reference material for both the fuel elements and the replaceable hexagonal reflectors. The latter consists of the upper and lower reflectors, central reflectors, and hexagonal side reflectors. These components are to be designed to meet the structural criteria for core graphite (Ref. 4-1). Unless otherwise noted, the material properties given below are mean values.

4.3. PHYSICAL AND CHEMICAL PROPERTIES

4.3.1. Density

The density of H-451 graphite is 1.74 Mg/m³ averaged over the log (Ref. 4-2).

4.3.2. Transport and Reaction Rates

4.3.2.1. Steam-Graphite Oxidation Rates. The Langmuir-Hinshelwood equation, Eq. 4-1, is used to predict chemical kinetically limited steam-graphite oxidation rates for H-451 graphite (Refs. 4-3 and 4-4):

$$\text{Rate} = \frac{K_1 P_{H_2O} F_b F_c}{1 + K_2 (P_{H_2})^n + K_3 P_{H_2O}}, \quad (4-1)$$

where Rate = local graphite mass fraction reacting per second (SI units),

Rate = local graphite mass percent reacting per hour (former units),

P_{H_2} , P_{H_2O} = local partial pressures of hydrogen and steam, respectively,

F_b , F_c = modifiers for effects of burnoff and presence of catalysts, respectively,

$$n = 0.75,$$

$$K_j = k_j \exp(E_j/RT),$$

where $j = 1, 2, \text{ or } 3,$

k_j = Arrhenius frequency factor,

E_j = activation energy,

$R = 8.314 \text{ j/mole}\cdot\text{K}.$

Constants are given in Table 4.3-1.

$$F_b = 0.447 + 0.8094 b - 0.3221 b^2 + 0.0681 b^3 \\ - 0.00613 b^4 + 12.32 \times 10^{-6} b^5 + 2.89 \times 10^{-5} b^6 \\ - 1.15 \times 10^{-6} b^7, \quad (4-2)$$

where b is the percent graphite burnoff and F_b is normalized to 1% burnoff; i.e., at 1% burnoff $F_b = 1.0$. The above equation is restricted to $0 \leq b \leq 13$; for higher burnoffs, the value of F_b at 13% burnoff should be used.

$$F_c = 1 + (C_{Ba} + 0.2 C_{Sr}) \exp(12.153 - 4.264 \times 10^{-3} T), \quad (4-3)$$

where C_{Ba} , C_{Sr} = concentration of barium and strontium catalyst (mg/g graphite),

T = temperature (K).

4.3.2.2. Air-Graphite Reaction Rates. The rate of oxidation of graphite by air is given by Eq. 4-4 (Ref. 4-8):

$$\text{Rate} = K \exp(-E/RT) P_{O_2}, \quad (4-4)$$

where Rate = local graphite mass fraction reacting per second (SI) or local graphite mass fraction reacting per hour (units normally used in OXIDE code calculations),

P_{O_2} = local partial pressure of oxygen.

Table 4.3-2 gives the system of units derived from H-327 experimental data. It is assumed that the air-graphite reaction rate of H-451 is identical to that of H-327.

TABLE 4.3-1
CONSTANTS FOR H-451 GRAPHITE OXIDATION RATE EQUATION

Units	k_1	k_2	k_3	E_1	E_2	E_3	R
SI	900 (s·Pa) ⁻¹	110 Pa ^{-0.75}	30 Pa ⁻¹	-274,000 J/mol	-74,660 J/mol	-95,850 J/mol	8.314 J/mol·K
OXIDE Code	3.28 x 10 ¹³ (% h·atm) ⁻¹	6.25 x 10 ⁵ atm ^{-0.75}	3.04 x 10 ⁶ atm ⁻¹	-65,460 cal/mol	-17,840 cal/mol	-22,900 cal/mol	1.986 cal/mol·K

TABLE 4.3-2
AIR-GRAPHITE REACTION RATE COEFFICIENTS

Systems of Units	K	E	T	R
SI	0.79 (s·Pa) ⁻¹	1.7 x 10 ⁵ J/mol·K	K	8.314 J/mol·K
OXIDE code	2.88 x 10 ¹⁰ (% h·atm) ⁻¹	4.06 x 10 ⁴ cal/mol	K	1.986 cal/mol·K

4.3.2.3. Radiolytic Effect on Oxidation Rate. Irradiation was shown to have no discernible effect on reaction rate of H-327 graphite in the temperature range of 385° to 566°C (Ref. 4-9). Eto, et al. (Ref. 4-10) showed that the contribution of radiolytic effect on the reaction rate was small enough to neglect above 1050 K, and neutron irradiation did not affect the reaction rate unless the graphite was at the initial stage of irradiation. For design analysis, the radiolytic effect on oxidation rate shall be disregarded.

4.3.2.4. Transport of Steam in Helium by Diffusion. The effective diffusion coefficient of steam in graphite is given by Eq. 4-5 (Refs. 4-5 through 4-7):

$$D_{H_2O} = \frac{1.0 \times 10^{-10} \times T^{1.58} \times P}{P_{total}} \text{ (m}^2\text{/s)} \quad , \quad (4-5)$$

where D_{H_2O} = effective diffusion coefficient through graphite,
 T = temperature (K),
 P = pressure at STP* (Pa),
 P_{total} = total pressure (Pa).

A parameter such as diffusion through graphite is recognized to vary by as much as a factor of three from sample to sample or from position to position in the graphite block. Equation 4-5 describes the present best estimate for H₂O diffusion in graphite having 1% average oxidation burnoff.

Equation 4-5 was obtained by pooling all available experimental data on steam diffusion through graphite in helium. No corrections were made for the differences in porosity and pore structure. Equation 4-5 is assumed to be applicable to all reference HTGR graphites.

*STP - standard temperature and pressure.

The effective diffusion coefficients recommended for carbon monoxide, oxygen, and hydrogen are as follows:

$$D_{CO} = D_{H_2O} \quad ,$$

$$D_{O_2} = D_{H_2O} \quad ,$$

$$D_{H_2} = 2D_{H_2O} \quad . \quad (4-6)$$

4.3.2.5. Transport of Steam in Helium by Convection. The transport of steam by convection involves the permeation of graphite. The permeability coefficients of graphite (Ref. 4.4-42) are:

$$K_I = 1.55E-13 \text{ m}^2 \quad ,$$

$$K_P = 9.20E-14 \text{ m}^2 \quad ,$$

where the subscripts represent the following regions of the hexagonal graphite blocks:

I = interior region consisting of a hexagonal block having an area in the plane of the hexagon one-seventh of the corresponding area of the entire block,

P = periphery region consisting of the entire hexagonal block minus the interior region.

The values of K_I and K_P are derived from data on H-327 graphite; they are assumed to apply to H-451 graphite.

4.4. THERMAL PROPERTIES

4.4.1. Specific Heat

The specific heat of H-451 graphite for temperatures from 250 to 3000 K is given below (Ref. 4-11):

$$\begin{aligned} C_p = & (0.54212 - 2.42667 \times 10^{-6} T - 9.02725 \times 10^1 T^{-1} \\ & - 4.34493 \times 10^4 T^{-2} + 1.59309 \times 10^7 T^{-3} \\ & - 1.43688 \times 10^9 T^{-4}) \times 4184 \quad , \end{aligned} \quad (4-7)$$

where C_p = specific heat at constant pressure (J/kg-K),
 T = temperature (K).

Equation 4-7 is also presented graphically in Fig. 4.4-1.

4.4.2. Thermal Expansivity

Mean Coefficient of Thermal Expansion. The mean CTE for unirradiated H-451 graphite between room temperature and 500°C is $4.09 \times 10^{-6}/^\circ\text{C}$ and $4.65 \times 10^{-6}/^\circ\text{C}$ in the axial and radial directions, respectively (Refs. 4-12 through 4-14). Its dependence on temperature can be calculated from the thermal strain given in Table 4.4-1 and Fig. 4.4-2.

The thermal expansivity of H-451 graphite changes during neutron irradiation. The fractional change in thermal expansivity, $(\alpha_i - \alpha_o)/\alpha_o$, is given in the following equation and Figs. 4.4-3 and 4.4-4 (Ref. 4-9):

$$\begin{aligned} (\alpha_i - \alpha_o)/\alpha_o = & (0.27830 - 4.2734 \times 10^{-4} T \\ & + 1.7815 \times 10^{-7} T^2) \Phi - 2.0664 \times 10^{-2} \Phi^2 \\ & + 1.3601 \times 10^{-3} \Phi^3 \quad , \end{aligned} \quad (4-8)$$

Fig. 4.4-1 Specific Heat of Graphite as a Function of Temperature

TABLE 4.4-1
THERMAL EXPANSION OF H-451 GRAPHITE

Temperature (°C)	Thermal Strain (10^{-3})	
	Axial	Radial
25	0	0
100	0.26	0.32
150	0.42	0.52
200	0.60	0.74
250	0.80	0.95
300	1.00	1.20
350	1.20	1.43
400	1.42	1.68
450	1.65	1.93
500	1.88	2.19
550	2.12	2.46
600	2.35	2.75
650	2.60	3.03
700	2.83	3.32
750	3.10	3.58
800	3.35	3.88
850	3.58	4.16
900	3.84	4.41
950	4.10	4.73
1000	4.33	5.06
1050	4.60	5.32
1100	4.88	5.62
1150	5.14	5.91
1200	5.42	6.23
1250	5.70	6.53
1300	6.00	6.85
1350	6.30	7.16
1400	6.60	7.50
1450	6.90	7.85
1500	7.24	8.20
1550	7.55	8.52
1600	7.90	8.90

Fig. 4.4-2. Thermal expansion of H-451 graphite

Fig. 4.4-3. Change in mean cte of H-451 graphite as a function of irradiation conditions (865-1205 K), axial and radial directions

Fig. 4.4-4. Change in mean cte of H-451 graphite as a function of irradiation conditions (1250-1705 K), axial and radial directions

where $\alpha_0 = \alpha$ (500°C) unirradiated,
 $\alpha_i = \alpha$ (500°C) irradiated,
 T = irradiation temperature (°C),
 Φ = neutron fluence (10^{25} n/m², $E > 29$ fJ)_{HTGR}.

The shifting rule for the mean CTE under nonisothermal irradiation shall be performed at equal neutron damage as determined from the dimensional change curve given in Section 4.6.1 (Rule 3 in Ref. 4-16).

4.4.3. Thermal Conductivity

The thermal conductivity of near-isotropic graphite is given by the current models reviewed in Ref. 4-17. This model considers the dependence of thermal conductivity (K) on the current measurement temperature (T_c) and on the past history of irradiation temperature (T_i) and fast neutron fluence (Φ). The model is extended here to the case of a non-isothermal irradiation.

The thermal conductivity as a function of current measurement temperature can be considered as a superposition of three temperature-dependent resistance mechanisms through Eq. 4-6 (Ref. 4-17):

$$K(T_c) = \frac{1}{a \left(\frac{1}{K_U(T_c)} + \frac{b}{K_b(T_c)} + \frac{d}{K_d(T_c)} \right)}, \quad (4-6)$$

where a = porosity-tortuosity factor,
 $K_U(T_c)$ = crystallite conductivity with Umklapp processing dominating,
 b = inverse of the crystallite boundary spacing,
 $K_b(T_c)$ = effect of the grain boundary scattering,
 d = irradiation damage parameter,
 $K_d(T_c)$ = effect of the irradiation damage.

All of the above quantities are given as known input data in Tables 4.4-2 and 4.4-3 except for the irradiation damage parameter, d . As shown below, parameter d can be obtained by comparing conductivities before and after irradiation.

4.4.3.1. Thermal Conductivity, Unirradiated. For unirradiated material, the damage parameter d in Eq. 4-6 is zero. Equation 4-6 reduces to

$$K_o(T_c) = \frac{1}{\alpha \left(\frac{1}{K_u(T_c)} + \frac{b}{K_b(T_c)} \right)} \quad (4-7)$$

4.4.3.2. Thermal Conductivity, Isothermal Irradiation. The damage parameter d in Eq. 4-6 can be found by comparing the unirradiated and irradiated conductivities at one particular measurement temperature. Room temperature (RT) is conveniently taken to be the reference temperature. Thus, Eqs. 4-6 and 4-7 combine to give the following:

$$d = \frac{K_d(RT)}{\alpha} \left(\frac{1}{K_i(RT)} - \frac{1}{K_o(RT)} \right) \quad (4-8)$$

where $K_o(RT)$ = unirradiated room temperature conductivity, found by evaluating Eq. 4-7 at $T_c = RT$,

$K_i(RT)$ = irradiated room temperature conductivity found by the procedure outlined below.

4.4.3.3. Thermal Conductivity, Nonisothermal Irradiation. The procedure to be used for calculating room temperature conductivity during a nonisothermal irradiation is as follows:

1. Divide the irradiation period into n isothermal intervals. The irradiation temperature during interval i is T_i . The

TABLE 4.4-2
TEMPERATURE-DEPENDENT CONDUCTIVITY COMPONENTS OF H-451 GRAPHITE(a)

Temperature (K)	Umklapp $K_U(T_c)$ (10^3 W/m $\cdot$ K)	Grain Boundary $K_b(T_c)$ (10^9 W/m $\cdot$ K)	Irradiation Damage $K_d(T_c)$ (10^3 W/m $\cdot$ K)
100	39.12	1.20	1.87
150	20.42	2.49	1.60
200	5.36	4.02	1.34
250	2.67	5.54	1.30
300	2.00	6.97	1.26
350	1.49	8.19	1.31
400	1.21	9.41	1.36
450	1.07	10.36	1.41
500	0.929	11.30	1.47
550	0.864	11.99	1.50
600	0.799	12.68	1.53
650	0.743	13.18	1.56
700	0.686	13.68	1.58
750	0.653	14.10	1.60
800	0.619	14.52	1.62
850	0.590	14.69	1.63
900	0.561	14.85	1.64
950	0.538	14.96	1.64
1000	0.515	15.06	1.65
1050	0.487	15.06	1.65
1100	0.460	15.06	1.65
1150	0.441	15.06	1.65
1200	0.423	15.06	1.65
1250	0.408	15.06	1.65
1300	0.393	15.06	1.65
1350	0.381	15.06	1.65
1400	0.368	15.06	1.65
1450	0.360	15.06	1.65
1500	0.352	15.06	1.65
1550	0.343	15.06	1.65
1600	0.335	15.06	1.65
1650	0.328	15.06	1.65
1700	0.320	15.06	1.65
1750	0.315	15.06	1.65
1800	0.310	15.06	1.65

(a) Refer to Eq. 4-6.

(b) The temperature points are equally spaced in order to facilitate the linear interpolation.

TABLE 4.4-3
MATERIAL CONSTANTS FOR H-451 GRAPHITE THERMAL CONDUCTIVITY

Symbol	Reference Equation	Temperature Range (K)	Value		Units (a)
			Axial	Radial	
A	4-10	573 to 873	0.2687	0.2687	10^{25} n/m ²
	4-10	873 to 1673	-0.5676	-0.5676	10^{25} n/m ²
B	4-10	573 to 873	0	0	--
	4-10	873 to 1673	9.58×10^{-4}	9.58×10^{-4}	10^{25} n/m ² ·K
C	4-11	573 to 1673	2.3897	2.2726	ln (W/m·K)
D	4-11	573 to 1673	1.207×10^{-3}	1.222×10^{-3}	K ⁻¹
α	4-6	573 to 1673	5.334	5.707	--
b	4-6	573 to 1673	5.192×10^6	6.165×10^6	m ⁻¹

(a) Neutron fluence units (10^{25} n/m²) are in terms of HTGR fast fluence, ($E > 29$ fJ)_{HTGR}.

fluence at the start of the interval is $(\Phi)_{i-1}$, and the fluence at the end of the interval is $(\Phi)_i$.

2. At the start of the first interval, the room temperature conductivity is initialized to $K_o(RT)$ through Eq. 4-7.
3. At the end of interval i , the room temperature irradiated conductivity is given by the recursive formula, Eq. 4-9:

$$K_i(RT) = K_{sat}^{RT}(T_i) + \left(K_{i-1}(RT) - K_{sat}^{RT}(T_i) \right) \exp - \frac{[(\Phi)_i - (\Phi)_{i-1}]}{\tau(T_i)} \quad (4-9)$$

where

$$\tau(T_i) = A + BT_i \quad , \quad (4-10)$$

and

$$K_{sat}^{RT}(T_i) = \exp(C + DT_i) \quad , \quad (4-11)$$

where Φ = fast neutron fluence (10^{25} n/m²)
($E > 29$ fJ)_{HTGR},

τ = relaxation time in units of fluence,

K_{sat}^{RT} = saturation value of the room conductivity,

A, B, C, D = constants given in Table 4.4-3.

T_i = irradiation temperature during interval
(K).

4. Calculate the conductivity at the assumed current temperature T_c by applying Eqs. 4-6 and 4-8.

4.4.3.4. Thermal Conductivity Input Data for Near-Isotropic Graphite.

The input data required to calculate the thermal conductivity of near-isotropic graphite in W/m·K in the axial and radial directions are given in Tables 4.4-2 and 4.4-3. The calculated curves are shown in Fig. 4.4-5.

4.4.3.5. Effect of Thermal Annealing. Thermal annealing on thermal conductivity appears to begin at 1273 K and is completed by 1573 K (Refs. 4-18 and 4-19). The fractional change decreases almost linearly with increasing temperature. The irradiation damage parameter, d in Eq. 4-6, is assumed to decrease linearly to zero over the above temperature range.

4.4.4 Emissivity

No emissivity data for H-451 graphite have been reported. However, emissivity does not vary much between graphite grades, and emissivity of 0.85 for a machined graphite surface shall be used (Refs. 4-20 through 4-22).

4.5. MECHANICAL PROPERTIES

4.5.1. Transversely Isotropic Linear Elastic Constants

The five independent linear elastic constants in the transversely isotropic material are two elastic moduli, E_1 and E_3 ; shear modulus, G_1 ; and two Poisson's ratios, ν_{12} and ν_{13} . The axes in the isotropic plane are designated 1-axis and 2-axis. The axis normal to the isotropic plane is labeled as the 3-axis.

Fig. 4.4-5. Thermal conductivity of H-451 graphite as a function of neutron irradiation

The mean values of these elastic constants at room temperature, including the effect of spatial distribution, are (Ref. 4-23):

$$\begin{aligned}
 E_1 &= 7.35 + 1.11 \times 10^{-2} \cdot r^2 + 2.95 \times 10^{-3} \cdot z^2 \\
 &\quad - 3.8 \times 10^{-5} r^2 z^2 \quad , \\
 E_3 &= 8.31 + 1.76 \times 10^{-2} \cdot r^2 + 1.53 \times 10^{-3} \cdot z^2 \\
 &\quad - 2.7 \times 10^{-5} r^2 z^2 \quad , \quad (4-12)
 \end{aligned}$$

$$G_1 = E_1/2(1+\nu) \quad ,$$

$$\text{all } \nu = 0.12 \quad ,$$

where E_1 , E_3 , and G_1 are in GPa,

r = radial distance from the axis of the billet, ≤ 8.5 in. (in.),

z = axial distance from midlength of the billet, ≤ 16 in. (in.).

The elastic moduli given above are the secant moduli of the second loading curve between 0 and 6.9 MPa.

The following modulus/temperature relationship applies to all E and G 's, except ν (Ref. 4-24):

$$C(T) = C_{RT} (1 + 1.5 \times 10^{-4} T) \quad , \quad (4-13)$$

where C_{RT} = E or G at room temperature (21°C) (GPa),

T = temperature -21°C (°C).

The fractional change in elastic modulus of H-451 graphite due to isothermal neutron irradiation is given in Table 4.5-1, which is also presented graphically in Fig. 4.5-1 (Ref. 4-25). The elastic modulus due to nonisothermal neutron irradiation shall be evaluated using the shifting rule identical to that for the dimensional change (Section 4.6.2).

TABLE 4.5-1
 PERCENTAGE CHANGE IN ELASTIC MODULUS OF H-451 GRAPHITE
 DURING NEUTRON IRRADIATION

Fast Neutron Fluence, Φ (10^{25} n/m ²) (E > 29 fJ) _{HTGR}	Change in Elastic Modulus at Irradiation Temperature (%)			
	673 K	873 K	1173 K	1473 K
0	0	0	0	0
0.25	83.0	68.0	54.0	52.0
0.50	90.5	76.8	63.8	62.0
0.75	95.0	81.6	68.6	66.6
1.00	98.1	85.3	71.4	68.5
1.25	100.8	88.0	73.2	69.0
1.50	102.8	90.4	75.0	69.0
1.75	104.8	92.0	75.7	69.0
2.00	106.5	93.5	76.7	69.0
2.25	108.0	94.8	77.0	69.0
2.50	109.8	95.5	77.3	69.0
2.75	111.3	96.5	78.0	69.0
3.00	113.0	97.5	78.7	69.0
3.25	114.5	98.4	79.3	69.2
3.50	116.3	99.0	80.8	70.0
3.75	117.4	100.0	82.3	70.5
4.00	119.3	100.8	85.2	71.0
4.25	121.0	101.2	90.6	71.5
4.50	122.8	102.0	95.9	72.7
4.75	124.3	102.8	101.0	73.2
5.00	126.0	103.4	106.0	74.3
5.25	127.4	104.0	111.3	75.2
5.50	129.0	104.7	116.8	76.7
5.75	130.6	105.3	122.0	78.1
6.00	132.2	105.9	127.2	79.8
6.25	133.8	106.5	132.4	81.5
6.50	135.4	107.1	137.6	83.4
6.75	137.0	107.8	142.8	85.9
7.00	138.6	108.4	148.0	88.5
7.25	140.2	109.0	153.2	91.2
7.50	141.8	109.6	158.4	94.8
7.75	143.4	110.2	163.6	98.4
8.00	145.2	110.6	169.0	103.0

Fig. 4.5-1. Fractional change in elastic modulus of H-451 graphite as a function of irradiation conditions

The Poisson's ratios, ν_{12} and ν_{13} , are assumed to remain constant with respect to temperature and neutron irradiation.

4.5.2. Stress-Strain Curve

A typical room temperature tensile and compressive stress-strain curve found for the axial direction of unirradiated H-451 graphite are presented in Figs. 4.5-2 and 4.5-3, respectively (Ref. 4-26). A typical tensile stress-strain curve in the radial direction can be constructed by increasing the axial strain at a given stress by 15%. This factor was obtained from the mean ratio of axial elastic modulus to radial elastic modulus. The mean failure point has a fracture strain of 8% higher in the axial direction than in the radial direction.

The irradiated tensile stress strain curve [LATER] Fig. 4.5-4 (Ref. 4-27).

4.5.3. Strength

4.5.3.1. Ultimate Tensile and Compressive Strength (UTS and UCS).

Per Core Graphite Structural Design Criteria (Ref. 4-1), mean ultimate strength is used in stress analyses to evaluate the structural integrity of a given core graphite component against the design and accident condition stresses. Spatial distribution of ultimate strength in both the axial and radial directions in a log may be considered.

Since UCS of H-451 is almost four times its UTS, only UTS is needed in the stress analysis.

The spatial distribution of room temperature mean UTS in the unirradiated reference H-451 log is presented by (Ref. 4-17):

$$UTS = a + br^2 + Cz^2 + dr^2z^2 \quad , \quad (4-14)$$

Fig. 4.5-2(a) Tensile stress-strain curve for H-451 graphite, axial orientation

Fig. 4.5-2(b) Tensile stress-strain curve for H-451 graphite, radial orientation

Fig. 4.5-3(a) Compressive stress-strain curve for H-451 graphite, axial orientation

Fig. 4.5-3(b) Compressive stress-strain curve for H-451 graphite, radial orientation

(Later)

Fig. 4.5-4a. Tensile stress-strain curve for irradiated H-451 graphite

(Later)

Fig. 4.5-4b. Compressive stress-strain curve for irradiated H-451 graphite

where UTS = mean ultimate tensile strength along either axial or radial direction (MPa),

r = radial distance from the axis of the billet, $\leq \pm 8.5$ in. (in.),

z = axial distance from midlength of the billet, $\leq \pm 16$ in. (in.)

$a = 12.406$ MPa for UTS(r),
 $= 10.712$ MPa for UTS(z),

$b = 0.0977$ MPa/in.² for UTS(r),
 $= 0.0636$ MPa/in.² for UTS(z),

$c = 0.0113$ MPa/in.² for UTS(r),
 $= 0.0310$ MPa/in.² for UTS(z),

$d = 0.000312$ MPa/in.⁴ for UTS(r),
 $= 0.000365$ MPa/in.⁴ for UTS(z),

and the origin ($r = 0$ and $z = 0$) is at the center of the log.

In the off-axis case the following Hankinson's formula is recommended for use:

$$UTS(\theta) = \frac{UTS(z) \times UTS(r)}{UTS(z) \sin^2 \theta + UTS(r) \cos^2 \theta}, \quad (4-15)$$

where θ is the angle between the direction of the principal stress and the axial axis. UTS(z) and UTS(r) are the UTS in the axial and radial directions, respectively.

The UTS increases with temperature. At the present, the percentage increase is assumed to be similar to that of 2020 graphite (the first factor on the right hand side of Eq. 3.3-11 in Section 3.3.4.3).

The change in UTS due to neutron irradiation is related to the irradiation-induced change in modulus by (Ref. 4-15):

$$\frac{S_i}{S_o} = \left(\frac{E_i}{E_o} \right)^{0.64}, \quad (4-16)$$

where S_o = UTS of unirradiated H-451,

S_i = UTS of irradiated H-451,

E_o = elastic modulus of unirradiated H-451,

E_i = elastic modulus of irradiated H-451.

The fractional changes in modulus during irradiation are given in Table 4.5-1.

4.5.3.2. Biaxial Strength. In the biaxial stress state, the Coulomb-Mohr theory, modified to include a maximum tensile strength cutoff, is the failure theory currently recommended for graphite (Ref. 4-21).⁸ To construct a failure surface, the UTS at any generic point of interest including the environmental effects governs the failure in the first tension/tension quadrant. In the third compression/compression quadrant, a constant ultimate compressive strength (UCS) of 51 MPa (7400 psi) is used for both the axial (A) and radial (R) directions. In the remaining two quadrants, the modified Coulomb-Mohr theory as defined by

$$\sigma_A = -51.0 + 2 \times \sigma_R \text{ MPa in the Fourth quadrant} \quad ,$$

$$\sigma_R = -51.00 + 2 \times \sigma_A \text{ MPa in the Second quadrant} \quad , \quad (4-17)$$

and the maximum principal stress theory, whichever is more restrictive, applies.

The effects of environment, such as temperature and neutron irradiation, are assumed to be identical to that of UTS (Section 4.5.3.1).

4.5.4. Fracture Toughness and the Critical Defect Size

Room temperature fracture toughness of unirradiated H-451 graphite is (Ref. 4-28):

$$\begin{array}{ll} K_{IC} = 1.54 \text{ MPa } \sqrt{\text{m}} \text{ (1400 psi } \sqrt{\text{in.}}) & \text{AR orientation} \\ 1.40 \text{ MPa } \sqrt{\text{m}} \text{ (1270 psi } \sqrt{\text{in.}}) & \text{RR orientation} \end{array}$$

The first letter in the orientation indicates the direction normal to the crack and the second letter the direction of propagation. A and R stand for the axial and radial directions, respectively.

The calculated critical defect size is 1.5 mm (0.06 in.).

The reduction of K_{IC} with oxidation follows the relationship (Ref. 4-22)

$$K_{IC}/(K_{IC})_0 = \exp(-4.66x) \quad , \quad (4-18)$$

where x = fractional weight loss due to oxidation. The calculated critical defect size increases with oxidation.

K_{IC} increases slightly with neutron irradiation (Ref. 4-29). For design use, K_{IC} is assumed to remain constant.

4.5.5. Effect of Oxidation on Mechanical Properties

The reduction in tensile strength (S) and elastic modulus (E) of uniformly oxidized H-451 graphite is represented by the following relationship (Ref. 4-30):

$$S/S_0 = \exp(-5x) \quad ,$$

$$E/E_0 = \exp(-6x) \quad , \quad (4-19)$$

where x = fractional weight loss due to oxidation,
 subscript "o" = the unoxidized state.

The relationship is valid for uniformly oxidized H-451 graphite with burnoff up to 20%.

4.6. NEUTRON IRRADIATION EFFECTS ON DIMENSIONS

4.6.1. Irradiation-Induced Dimensional Change (Refs. 4-15 4-25, 4-31, 4-32, and 4-33)

The permanent dimensional change (ϵ^I) due to fast neutron damage has been expressed in terms of average irradiation temperature (T_ϕ) and fast neutron fluence (Φ) for H-451 graphite. The irradiation-induced dimensional change (ϵ^I) is expressed by the polynomial in Eq. 4-20, which is valid for irradiation between 623 and 1573 K and to fast neutron fluences of 10×10^{25} n/m² ($E > 29$ fJ)_{HTGR}:

$$\begin{aligned} \epsilon^I = & (C_1 + C_2 T_\phi + C_3 T_\phi^2 + C_4 T_\phi^3 + C_5 T_\phi^4) \Phi \\ & + (C_6 + C_7 T_\phi + C_8 T_\phi^2 + C_9 T_\phi^3 + C_{10} T_\phi^4 + C_{16} T_\phi^5) \Phi^2 \\ & + (C_{11} + C_{12} T_\phi + C_{13} T_\phi^2 + C_{14} T_\phi^3 + C_{15} T_\phi^4 \\ & + C_{17} T_\phi^5 + C_{18} T_\phi^6) \Phi^3 \quad , \end{aligned} \quad (4-20)$$

where ϵ^I = irradiation-induced dimensional change, $\Delta L/L$ (%),

Φ = fast neutron fluence ($E > 29$ fJ)_{HTGR} (10^{25} n/m²),

T_ϕ = average irradiation temperature - 273 (K),

C_i = coefficients determined for each orientation of H-451 graphite (coefficients are listed in Table 4.6-1).

The design curves described by the polynomial (Eq. 4-20) are presented graphically in Figs. 4.6-1 and 4.6-2.

TABLE 4.6-1
 POLYNOMIAL COEFFICIENTS FOR DIMENSIONAL CHANGE
 DESIGN EQUATIONS: H-451 GRAPHITE

Coefficient	Axial	Radial
C ₁	1.11617	1.15132
C ₂	-0.92197 x 10 ⁻²	-0.82968 x 10 ⁻²
C ₃	+0.20463 x 10 ⁻⁴	+0.17060 x 10 ⁻⁴
C ₄	-0.16458 x 10 ⁻⁷	-0.12645 x 10 ⁻⁷
C ₅	+0.40809 x 10 ⁻¹¹	+0.27657 x 10 ⁻¹¹
C ₆	+0.64947	+0.39177
C ₇	-0.56929 x 10 ⁻²	-0.36540 x 10 ⁻²
C ₈	+0.18972 x 10 ⁻⁴	+0.12750 x 10 ⁻⁴
C ₉	-0.29277 x 10 ⁻⁷	-0.20230 x 10 ⁻⁷
C ₁₀	+0.20435 x 10 ⁻¹⁰	+0.14233 x 10 ⁻¹⁰
C ₁₁	-0.59274 x 10 ⁻²	+0.13110 x 10 ⁻¹
C ₁₂	-0.65404 x 10 ⁻⁵	-0.18768 x 10 ⁻³
C ₁₃	+0.32751 x 10 ⁻⁶	+0.10199 x 10 ⁻⁵
C ₁₄	-0.13449 x 10 ⁻⁸	-0.27004 x 10 ⁻⁸
C ₁₅	+0.22245 x 10 ⁻¹¹	+0.36498 x 10 ⁻¹¹
C ₁₆	-0.51973 x 10 ⁻¹⁴	-0.35768 x 10 ⁻¹⁴
C ₁₇	-0.16038 x 10 ⁻¹⁴	-0.23579 x 10 ⁻¹⁴
C ₁₈	+0.41756 x 10 ⁻¹⁸	+0.57329 x 10 ⁻¹⁸

Fig. 4.6-1. Design curves for dimensional change of H-451 graphite, axial orientation, as a function of irradiation conditions

Fig. 4.6-2. Design curves for dimensional change of H-451 graphite, radial orientation, as a function of irradiation conditions

The maximum densification point and crossover point [LATER] are shown in Fig. 4.6-3 (Ref. 4-34).

The following horizontal shifting rule for the dimensional change shall be used for the nonisothermal operating condition:

1. Usable lifetime is conservatively defined as the fluence when the graphite under irradiation returns to its original volume. This fluence is represented by $L(T_i)$ at temperature T_i .
2. The fraction of lifetime used by a fluence increment of $\Delta\gamma(T_i)$ is $\Delta U_i = \Delta\gamma(T_i)/L(T_i)$.
3. The cumulative usage fraction is $\sum_i \Delta U_i = U_i$.
4. A shift from the $\epsilon^I(T_i)$ curve to $\epsilon^I(T_{i+1})$ curve under the non-isothermal condition is performed at equal U_i . The $\epsilon^I(T_{i+1})$ curve at U_i and beyond is horizontally shifted to the vertical line (constant fluence) with the same U_i on the $\epsilon^I(T_i)$ curve.
5. The vertical gap in ϵ^I [between the $\epsilon^I(T_i)$ and the shifted $\epsilon^I(T_{i+1})$ at U_i] is assumed to be closed by the transient expression:

$$\epsilon^I(T_{i+1}) = \epsilon_{sh}^I(T_{i+1}) + \Delta\epsilon_{sh}^I(T_{i+1}) \exp - \frac{\Delta\gamma(T_{i+1})}{\tau}, \quad (4-21)$$

where $\epsilon^I(T_{i+1})$ = the predicted dimensional change at T_{i+1} ,

$\epsilon_{sh}^I(T_{i+1}) = \epsilon^I$ on the shifted $\epsilon^I(T_{i+1})$ curve,

$\Delta\epsilon_{sh}^I(T_{i+1})$ = the vertical gap at $\Delta\gamma(T_{i+1}) = 0$,

(Later)

Fig. 4.6-3. Maximum densification point and crossover point for irradiated H-451 graphite as a function of irradiation temperature

$\Delta\gamma(t_{i+1})$ = the fluence measured from the point with
 U_i (the temperature change point),

τ = a fluence constant, equal to 0.8×10^{21} n/cm² ($E > 29$ fJ)_{HTGR}.

4.6.2. Irradiation-Induced Creep

4.6.2.1. Rheological Model. Mechanical behavior of graphite under irradiation has always been modeled for the HTGR as a standard linear solid, as proposed by Head (Ref. 4-35). The one-dimensional standard linear solid consists of a Kelvin element (spring and dashpot in parallel) and a Maxwell element (spring and dashpot in series) in series. The Kelvin element represents the transient response, and the Maxwell element the steady-state response. Beside the above two elements, there are two black box elements to represent the thermal strain and irradiation strain components.

In the standard linear solid model, the total strain at any generic point in an irradiated material body can be conveniently partitioned into the following five components:

1. Thermal strain, ϵ^θ .
2. Irradiation-induced dimensional change also called irradiation strain, ϵ^I .
3. Elastic strain, ϵ^e .
4. Transient creep strain, ϵ^T .
5. Steady-state creep strain, ϵ^S .

ϵ^θ and ϵ^I are the stress-free strain components. ϵ^θ and ϵ^e are instantaneously recoverable, but the amount recovered may differ from the initial strain imposed. ϵ^T has delayed recovery. ϵ^I and ϵ^S are irrecoverable.

The thermal strain, ϵ^θ , can be calculated for a given temperature distribution and thermal expansivity given in Section 4.4.2. The irradiation-induced dimensional change, ϵ^I , can be obtained from Section 4.6.2. The remaining three strain components will be discussed later.

Generalization of the one-dimensional creep model to multiaxial case was reported in Ref. 4-36. The remaining three strain components in the multiaxial case can be represented as a system of matrix differential equations. These are:

Elastic

$$\mathcal{Q} = \mathbb{E}^e \mathcal{E}^e \quad . \quad (4-22)$$

Transient Creep

$$\dot{\mathcal{E}}^T = \mathbb{M}^T (\mathcal{Q} - \mathbb{E}^T \mathcal{E}^T) \quad . \quad (4-23)$$

Steady Creep

$$\dot{\mathcal{E}}^S = \mathbb{M}^S \mathcal{Q} \quad , \quad (4-24)$$

where the dot represents differentiation with respect to fluence.

Equations 4-22 to 4-24 are coupled by the fact that the total strain, $\mathcal{E}$, is the sum of five components:

$$\mathcal{E} = \mathcal{E}^e + \mathcal{E}^T + \mathcal{E}^S + \mathcal{E}^\theta + \mathcal{E}^I \quad . \quad (4-25)$$

In the last four equations, $\mathcal{Q}$ and all $\mathcal{E}$'s are all (6x1) vectors, while the material properties $\mathbb{E}^e$, $\mathbb{E}^T$, $\mathbb{M}^S$, and $\mathbb{M}^T$ are (6x6) matrices. Using the

assumption of transverse isotropy and referring to a rectangular Cartesian coordinate system, typical vectors and matrices of these quantities can be represented in component form as:

$$\underline{\sigma} = \{\sigma_x, \sigma_y, \sigma_z, \tau_{xy}, \tau_{yz}, \tau_{zx}\} \quad , \quad (4-26)$$

$$\underline{\epsilon} = \{\epsilon_x, \epsilon_y, \epsilon_z, \gamma_{xy}, \gamma_{yz}, \gamma_{zx}\} \quad , \quad (4-27)$$

and

$$(\underline{E}^T)^{-1} = \begin{bmatrix} \frac{1}{E_x^T} - \frac{\nu_{xy}^T}{E_x^T} - \frac{\nu_{zx}^T}{E_z^T} & 0 & 0 & 0 \\ \frac{1}{E_x^T} - \frac{\nu_{zx}^T}{E_z^T} & 0 & 0 & 0 \\ \frac{1}{E_z^T} & 0 & 0 & 0 \\ \frac{2(1+\nu_{xy}^T)}{E_x^T} & 0 & 0 & 0 \\ \text{Symmetric} & & & \\ & \frac{1}{G_{zx}^T} & 0 & 0 \\ & & \frac{1}{G_{zx}^T} & 0 \end{bmatrix} \quad (4-28)$$

$$\underline{M}^S = \begin{bmatrix} M_x^S & -\nu_{xy}^S M_x^S & -\nu_{zx}^S M_z^S & 0 & 0 & 0 \\ & M_x^S & -\nu_{zx}^S M_z^S & 0 & 0 & 0 \\ & & M_z^S & 0 & 0 & 0 \\ & & & 2(1+\nu_{xy}^S)M_x^S & 0 & 0 \\ & \text{Symmetric} & & & M_{zx}^S & 0 \\ & & & & & M_{zx}^S \end{bmatrix}, \quad (4-29)$$

$$\underline{\epsilon}^S = \frac{E}{\xi} \underline{\epsilon} = \begin{bmatrix} \eta(1-\eta\nu_{zx}^2) & \eta(\nu_{xy}+\eta\nu_{zx}^2) & \eta\delta & 0 & 0 & 0 \\ & \eta(1-\eta\nu_{zx}^2) & \eta\delta & 0 & 0 & 0 \\ & & 1-\nu_{xy}^2 & 0 & 0 & 0 \\ & & & \frac{\eta\psi}{2} & 0 & 0 \\ & \text{Symmetric} & & & G_{zx} \frac{\xi}{E_z} & 0 \\ & & & & & G_{zx} \frac{\xi}{E_z} \end{bmatrix}, \quad (4-30)$$

$$\text{where } \eta = \frac{E_x}{E_z} \quad ,$$

$$\psi = 1 - \nu_{xy} - 2\eta\nu_{zx}^2 \quad ,$$

$$\xi = (1 + \nu_{xy}) (1 - \nu_{xy} - 2\eta \nu_{zx}^2) \quad ,$$

$$\delta = \nu_{zx} (1 + \nu_{xy}) \quad . \quad (4-31)$$

It should be clear that there are five independent material parameters contained in each of the material property matrices as a direct consequence of the transverse isotropy assumption.

A further reduction in the number of primitive material parameters is made by assuming:

$$\tilde{M}^T \tilde{E}^T = \frac{\tilde{I}}{\Phi_R} \quad , \quad (4-32)$$

where $\tilde{I}$ is an identity matrix and Φ_R is a scalar called the "relaxation time." With this assumption, the system of matrix Eq. 4-23 becomes:

$$\dot{\tilde{\xi}}^T = \frac{1}{\Phi_R} \left((\tilde{E}^T)^{-1} \tilde{\sigma} - \tilde{\xi}^T \right) \quad , \quad (4-33)$$

which is decoupled and, therefore, can be integrated easily. The physical implication of the assumption (4-23) is that the relaxation time constant is the same in all directions and that the Poisson's ratios are the same in both the parallel spring and the dashpot mechanisms, $\tilde{M}^T$ and $\tilde{E}^T$.

An intuitive assumption is introduced for G_{zx} , M_{zx}^S , and G_{zx}^T :

$$G_{zx} = \frac{1}{2} \frac{E_x + E_z}{(1 + \nu_{zx})} \quad ,$$

$$\frac{1}{M_{zx}^S} = \frac{\frac{1}{2} \frac{1}{M_x^S} + \frac{1}{M_z^S}}{1 + \nu_{zx}^S}, \quad (4-34)$$

$$G_{zx}^T = \frac{\frac{1}{2} \frac{E_x^T}{x} + \frac{E_z^T}{z}}{1 + \nu_{zx}^T}.$$

After the last two assumptions, the independent material parameters for the viscoelastic response of core graphite are:

Elastic

$$E_x, E_z, \nu_{xy}, \nu_{zx}.$$

Steady Creep

$$M_x^S, M_z^S, \nu_{xy}^S, \nu_{zx}^S.$$

Transient Creep

$$\phi_R, E_x^T, E_z^T, \nu_{xy}^T, \nu_{zx}^T.$$

The linear elastic material properties are given in Section 4.5.1. The remaining material properties will be specified in the next section.

4.6.2.2. Irradiation Creep Parameter. All the Poisson's ratios in creep, namely, ν_{xy}^S , ν_{zx}^S , ν_{xy}^T , and ν_{zx}^T are assumed to be constant. This is due to two considerations. First, the creep data are not sufficient and derive a set of values as a function of temperature and fluence. Secondly, the more important one is that the stress results are not

sensitive to the creep Poisson's ratios. Based on the OC creep series, the following value is recommended for use (Ref. 4-37):

$$\nu_{xy}^S = \nu_{zx}^S = 0.5 \quad ,$$

$$\nu_{xy}^T = \nu_{zx}^T = 0 \quad .$$

The "relaxation time," Φ_R , is best estimated to be 4×10^{19} n/cm² ($E > 0.18$ MeV, HTGR) from pooled data of all available graphite experiments (Ref. 4-38). This value is assumed to apply to H-451 graphite. The relaxation time does not have significant effect on the irradiation stress at or beyond a fluence of, say, five times the "relaxation time."

The transient creep elastic moduli, E_x^T and E_z^T , are taken to equal the respective elastic moduli at the "time" loading or unloading occurs (Ref. 4-38).

The remaining last two material properties are the steady creep mobility coefficients in two directions (or called steady-state creep coefficients), M_x^S and M_z^S . Due to small number of radial creep specimens, it is reasonable to assume:

$$M_x^S = M_z^S \quad .$$

Reference 4-39 recommends the following expression for design use:

$$\begin{aligned} \epsilon^C &= \epsilon^T + \epsilon^S \\ &= \frac{\sigma}{E} [1 - \exp(-25 \Phi)] + \frac{\sigma}{E} (2.87128 \Phi + 0.14853 \Phi T \\ &\quad - 2.48083 \Phi^2 + 0.25992 \Phi^2 T + 0.44420 \Phi^3 \\ &\quad - 0.05671 \Phi^2 T) \quad , \end{aligned} \quad (4-35)$$

where Φ = fast neutron fluence ($n/cm^2 \times 10^{-21}$, $E > 29$ fJ),

T = irradiation temperature ($^{\circ}C/100$),

E = elastic modulus at the "time" loading or unloading occurs (GPa),

σ = applied stress (MPa).

4.6.3.2. Effect of Creep Strain on Physical Properties. Creep strain up to 4.5% does not significantly alter density, elastic modulus, defect size (hence sonic attenuation) and electrical resistivity (Refs. 4-40 and 4-41). Thermal expansivity is the only property known to be noticeably affected by a creep strain component. The following relationship is obtained at 800 $^{\circ}C$ from axial specimens in a compression creep series (Ref. 4-41):

$$\alpha_c = \alpha_o - 0.504 \epsilon^c .$$

where α_c = coefficient of thermal expansion (to 800 $^{\circ}C$) of a creep specimen with creep strain of ϵ^c ($10^{-6}/^{\circ}C$),

α_o = coefficient of thermal expansion (to 800 $^{\circ}C$) of an unstressed control specimen irradiated under the same condition as the creep specimen ($10^{-6}/^{\circ}C$),

ϵ^c = creep strain, negative for compressive creep strain (%).

The relationship is assumed to be applicable to tensile creep region as well as to the radial direction.

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