CYCLIC FATIGUE OF NEAR-ISOTROPIC GRAPHITE: INFLUENCE OF STRESS CYCLE AND NEUTRON IRRADIATION

by
R. J. PRICE

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INFLUENCE OF STRESS CYCLE AND NEUTRON IRRADIATION

by

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ABSTRACT

For this study, near-isotropic graphites H-451 and PGX were tested in uniaxial cyclic fatigue, and fatigue life (S-N) curves were generated to a maximum of 10^5 cycles. The stress ratio, R (minimum stress during a cycle divided by maximum stress) ranged from -1 to +0.5. With $R = -1$, the homologous stress limits (maximum applied fatigue stress divided by the tensile strength) for 50% specimen survival to 10^5 cycles averaged 0.63 in the axial direction and 0.74 in the radial direction. Corresponding homologous stress limits for 99% specimen survival (99/95 tolerance limits) were 0.48 and 0.53. Higher R-values resulted in longer fatigue lives and increased stress limits. H-451 graphite specimens irradiated with fast neutrons at 1173 to 1263 K at fluences of up to 10^{26} n/m² (equivalent fission fluence) showed fatigue stress limits of about twice the unirradiated levels when the unirradiated tensile strength was used as the basis for normalization.

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1. INTRODUCTION

Graphite components in high-temperature gas-cooled nuclear reactors (HTGR) are subject to cyclic stresses from power cycling, operating vibrations, and possibly seismic shaking. Design of the components requires a knowledge of the cyclic fatigue behavior of graphite under loading cycles with different ratios of minimum stress to maximum stress (R-value) and under fast neutron irradiation. The inherent scatter in mechanical property determinations on graphites requires that sufficient tests be made for statistical analysis.

Most previously reported measurements on the cyclic fatigue properties of graphites (Ref. 1-9) are too limited in scope to be directly used in engineering design. The most extensive data are those of Leichter and Robinson (Ref. 5), who used rotating beam tests (corresponding to an R-value of -1) on Poco AXF graphite, together with previously reported data on other grades, to make a plot of homologous stress (maximum applied fatigue stress divided by the tensile strength) versus the number of cycles to failure (S-N curve). The curve has the same form as S-N curves for many metals, with an apparent endurance limit of about 0.64 times the first cycle strength for a survival probability of 50% and 0.47 times the first cycle strength for a survival probability of 99%.

Bullock (Ref. 9) has reported data from uniaxial fatigue tests on ATJ graphite which show a higher endurance limit for specimens cycled between zero stress and tension ($R = 0$) than for specimens cycled between compression and tension ($R = -1$). Similar trends are apparent in data reported by Brocklehurst (Ref. 8). The only reported fatigue measurements on neutron-irradiated graphite are those by Brocklehurst (Ref. 8), who subjected a few specimens of a gilsocarbon-based isotropic graphite irradiated to a fluence

of $2.5 \times 10^{25} \text{ n/m}^2$ (Dido nickel equivalent) at 1173 K (900°C) to flexural fatigue tests. When plotted on an S-N curve in terms of homologous stress, the points fell into the same scatter band as unirradiated specimens.

The present work consisted of uniaxial fatigue tests on H-451 graphite (Great Lakes Carbon Company) and PGX graphite (Union Carbide Corporation) with R-values ranging from -1 to +0.5. Additional tests were conducted on H-451 graphite irradiated to fluences of up to 10^{26} n/m^2 [equivalent fission fluence for graphite damage (Ref. 10)] at 1173 to 1263 K (900° to 990°C).

2. EXPERIMENTATION

2.1. MATERIAL

H-451 is an extruded, near-isotropic, petroleum coke-based, nuclear grade graphite made by Great Lakes Carbon Company. It is the reference material for the fuel and replaceable reflector blocks in HTGRs. The extruded log size is 0.46 m in diameter by 0.86 m long. Specimens for the unirradiated fatigue tests were taken in both axial and radial orientations a quarter of the way along the length of the parent log and between 25 and 100 mm from the edge. Specimens for irradiation testing were taken from near the log axis at the mid-length location of a different log. Graphite from the latter location is typically of lower strength than graphite from the former location.

Grade PGX is a large diameter, molded, petroleum coke-based graphite made by Union Carbide Corporation. It is the reference material for support floor blocks in HTGRs. The fabricated log size is 1.14 m in diameter by 1.83 m long. Fatigue specimens were taken in the axial and radial orientations between 50 and 150 mm from the end of the log and between 150 and 280 mm from the log axis. No irradiations were carried out on PGX specimens.

For a given series of tests, specimens were taken from locations spread uniformly over the sampling zone to prevent possible bias from local inhomogeneities in strength. The locations of individual specimens are given in the Appendix.

2.2. SPECIMENS

Except for the specimens subjected to neutron irradiation, cylindrical specimens 12.7 mm in diameter by 25.4 long were used. Space limitations in the irradiation capsules restricted the size of the irradiated specimens to 5.1 mm in diameter by 10.2 mm long. Prior to testing, the specimens were cemented between cylindrical steel end-pieces with epoxy cement. The assemblies were held in V-block jigs while the cement hardened to ensure coaxial alignment.

2.3. APPARATUS

All tests were run in air at ambient temperature. Tests were conducted in a modified Fatigue Dynamics Model VSP 150 crank-and-lever fatigue machine equipped with a load cell and a specially constructed test cage. A pair of opposed loading rams in the cage move on coaxial linear ball bearings to ensure uniaxial loading in both tension and compression. The specimen end-pieces are seated in machined recesses in the rams.

The maximum and minimum load during a cycle were set at the start of the test and checked occasionally during the test. Tests were run at 7 Hz until the specimen fractured or until 100,000 cycles were reached without fracture.

2.4. IRRADIATION

Three groups of specimens of H-451 graphite were irradiated in graphite crucibles in temperature-controlled capsules in the C-3 position of the Oak Ridge reactor. Irradiation conditions are given in Section 3.2. The fast neutron fluence was measured from the activation of iron and titanium dosimeters and is expressed as the equivalent fission fluence for graphite damage (EFFGD) (Ref. 10) and also in terms of neutrons with energies greater than 29 fJ (0.18 Mev) in a typical HTGR spectrum. The temperatures were measured with chromel-alumel thermocouples. The temperatures fluctuated by ± 20 K during the irradiations.

3. RESULTS

3.1. UNIRRADIATED SPECIMENS

For each material and orientation, the first test series consisted of 30 to 35 control tensile tests on standard fatigue specimens mounted in the fatigue machine. These tests established the mean tensile strengths, which are listed in Table 1. Individual test data are given in the Appendix.

Fatigue tests were run using R-values of -1, -0.5, 0, and +0.5 for H-451 graphite and -1 and 0 for PGX graphite. Forty to 50 specimens were included in each series of tests. Between seven and ten specimens were cycled at each of five maximum stress levels, which ranged from 0.6 to 1.0 times the mean tensile strength. The stress levels were selected to avoid an excessive number of run-outs beyond 100,000 cycles. Individual test data, showing maximum and minimum stresses and the number of cycles at failure, are listed in the Appendix.

A typical S-N curve, in which the logarithm of the maximum stress, S , is plotted against the logarithm of the number of cycles at failure, N , is shown in Fig. 1 for axial specimens of H-451 graphite run with an R-value of -1. The stresses are normalized by dividing by the mean tensile strength. The tensile data and first-cycle failures are plotted at $N = 0.25$, and run-outs (specimens which survived 100,000 cycles without failure) are shown as open circles at $N = 100,000$. A complete set of S-N curves is included in the Appendix.

The S-N curves have the same form as those of many metals, except that the scatter band is wider. The data do not extend to high enough values of N to confirm the existence of an absolute endurance limit suggested by Leichter and Robinson's measurements on Poco graphite (Ref. 5).

TABLE 1
MEAN TENSILE STRENGTH OF UNIRRADIATED H-451 AND PGX GRAPHITE
SPECIMENS USED IN FATIGUE STUDY

Grade	Location in Log	Orientation	Mean Tensile Strength ($\pm$ Standard Deviation) (MPa)
H-451	Quarter-length, edge	Axial	18.9 ± 1.8
H-451	Quarter-length, edge	Radial	13.9 ± 2.3
PGX	End, one-third radius	Axial	7.6 ± 0.4
PGX	End, one-third radius	Radial	9.5 ± 1.0

Fig. 1. Fatigue test data on H-451 graphite, axial orientation, quarter-length edge location, in air at ambient temperature. Log-log plot of normalized maximum stress versus number of cycles to failure with $R = -1$. Lower x/y tolerance limits represent the limits above which at least x% of all data would fall, with y% confidence.

The curves were statistically analyzed using a model different from those reported previously. The usual practice has been to deduce the N-value corresponding to a particular failure probability from the dispersion of log (N) values at a given stress setting, assuming a Weibull or a Gaussian distribution. This procedure has several disadvantages when applied to graphite; in particular, it provides no information on low failure probabilities in the high-cycle regime. The problem is best approached by inverting the usual practice and assuming that for a constant life the failure stresses follow a specific distribution (Ref. 5). For present purposes, the following statistical model was assumed:

$$\log_{10} \left(\frac{\sigma_{\max}}{\bar{S}} \right) = \alpha + \beta \log_{10} (N) + \epsilon \quad , \quad (1)$$

where $\sigma_{\max}$ is the peak tensile stress, $\bar{S}$ is the mean tensile strength, α and β are constants, and ϵ is a random variable distributed normally with a mean of zero and a standard deviation s . The data were analyzed according to the model of Eq. 1, including the tensile tests at $N = 0.25$ but excluding the specimens which ran out beyond 10^5 cycles. The least-squares straight line through the data and the x/y lower tolerance limits (representing the limits above which at least x% of all observations would fall, with y% confidence) were calculated for the x/y combinations 90/90, 95/95 and 99/95 and are included in Fig. 1. The data support the linear relationship between $\log (\sigma_{\max})$ and $\log (N)$ assumed in Eq. 1. Results of the statistical analyses are summarized in Tables 2 and 3.

The downward slope of the S-N curves (β in Tables 2 and 3) became steeper as the stress ratio R decreased (i.e., as the stress became compressive during a part of the cycle). For example, the homologous stress limit for 50% survival to 10^5 cycles in axial specimens of H-451 graphite decreased from 0.81 at $R = 0.5$ to 0.60 at $R = -1$. There was some tendency for the scatter band to increase at low values of R , as indicated by an increase in s (Tables 2 and 3).

TABLE 2
RESULTS OF STATISTICAL ANALYSIS OF FATIGUE DATA FOR UNIRRADIATED H-451 GRAPHITE

Orientation	Stress Ratio, R $\left(\frac{\sigma_{\min}}{\sigma_{\max}}\right)$	Intercept of Least Squares Line, $\alpha(a)$	Slope of Least Squares Line, $\beta(a)$	Standard Deviation $s(a)$	Homologous Stress Limit $\left(\frac{\sigma_{\max}}{S}\right)$ for Survival to 10^5 Cycles (a)	
					50% Probability	99/95 Lower Tolerance Limit
Axial	0.5	-0.023	-0.014	0.042	0.81	0.60
Axial	0	-0.025	-0.026	0.038	0.70	0.54
Axial	-0.5	-0.019	-0.037	0.052	0.63	0.44
Axial	-1.0	-0.032	-0.038	0.048	0.60	0.44
Radial	0.5	-0.010	-0.004	0.056	0.93	0.62
Radial	0	-0.019	-0.016	0.057	0.80	0.54
Radial	-0.5	-0.018	-0.021	0.059	0.75	0.50
Radial	-1.0	-0.025	-0.020	0.058	0.75	0.50

(a) Based on the model of Eq. 1.

TABLE 3
RESULTS OF STATISTICAL ANALYSIS OF FATIGUE DATA FOR UNIRRADIATED PGX GRAPHITE

Orientation	Stress Ratio, R $\left(\frac{\sigma_{\min}}{\sigma_{\max}}\right)$	Intercept of Least Squares Line, $\alpha^{(a)}$	Slope of Least Squares Line, $\beta^{(a)}$	Standard Deviation, $s^{(a)}$	Homologous Stress Limit $\left(\frac{\sigma_{\max}}{\bar{S}}\right)$ for Survival to 10^5 Cycles ^(a)	
					50% Probability	99/95 Lower Tolerance Limit
Axial	0	-0.026	-0.021	0.031	0.74	0.60
	-1	-0.013	-0.034	0.035	0.66	0.52
Radial	0	-0.009	-0.013	0.040	0.85	0.64
	-1	-0.017	-0.023	0.042	0.74	0.56

(a) Based on the model of Eq. 1.

For engineering design it is convenient to plot the results on a constant life fatigue diagram (Goodman diagram), which relates fatigue life to the following interdependent loading cycle parameters: maximum stress, minimum stress, stress amplitude, and mean stress. Figure 2 shows an example of a Goodman diagram relating the loading cycle parameters for 50% survival to 10^2 , 10^3 , 10^4 and 10^5 cycles in axial specimens of H-451 graphite. A full set of Goodman diagrams is included in the Appendix.

When normalized by dividing by the mean tensile strength, the homologous stress limits for radial specimens were somewhat greater than those for axial specimens under similar conditions (Tables 2 and 3). This was true for both H-451 graphite and PGX graphite, in spite of the fact that the former has an extruded texture and the latter has a molded texture. In most cases, the homologous stress limits for PGX graphite were slightly higher than those for H-451 graphite.

Under reversed stress cycling ($R = -1$), the homologous stress limits for survival of axial specimens to 10^5 cycles averaged 0.63 for 50% survival and 0.48 for 99% survival (99/95 tolerance limit). These averages agree well with Leichter and Robinson's results (Ref. 5). The homologous stress limits for radial specimens averaged a little higher (0.74 and 0.53, respectively).

3.2. IRRADIATED SPECIMENS

Three groups of 42 specimens of H-451 graphite were irradiated at 1173 to 1263 K to different neutron exposures. The irradiation conditions are listed in Table 4. Ten specimens out of each group were tensile-tested in the fatigue machine to establish the mean tensile strength. The values are listed in Table 4, together with the strengths of unirradiated companions from the same log. All groups showed the expected increase in strength after irradiation (Ref. 11). The remainder of the specimens in each group were used for tension-compression fatigue tests ($R = -1$).

Fig. 2. Constant life fatigue diagram (Goodman diagram) for H-451 graphite, axial orientation, tested in air at ambient temperature

TABLE 4
IRRADIATION CONDITIONS AND MEAN TENSILE STRENGTH OF IRRADIATED
H-451 GRAPHITE USED IN FATIGUE STUDY
(All Specimens Midlength-Center Location)

Orientation	Fast Neutron Fluence (10^{25} n/m^2)		Irradiation Temperature		Mean Tensile Strength ($\pm$ Standard Deviation) (MPa)	Mean Tensile Strength of Unirradiated Companions ($\pm$ Standard Deviation) (MPa)
	Equivalent Fission Fluence	E > 29 fJ, HTGR	K	$^{\circ}\text{C}$		
Axial	3.8	3.0	1173	900	14.5 ± 2.1	10.8 ± 0.9
Radial	7.1	5.7	1223 - 1263	950 - 990	22.4 ± 2.6	11.5 ± 1.7
Axial	10.6	8.5	1173 - 1243	900 - 970	20.2 ± 1.9	10.8 ± 0.9

Eight specimens were cycled at each of four stress levels until they failed or reached 100,000 cycles without failure. Individual test data are given in the Appendix.

A homologous stress S-N curve for axial specimens of H-451 graphite irradiated to $3.8 \times 10^{25} \text{ n/m}^2$ (EFFGD) at 1173 K is shown in Fig. 3. Comparison between Fig. 1 and Fig. 3 shows that the homologous stress limits for fatigue endurance are increased by neutron irradiation. The results of statistical analysis of the S-N curves for all the irradiated H-451 specimens are given in Table 5. The homologous stress limits for survival to 10^5 cycles are substantially higher than for unirradiated H-451 tested with $R = -1$ (Table 2), at least for the axial specimens. The homologous stress 99/95 lower tolerance limit is lower at higher fluences as the result of increased data scatter, but it remains above the unirradiated level. The increased scatter may be caused by slight warpage in the highly irradiated specimens, which interferes with accurate uniaxial alignment.

If the fatigue stress limits are normalized by dividing by the unirradiated tensile strength instead of the irradiated tensile strength, the limits increase by more than a factor of two during irradiation. The stress limits for 50% survival to 10^5 cycles and the 99/95 lower tolerance limits normalized to the unirradiated strength are plotted against neutron fluence in Fig. 4.

Fig. 3. Ambient temperature fatigue test data for H-451 graphite, axial orientation, irradiated to $3.8 \times 10^{25} \text{ n/m}^2$ (equivalent fission fluence) at 1173 K (900°C). Log-log plot of normalized peak stress versus number of cycles to failure, with stress ratio, $R = -1$. Lower x/y tolerance limits represent the limits above which x% of all observations would fall, with y% confidence. Open circles represent run-outs.

TABLE 5
RESULTS OF STATISTICAL ANALYSIS OF FATIGUE DATA FOR H-451 GRAPHITE IRRADIATED AT 1173 - 1263 K
(Stress Ratio, R = 1)

Orientation	Fast Neutron Fluence (10^{25} n/m^2) (EFFGD)	Intercept of Least Squares Line, $\alpha^{(a)}$	Slope of Least Squares Line, $\beta^{(a)}$	Standard Deviation, $s^{(a)}$	Homologous Stress Limit $\left(\frac{\sigma_{\max}}{S}\right)$ for Survival to 10^5 Cycles $^{(a)}$	
					50% Probability	99/95 Lower Tolerance Limit
Axial	3.8	-0.010	-0.004	0.046	0.93	0.66
Radial	7.1	-0.020	-0.022	0.044	0.74	0.54
Axial	10.6	-0.033	-0.012	0.056	0.81	0.51

^(a) Based on the model of Eq. 1.

Fig. 4. Fatigue stress limits for survival of H-451 graphite to 10^5 cycles, normalized to the unirradiated tensile strength, versus the fast neutron fluence at an irradiation temperature of 1173 to 1263 K (900° to 990°C)

4. DISCUSSION

The general form of the S-N curves for graphite (Fig. 1) resembles that of many metals. In addition, the dependence of the fatigue stress limits on the stress ratio R (Fig. 2) is similar to metallic behavior, with more fatigue damage occurring during a tension-compression cycle ($R = -1$) than during a tensile stress cycle ($R \geq 0$). Marshall and Priddle (Ref. 7) measured the fatigue crack growth rate, $\frac{da}{dN}$, in isotropic graphite as a function of the applied stress intensity range, ΔK , and found the following relationship:

$$\frac{da}{dN} \propto (\Delta K - \Delta K_0)^4, \quad (2)$$

where ΔK_0 is the threshold stress intensity range for crack propagation. This relationship is similar to that often found with metals. It seems reasonable to conclude that cyclic fatigue in graphite, as in metals, takes place by limited plastic flow at the tip of the advancing fatigue crack. This contrasts with the behavior of most ceramic materials and of isotropic pyrolytic carbons, whose dislocations are almost immobile (Ref. 12) and which are resistant to cyclic fatigue (Ref. 13).

Neutron irradiation reduces the mobility of basal dislocations in graphite. The resulting reduction in plasticity at the tip of a fatigue crack may slow crack growth and account for the increased fatigue resistance of irradiated materials found in this study.

Brocklehurst (Ref. 8) has recently used Marshall and Priddle's crack propagation relationship (Eq. 2) to predict the effect of the stress cycle on fatigue life. With the crack growth parameters measured by Marshall and Priddle, the model predicts no fatigue effects for $R \geq 0.5$ and a

homologous stress limit of about 0.6 for 50% specimen survival to 10^5 cycles when $R = 0$. Fatigue effects for negative R -values are not directly predicted, because Marshall and Priddle's data did not include compressive cycling. However, Brocklehurst estimated a homologous stress limit of about 0.5 at 10^5 cycles at $R = -1$, using the assumption that compressive stresses are 20% as effective as tensile stresses in propagating fatigue cracks. The homologous stress limits found in this study (Tables 2 and 3) are lower than these predictions at $R = 0.5$ and higher than those predicted at $R = 0$ and $R = -1$. The discrepancy suggests that the crack growth parameters for H-451 and PGX graphites differ from those for the materials used by Marshall and Priddle. The differences in fatigue properties between the two grades, as well as between axial and radial orientations, suggest that crack growth parameters depend on the graphite microstructure.

5. SUMMARY AND CONCLUSIONS

More than 800 uniaxial cyclic fatigue tests at ambient temperature were made on near-isotropic graphites H-451 and PGX. Tests were run at 7 Hz to 10^5 cycles or until the specimen fractured. The stress ratio, R (minimum stress during a cycle divided by maximum stress) ranged from -1 to $+0.5$. Specimens of H-451 graphite irradiated at 1173 to 1253 K (900 to 990°C) to neutron fluences up to 10^{26} n/m² (equivalent fission fluence) were included. The following observations were made:

1. The graphites showed cyclic fatigue life curves (S-N curves) generally resembling those of metals, but with more scatter (Fig. 1).
2. For reversed stress cycling ($R = -1$), the homologous stress limits (maximum applied fatigue stress divided by the tensile strength) for 50% specimen survival to 10^5 cycles averaged 0.63 in the axial direction and 0.74 in the radial direction. Corresponding homologous stress limits for 99% specimen survival (99/95 tolerance limits) were 0.48 and 0.53 (Tables 2 and 3).
3. The fatigue life and the homologous stress limits increased as R increased. The results can be plotted on a Goodman diagram (Fig. 2).
4. Neutron irradiation increases the homologous stress limits for fatigue endurance. If the unirradiated tensile strength is used as the basis for normalization, the fatigue stress limits are about doubled by irradiation.

5. Fatigue in graphite probably takes place by limited plastic flow at the tip of the advancing fatigue crack.
6. Fatigue behavior varies with both orientation and the grade of graphite. Fatigue life predictions based on crack growth relationships for other graphites are therefore subject to error.

6. ACKNOWLEDGEMENTS

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REFERENCES

1. Green, L., "The Behavior of Graphite Under Alternating Stress," J. Appl. Mech., 18 (1951), p. 345.
2. Dally, J. W., and L. N. Hjelm, "Proof-Testing Graphite and its Design Implications," J. Am. Ceram. Soc., 48 (1965), p. 338.
3. Barabanov, V. N., et al., "Some Special Features of the Method of Testing Graphite for Fatigue in Alternate-Reversing Bending, and the Results Obtained," Ind. Lab. (USSR), 32 (1966), p. 567.
4. Bazaj, D. K., and E. E. Cox, "Stress-Concentration Factors and Notch-Sensitivity of Graphite," Carbon, 7, (1969), p. 689.
5. Leichter, H. L. and E. Robinson, "Fatigue Behavior of a High Density Graphite and General Design Correlation," J. Am. Ceram. Soc., 53 (1970), p. 197.
6. Wilkins, B. J. S., "Probability of Failure of Brittle Materials Subjected to Dynamic or Static Fatigue," J. Materials, 7 (1972), p. 251.
7. Marshall, P., and E. K. Priddle, "Room Temperature Fatigue Crack Propagation in Reactor Graphites," Carbon, 11 (1973), p. 541.
8. Brocklehurst, J. E., "Fracture in Polycrystalline Graphite," Chem. Phys. Carbons, 13 (1977), p. 145.
9. Bullock, R. E., "Fatigue Behavior of ATJ Graphite," J. Materials Science, 12 (1977), p. 1215.
10. ASTM Standard E525-74, "Standard Recommended Practice for Reporting Dosimetry Results on Nuclear Graphite," Annual Book of ASTM Standards, 45 (1976), p. 951.
11. Price, R. J., "Tensile Properties of Neutron-Irradiated Graphites," in Extended Abstracts of the Thirteenth Biennial Conference on Carbon (American Carbon Society, 1977), p. 242.

12. Tsuzuku, T., "Mechanical Energy Losses Due to Motion of Dislocations in Graphite and Carbons," Carbon, 1 (1963), p. 25.
13. Schoen, F. J., "On the Fatigue Behavior of Pyrolytic Carbon," Carbon, 11 (1973), p. 413.

APPENDIX
SAMPLING PLAN AND TEST DATA

APPENDIX
SAMPLING PLAN AND TEST DATA

A.1. SAMPLING PLAN

The specimens of unirradiated H-451 graphite were taken from log 5651-90 (Great Lakes Carbon Company Lot No. 408, piece No. 48), slab 5B. The location of slab 5B in the parent log is shown in Fig. A-1. The positions of individual specimens and their reference numbers are shown in Fig. A-2. Irradiated specimens of H-451 graphite were taken from the midlength-center zone of log 5651-28 (Great Lakes Carbon Company Lot No. 266, piece No. 18).

Specimens of PGX graphite were taken from a slab from log 6484-74 (Union Carbide Corporation log No. 3C5-4). The location of the slab in the parent log and the location of the test specimens in the slab are shown in Figs. A-3 and A-4, respectively.

A.2. TEST DATA

Individual test data are listed in Tables A-1 through A-22. Tables A-1 through A-10 record data on unirradiated H-451 graphite, Tables A-11 through A-16 record data on unirradiated PGX graphite, and Tables A-17 through A-22 record data on irradiated H-451. In each case the results of control tensile tests precede the tabulated fatigue data.

A full set of S-N curves appears in Figs. A-5 through A-19. The order of presentation is the same as for the tabulated data.

Figures A-20 through A-23 are constant life fatigue diagrams (Goodman diagrams) showing the homologous stress amplitude and mean stress for survival to 10^2 , 10^3 , 10^4 , or 10^5 cycles for a 50% survival probability.

Fig. A-1. Slab diagram for H-451 graphite

Fig. A-2. Coring plan for H-451 graphite

FATIGUE SPECIMENS FROM PGX GRAPHITE, LOG 6484-74

SPECIMENS TAKEN FROM THIS ARE
ACCORDING TO CORING PLAN ATTACHED

MACHINING:

AXIAL, CORES 2 THROUGH 100: CENTERLESS
GRIND TO 0.500 IN. DIAM. MAKE 3
SPECIMENS 1.00 IN. LONG FROM EACH CORE-
IDENTIFY BY CORE NUMBER + A, B OR C

CORES 102 THROUGH 120: HOLD FOR SPARES

RADIAL, CORES 1 THROUGH 99: CENTERLESS
GRIND TO 0.500 IN. DIAM. MAKE 4 SPECIMENS
1.00 IN. LONG FROM EACH CORE. IDENTIFY BY
CORE NUMBER + A, B, C OR D.

CORES 81 THROUGH 99: HOLD FOR SPARES

Fig. A-3. Slab diagram for PGX graphite

FATIGUE SPECIMENS

SLAB 6 AX 270° to 0°

Fig. A-4. Coring plan for PGX graphite

TABLE A-1
FATIGUE TESTS ON H-451 GRAPHITE

LOT NO: 408

LOG NO: 5651-90

ORIENTATION: AXIAL

LOCATION: QUARTER-LENGTH EDGE

CONTROL TENSILE TESTS

SPECIMEN NO.	DIAMETER (MM)	FRACTURE LOAD (KN)	TENSILE STRENGTH (MPA)
3-A	12.70	2.66	21.0
4-A	12.70	2.56	20.2
5-A	12.69	2.36	18.6
6-A	12.71	2.22	17.5
8-A	12.70	2.25	17.8
9-A	12.68	2.44	19.3
10-A	12.70	1.96	15.4
11-A	12.70	2.57	20.3
12-A	12.70	2.79	22.0
13-A	12.70	2.09	16.5
14-A	12.70	2.31	18.2
15-A	12.70	2.31	18.2
16-A	12.70	2.66	21.0
17-A	12.70	2.57	20.3
25-A	12.70	2.79	22.0
26-A	12.70	1.98	15.6
27-A	12.70	2.20	17.3
28-A	12.70	2.52	19.9
29-A	12.65	2.36	18.8
30-A	12.71	2.57	20.3
31-A	12.70	2.74	21.6
32-A	12.70	2.49	19.7
34-A	12.70	2.47	19.5
35-A	12.71	2.28	18.0
36-A	12.70	2.15	16.9
37-A	12.70	2.20	17.3
38-A	12.70	2.25	17.8
39-A	12.70	2.36	18.6

MEAN: 18.9 MPA
(2745.PSI)

STD. DEV: 1.8 MPA
(263.PSI)

TABLE A-2
FATIGUE TESTS ON H-451 GRAPHITE

LOT NO: 478

LOG NO: 5651-90

ORIENTATION: AXIAL

LOCATION: QUARTER-LENGTH EDGE

STRESS RATIO, R (MIN. STRESS / MAX. STRESS): -1.0

SPECIMEN NO.	MAX. STRESS (MPA)	MIN. STRESS (MPA)	CYCLES TO FAILURE
3-C	10.2	-10.2	13100
16-E	10.2	-10.2	4500
10-D	10.2	-10.2	> 121200 (RUNOUT)
22-C	10.6	-10.2	> 103000 (RUNOUT)
32-D	10.6	-10.6	> 119000 (RUNOUT)
34-B	11.6	-11.6	39300
42-B	11.7	-12.9	17900
21-A	11.8	-12.7	12400
38-B	12.1	-12.3	> 115100 (RUNOUT)
20-A	12.3	-12.3	3851
39-B	12.3	-12.7	7600
41-B	12.3	-12.7	465
37-B	12.5	-12.5	200
36-B	12.5	-12.5	> 121200 (RUNOUT)
35-B	12.5	-12.5	> 100000 (RUNOUT)
22-B	13.1	-13.1	7000
23-B	13.5	-13.5	7768
31-B	13.5	-14.0	59
27-B	13.6	-14.0	6
29-B	13.6	-13.6	56
32-B	13.8	-13.8	117
26-B	14.0	-13.6	577
25-B	14.0	-13.6	351
28-B	14.0	-13.6	137
30-B	14.0	-13.6	115
20-B	14.8	-14.8	2
18-B	14.8	-14.8	3
21-B	14.8	-15.7	162
8-B	14.8	-15.7	162
17-B	15.2	-15.2	87
9-B	15.3	-14.8	< 1 (FIRST CYCLE)
5-B	15.3	-14.9	24
19-B	15.3	-15.3	36
6-B	15.7	-14.8	3
14-B	16.1	-11.9	< 1 (FIRST CYCLE)
10-B	16.6	-18.3	34
11-B	16.9	-16.9	5200
7-B	17.0	-17.8	115
3-B	17.1	-16.7	10
12-B	17.1	-17.1	45
45-B	17.2	-19.1	< 1 (FIRST CYCLE)
46-B	17.2	-19.5	< 1 (FIRST CYCLE)
16-B	17.4	-16.1	832
15-B	17.6	-16.5	16
13-B	17.6	-16.5	40

TABLE A-2 (Continued)

47-B	17.8	-18.6	<	1 (FIRST CYCLE)
48-B	18.6	-19.0	<	1 (FIRST CYCLE)
18-A	19.0	-19.0	<	1 (FIRST CYCLE)
19-A	19.1	-19.1	<	1 (FIRST CYCLE)
43-B	19.7	-19.7		5
44-B	19.7	-19.9		3

TABLE A-3
FATIGUE TESTS ON H-451 GRAPHITE

LOT NO: 408
ORIENTATION: AXIAL

LOG NO: 5651-90
LOCATION: QUARTER-LENGTH EDGE

STRESS RATIO, R (MIN. STRESS / MAX. STRESS): -.5

SPECIMEN NO.	MAX. STRESS (MPA)	MIN. STRESS (MPA)	CYCLES TO FAILURE
38-C	10.0	-5.4	16900
37-C	10.0	-5.4	> 186000 (RUNOUT)
35-C	10.0	-5.4	3100
41-C	10.0	-5.4	1700
42-C	10.0	-5.4	> 100000 (RUNOUT)
39-C	10.0	-5.4	> 196000 (RUNOUT)
36-C	10.0	-5.4	> 102000 (RUNOUT)
31-C	12.5	-7.1	> 114000 (RUNOUT)
30-C	12.9	-6.7	> 100000 (RUNOUT)
26-C	12.9	-6.7	31500
28-C	12.9	-6.7	30
27-C	12.9	-6.7	10800
34-C	12.9	-6.7	> 194300 (RUNOUT)
29-C	12.9	-6.7	1756
4-C	14.3	-7.9	1033
9-C	14.5	-7.1	100
6-C	14.5	-7.5	122
5-C	14.5	-7.5	139
10-C	14.6	-7.1	37
8-C	14.7	-7.1	412
7-C	14.7	-7.1	50
43-C	15.0	-7.1	176
44-C	15.0	-7.1	210
45-C	15.0	-7.1	3000
48-C	16.2	-8.3	96
47-C	16.2	-8.3	13
46-C	16.2	-8.3	28
11-C	16.6	-8.7	193
17-C	16.6	-8.3	258
13-C	16.6	-8.7	105
16-C	17.0	-8.3	748
12-C	17.0	-8.3	302
14-C	17.0	-8.3	49
15-C	17.0	-8.3	1
23-C	17.8	-9.5	< 1 (FIRST CYCLE)
20-C	19.1	-10.0	85
22-C	19.1	-9.5	< 1 (FIRST CYCLE)
25-C	19.1	-10.0	5
18-C	19.5	-9.5	51
21-C	19.5	-9.5	9
19-C	19.6	-9.6	55

TABLE A-4
FATIGUE TESTS ON H-451 GRAPHITE

LOT NO: 408
ORIENTATION: AXIAL

LOG NO: 5651-90
LOCATION: QUARTER-LENGTH EDGE

STRESS RATIO, R (MIN. STRESS / MAX. STRESS): .0

SPECIMEN NO.	MAX. STRESS (MPA)	MIN. STRESS (MPA)	CYCLES TO FAILURE
34-D	10.0	.0	> 207400 (RUNOUT)
38-D	10.4	.0	> 532600 (RUNOUT)
32-D	10.4	.0	> 120400 (RUNOUT)
35-D	10.4	.0	> 100000 (RUNOUT)
39-D	10.4	.0	> 103000 (RUNOUT)
37-D	10.4	.0	> 118000 (RUNOUT)
36-D	10.5	.0	> 252900 (RUNOUT)
30-D	12.4	.0	5800
25-D	12.4	.0	> 105500 (RUNOUT)
26-D	12.6	.0	> 203800 (RUNOUT)
31-D	12.6	.0	> 242000 (RUNOUT)
28-D	12.6	.0	> 100000 (RUNOUT)
29-D	12.7	.0	11800
27-D	13.0	.0	2388
18-D	14.7	.0	756
21-D	14.7	.0	3359
17-D	14.7	.0	835
19-D	14.7	.0	6666
20-D	15.1	.0	55
23-D	15.5	.0	189
22-D	15.9	.0	198
8-D	16.7	.0	< 1 (FIRST CYCLE)
9-D	16.7	.0	< 1 (FIRST CYCLE)
23-E	16.8	.0	< 1 (FIRST CYCLE)
15-D	16.8	.0	1
12-D	16.8	.0	1232
41-D	16.8	.0	< 1 (FIRST CYCLE)
14-D	16.8	.0	1
13-D	16.8	.0	48
11-D	17.2	.0	313
16-D	17.2	.0	93
43-D	17.6	.0	67
42-D	17.7	.0	50
44-D	17.7	.0	15
10-D	17.7	.0	< 1 (FIRST CYCLE)
3-D	17.7	.0	< 1 (FIRST CYCLE)
6-D	18.1	.0	< 1 (FIRST CYCLE)
5-D	18.1	.0	< 1 (FIRST CYCLE)
7-D	18.4	.0	< 1 (FIRST CYCLE)
45-D	18.7	.0	< 1 (FIRST CYCLE)
4-D	19.0	.0	< 1 (FIRST CYCLE)

TABLE A-5
FATIGUE TESTS ON H-451 GRAPHITE

LOT NO: 408
ORIENTATION: AXIAL

LOG NO: 5651-90
LOCATION: QUARTER-LENGTH EDGE

STRESS RATIO, R (MIN. STRESS / MAX. STRESS): .5

SPECIMEN NO.	MAX. STRESS (MPA)	MIN. STRESS (MPA)	CYCLES TO FAILURE
4-E	10.0	5.0	> 139800 (RUNOUT)
5-E	10.0	5.0	> 293300 (RUNOUT)
32-E	14.1	7.1	> 100000 (RUNOUT)
34-E	14.1	7.1	> 119300 (RUNOUT)
30-E	14.1	7.1	> 101300 (RUNOUT)
28-E	14.1	7.1	> 103200 (RUNOUT)
46-C	14.1	7.1	> 220200 (RUNOUT)
35-E	14.1	7.1	> 305300 (RUNOUT)
48-C	14.1	7.1	> 116300 (RUNOUT)
36-E	14.1	7.1	> 109200 (RUNOUT)
47-C	14.1	7.1	> 104100 (RUNOUT)
29-E	14.3	7.1	382
43-A	14.9	7.5	> 104400 (RUNOUT)
15-E	15.0	8.3	< 1 (FIRST CYCLE)
45-A	15.0	7.5	725
46-A	15.0	7.5	4
47-A	15.0	7.5	2530
42-A	15.0	7.5	> 100000 (RUNOUT)
48-A	15.0	7.5	1759
44-A	15.0	7.5	455
46-E	15.8	8.7	< 1 (FIRST CYCLE)
22-E	16.6	8.3	56
12-E	16.6	8.3	> 248800 (RUNOUT)
27-E	16.6	8.3	4844
23-E	16.6	8.3	900
26-E	16.6	8.3	621
14-E	16.6	8.3	380
44-E	16.8	8.7	< 1 (FIRST CYCLE)
41-E	17.1	9.6	< 1 (FIRST CYCLE)
45-E	17.1	8.7	< 1 (FIRST CYCLE)
37-E	17.2	9.6	< 1 (FIRST CYCLE)
6-E	17.4	9.5	< 1 (FIRST CYCLE)
43-E	17.5	8.7	39
42-E	17.5	8.7	464
9-E	17.5	9.6	< 1 (FIRST CYCLE)
47-E	17.5	8.7	423
38-E	17.5	9.6	< 1 (FIRST CYCLE)
48-E	17.5	8.7	3
11-E	18.7	9.1	1367
8-E	19.1	9.5	94
7-E	19.1	9.6	175

TABLE A-6
FATIGUE TESTS ON H-451 GRAPHITE

LOT NO: 408
ORIENTATION: RADIAL

LOG NO: 5651-90
LOCATION: QUARTER-LENGTH EDGE

CONTROL TENSILE TESTS

SPECIMEN NO.	DENSITY (MG/M ³)	DIA. (MM)	FRACTURE LOAD (KN)	TENSILE STRENGTH (MPA)
101A	1.742	12.70	1.51	11.9
103A	1.743	12.70	1.88	14.8
105A	1.740	12.70	1.63	12.9
107A	1.749	12.70	1.58	12.5
109A	1.744	12.70	1.56	12.3
111A	1.746	12.70	1.50	11.8
113A	1.746	12.70	1.59	12.6
115A	1.741	12.70	1.55	12.2
117A	1.752	12.70	1.90	15.0
119A	1.744	12.70	1.80	14.2
121A	1.741	12.70	1.71	13.5
123A	1.753	12.71	1.69	13.3
125A	1.744	12.70	1.31	10.3
127A	1.747	12.69	1.47	11.6
129A	1.747	12.70	1.70	13.4
131A	1.736	12.63	1.89	15.1
133A	1.740	12.71	1.86	14.7
135A	1.738	12.70	1.43	11.3
137A	1.736	12.70	1.70	13.4
139A	1.739	12.65	1.82	14.5
141A	1.734	12.71	1.78	14.0
143A	1.738	12.70	1.77	14.0
145A	1.736	12.70	1.85	14.6
147A	1.739	12.70	1.48	11.7
149A	1.732	12.70	1.75	13.8
153A	1.736	12.71	2.46	19.4
155A	1.733	12.71	2.18	17.2
157A	1.789	12.70	2.53	20.0
159A	1.730	12.70	2.28	18.0
MEAN:	1.743		MEAN:	13.9 MPA (2021.PSI)
STD. DEV:	.011		STD. DEV:	2.3 MPA (335.PSI)

TABLE A-7
FATIGUE TESTS ON H-451 GRAPHITE

LOT NO: 408 LOG NO: 5651-90
ORIENTATION: RADIAL LOCATION: QUARTER-LENGTH EDGE

STRESS RATIO, R (MIN. STRESS / MAX. STRESS): -1.0

SPECIMEN NO.	DENSITY (MG/M ³)	MAX. STRESS (MPA)	MIN. STRESS (MPA)	CYCLES TO FAILURE
105B	1.738	8.6	-9.0	>110700 (RUNOUT)
143B	1.735	8.7	-8.7	>109000 (RUNOUT)
135B	1.736	8.8	-8.8	>107800 (RUNOUT)
120A	1.741	8.8	-8.7	>112100 (RUNOUT)
113B	1.750	8.8	-8.8	>102500 (RUNOUT)
158A	1.732	8.8	-8.8	>156000 (RUNOUT)
150A	1.739	8.8	-8.8	>167700 (RUNOUT)
128A	1.747	8.8	-9.0	>109100 (RUNOUT)
149B	1.739	10.3	-10.3	>100100 (RUNOUT)
141B	1.744	10.3	-10.5	>101900 (RUNOUT)
126A	1.749	10.3	-9.9	21800
119B	1.747	10.3	-10.6	600
156A	1.735	10.3	-10.7	>102400 (RUNOUT)
104A	1.736	10.3	-10.0	>101400 (RUNOUT)
111B	1.754	10.4	-10.5	225
134A	1.725	10.4	-10.4	>141700 (RUNOUT)
138A	1.740	10.7	-13.7	< 1 (FIRST CYCLE)
152A	1.733	11.2	-11.3	>107300 (RUNOUT)
144A	1.734	11.2	-11.2	>133900 (RUNOUT)
137B	1.733	11.2	-11.2	>109100 (RUNOUT)
102A	1.748	11.2	.0	< 1 (FIRST CYCLE)
159B	1.729	11.2	-11.2	87700
123B	1.754	11.8	-14.2	< 1 (FIRST CYCLE)
140A	1.734	11.9	-11.8	1000
147B	1.741	11.9	-11.8	43
117B	1.713	12.0	-11.6	18
125B	1.749	12.0	-12.0	137
110A	1.755	12.0	-12.0	456
155B	1.733	12.0	-12.0	>104400 (RUNOUT)
132A	1.734	12.1	-12.0	>107900 (RUNOUT)
107B	1.740	12.5	-12.9	3
131B	1.725	12.8	-13.9	< 1 (FIRST CYCLE)
114A	1.747	12.9	-12.9	5
122A	1.744	12.9	-12.9	17
129B	1.746	12.9	-12.9	57
101B	1.749	13.3	-13.3	3
116A	1.753	13.5	-13.5	< 1 (FIRST CYCLE)
146A	1.741	13.7	-14.0	1
153B	1.738	13.7	-13.7	3
108A	1.753	14.0	-14.0	7

TABLE A-8
FATIGUE TESTS ON H-451 GRAPHITE

LOT NO: 408

LOG NO: 5651-90

ORIENTATION: RADIAL

LOCATION: QUARTER-LENGTH EDGE

STRESS RATIO, R (MIN. STRESS / MAX. STRESS): -.5

SPECIMEN NO.	DENSITY (MG/CM ³)	MAX. STRESS (MPA)	MIN. STRESS (MPA)	CYCLES TO FAILURE
143C	1.734	8.7	-4.4	>118700 (RUNOUT)
152B	1.729	8.7	-4.4	>113500 (RUNOUT)
160A	1.734	8.7	-4.4	>100100 (RUNOUT)
134B	1.717	8.7	-4.4	>104000 (RUNOUT)
126B	1.741	8.7	-4.4	>106300 (RUNOUT)
116B	1.749	8.7	-4.4	>103600 (RUNOUT)
108B	1.742	8.7	-4.4	3900
158A	1.731	10.0	-5.2	>119300 (RUNOUT)
150B	1.731	10.0	-5.2	>105300 (RUNOUT)
142A	1.732	10.0	-5.2	>106400 (RUNOUT)
133B	1.743	10.0	-5.2	>103000 (RUNOUT)
115B	1.748	10.0	-5.5	36700
105A	1.737	10.0	-5.5	>109600 (RUNOUT)
124A	1.744	10.0	-6.1	2200
157B	1.731	11.3	-6.1	>112500 (RUNOUT)
104B	1.729	11.3	-5.8	16
113C	1.747	11.3	-5.8	205
122B	1.735	11.3	-6.1	131
148A	1.740	11.3	-5.8	>126300 (RUNOUT)
140B	1.741	11.3	-5.8	>109200 (RUNOUT)
131C	1.742	11.5	-5.9	>107600 (RUNOUT)
120B	1.750	12.4	-6.0	1221
112A	1.745	12.4	-6.1	321
155C	1.731	12.4	-6.0	15
103B	1.742	12.5	-6.1	19
138B	1.734	12.5	-5.9	760
146B	1.734	12.5	-6.0	1330
130A	1.744	12.5	-6.3	225
101C	1.744	12.9	.0	< 1 (FIRST CYCLE)
128B	1.739	13.4	.0	< 1 (FIRST CYCLE)
136A	1.727	13.4	-6.9	479
145B	1.725	13.7	-6.6	31
154A	1.734	13.7	-6.0	971
118A	1.743	13.7	-6.9	3
110B	1.743	13.7	.0	< 1 (FIRST CYCLE)

TABLE A-9
FATIGUE TESTS ON H-451 GRAPHITE

LOT NO: 408

LOG NO: 5651-90

ORIENTATION: RADIAL

LOCATION: QUARTER-LENGTH EDGE

STRESS RATIO, R (MIN. STRESS / MAX. STRESS): .0

SPECIMEN NO.	DENSITY (MG/CM ³)	MAX. STRESS (MPA)	MIN. STRESS (MPA)	CYCLES TO FAILURE
115C	1.744	8.6	.0	>11800 (RUNOUT)
144B	1.735	8.6	.0	>13500 (RUNOUT)
108C	1.737	8.6	.0	>127400 (RUNOUT)
136B	1.733	8.6	.0	>149200 (RUNOUT)
159C	1.734	8.6	.0	>100100 (RUNOUT)
151B	1.736	8.6	.0	>112800 (RUNOUT)
129C	1.745	8.6	.0	>162000 (RUNOUT)
124B	1.747	8.6	.0	>106000 (RUNOUT)
133C	1.747	9.9	.0	>115100 (RUNOUT)
114B	1.741	9.9	.0	>100000 (RUNOUT)
142B	1.735	9.9	.0	>100500 (RUNOUT)
106B	1.744	9.9	.0	>134900 (RUNOUT)
157C	1.734	9.9	.0	62800
150C	1.732	9.9	.0	>100900 (RUNOUT)
135C	1.739	9.9	.0	>100700 (RUNOUT)
127B	1.751	9.9	.0	21100
156B	1.729	11.2	.0	>122300 (RUNOUT)
148B	1.730	11.2	.0	>106300 (RUNOUT)
121B	1.748	11.2	.0	1244
141C	1.733	11.2	.0	1380
133C	1.732	11.2	.0	>101000 (RUNOUT)
105C	1.748	11.2	.0	4415
126C	1.745	11.2	.0	4218
147C	1.730	12.0	.0	< 1 (FIRST CYCLE)
117C	1.744	12.4	.0	< 1 (FIRST CYCLE)
111C	1.748	12.4	.0	1392
103C	1.750	12.5	.0	21
160B	1.736	12.5	.0	8113
154B	1.732	12.5	.0	49
120C	1.752	12.5	.0	94
132B	1.733	12.5	.0	8401
139B	1.724	12.5	.0	169
130B	1.750	12.9	.0	1
118B	1.748	12.9	.0	< 1 (FIRST CYCLE)
153C	1.736	12.9	.0	< 1 (FIRST CYCLE)
145C	1.729	13.7	.0	4162
102B	1.739	13.7	.0	3
109B	1.751	13.7	.0	5
138C	1.739	14.0	.0	2803

TABLE A-10
FATIGUE TESTS ON H-451 GRAPHITE

LOT NO: 498

LOT NO: 5651-90

ORIENTATION: RADIAL

LOCATION: QUARTER-LENGTH EDGE

STRESS RATIO, R (MIN. STRESS / MAX. STRESS): .5

SPECIMEN NO.	DENSITY (MG/CM ³)	MAX. STRESS (MPa)	MIN. STRESS (MPa)	CYCLES TO FAILURE
158C	1.734	11.2	5.2	>103100 (RUNOUT)
149C	1.733	11.2	5.2	>113000 (RUNOUT)
140C	1.762	11.2	5.2	>110500 (RUNOUT)
152	1.732	11.2	5.2	>118400 (RUNOUT)
116C	1.744	11.2	5.2	>117100 (RUNOUT)
107C	1.747	11.2	5.2	>126500 (RUNOUT)
132C	1.733	11.2	5.2	>106100 (RUNOUT)
125C	1.747	12.0	5.9	>103000 (RUNOUT)
118C	1.751	12.0	5.9	>116000 (RUNOUT)
109C	1.745	12.0	5.9	>100000 (RUNOUT)
134C	1.720	12.0	5.9	>167100 (RUNOUT)
151C	1.731	12.4	6.4	>110000 (RUNOUT)
160	1.725	12.5	6.4	12800
142C	1.733	12.5	6.4	>100300 (RUNOUT)
152D	1.734	12.5	6.0	>101000 (RUNOUT)
148C	1.745	12.5	6.0	>103400 (RUNOUT)
130C	1.739	12.5	5.8	1982
139C	1.725	12.5	6.0	>101000 (RUNOUT)
122C	1.739	12.6	5.9	98
128C	1.745	12.9	7.3	< 1 (FIRST CYCLE)
114C	1.753	12.9	6.4	195
106C	1.751	12.9	6.4	23
102C	1.747	13.1	7.3	4
119C	1.748	13.1	7.3	36
136C	1.737	13.5	7.1	9000
110C	1.743	13.5	7.3	882
144C	1.735	13.6	7.1	>100500 (RUNOUT)
121C	1.751	13.6	7.3	< 1 (FIRST CYCLE)
152C	1.735	13.6	7.1	>104300 (RUNOUT)
127C	1.746	13.7	7.3	29800
146C	1.731	13.8	7.3	6
104C	1.754	13.9	7.8	< 1 (FIRST CYCLE)
112C	1.745	14.0	7.7	< 1 (FIRST CYCLE)
154C	1.730	14.6	8.2	>109100 (RUNOUT)
137C	1.735	14.6	8.2	872

TABLE A-11
FATIGUE TESTS ON PGX GRAPHITE

LOT NO: --
ORIENTATION: AX

LOG NO: 6484-74
LOCATION: END-ONE THIRD RADIUS

CONTROL TENSILE TESTS

SPECIMEN NO.	DENSITY (MG/M**3)	DIA. (MM)	FRACTURE LOAD (KN)	TENSILE STRENGTH (MPA)
2A	1.739	12.71	.88	6.9
4B	1.768	12.70	1.01	7.9
6C	1.762	12.70	.96	7.5
10A	1.733	12.70	.96	7.5
12B	1.750	12.70	.90	7.1
14C	1.701	12.70	.93	7.3
18A	1.722	12.71	.98	7.7
20B	1.723	12.70	.93	7.3
22C	1.762	12.71	1.06	8.3
26A	1.759	12.71	.87	6.8
28B	1.763	12.71	1.01	7.9
30C	1.750	12.71	.90	7.1
34A	1.747	12.71	.98	7.7
36B	1.760	12.71	1.01	7.9
38C	1.766	12.71	1.01	7.9
42A	1.760	12.71	1.08	8.5
44B	1.761	12.71	1.03	8.1
46C	1.763	12.71	.96	7.5
50A	1.765	12.70	1.06	8.3
52B	1.761	12.71	1.01	7.9
54C	1.760	12.70	.90	7.1
58A	1.752	12.70	1.01	7.9
60B	1.938	12.70	.98	7.7
62C	1.762	12.70	.96	7.5
66A	1.754	12.70	1.01	7.9
68B	1.761	12.70	.93	7.3
70C	1.761	12.70	.98	7.7
74A	1.749	12.70	.96	7.5
76B	1.755	12.70	.93	7.3
78C	1.762	12.70	.96	7.5
82A	1.745	12.70	1.01	7.9
84B	1.747	12.70	1.01	7.9
86C	1.763	12.69	.88	7.0
90A	1.768	12.69	.85	6.8
MEAN:	1.759		MEAN:	7.6 MPA (1105.PSI)
STD. DEVI	.035		STD. DEVI	.4 MPA (63.PSI)

TABLE A-12
FATIGUE TESTS ON PGX GRAPHITE

LOT NO: --
ORIENTATION: AX

LOG NO: 6484-74
LOCATION: END-ONE THIRD RADIUS

STRESS RATIO, R (MIN. STRESS / MAX. STRESS): -1.0

SPECIMEN NO.	DENSITY (MG/M**3)	MAX. STRESS (MPA)	MIN. STRESS (MPA)	CYCLES TO FAILURE
34C	1.771	4.3	4.3	>121500 (RUNOUT)
46B	1.765	4.3	4.3	>119600 (RUNOUT)
28A	1.767	4.3	4.3	>100100 (RUNOUT)
18B	1.763	4.3	4.3	11000
8C	1.760	4.3	4.3	>104000 (RUNOUT)
60C	1.764	4.3	4.3	500
72B	1.765	4.3	4.3	>163590 (RUNOUT)
54A	1.757	4.3	4.3	>146900 (RUNOUT)
80A	1.768	4.3	4.3	>137800 (RUNOUT)
88C	1.776	4.3	4.3	>100500 (RUNOUT)
40B	1.761	5.4	5.4	16101
48A	1.759	5.4	5.4	1342
28C	1.760	5.4	5.4	1825
56C	1.767	5.4	5.4	55900
22A	1.778	5.4	5.4	859
14B	1.753	5.4	5.4	231
82C	1.765	5.4	5.4	16000
66B	1.767	5.4	5.4	>126800 (RUNOUT)
76A	1.769	5.4	5.4	2500
2C	1.758	5.6	5.6	474
34B	1.765	6.2	6.2	208
44A	1.766	6.3	6.3	605
24C	1.764	6.3	6.3	496
16A	1.757	6.3	6.3	23
8B	1.759	6.3	6.3	82
50C	1.775	6.3	6.3	2130
76C	1.773	6.3	6.3	646
70A	1.761	6.3	6.3	260
62B	1.760	6.3	6.3	418
88B	1.760	6.3	6.3	176
44C	1.759	6.9	6.9	17
38A	1.757	6.9	6.9	44
30B	1.768	6.9	6.9	113
18C	1.746	6.9	6.9	193
56B	1.757	6.9	6.9	16
2B	1.774	6.9	6.9	38
82B	1.768	6.9	6.9	79
12A	1.753	6.9	6.9	8
72C	1.766	6.9	6.9	36
64A	1.779	6.9	6.9	27
78B	1.759	7.4	.0	1 (FIRST CYCLE)
40C	1.761	7.8	.0	1
24B	1.768	7.8	7.8	18
12C	1.755	7.8	7.8	5

TABLE A-12 (Continued)

50B	1.768	7.8	.0	2
32A	1.765	7.8	7.8	8
6A	1.760	7.8	7.8	3
66C	1.763	7.8	7.8	12
60A	1.772	7.8	.0	1
98A	1.776	7.8	7.8	3

TABLE A-13
FATIGUE TESTS ON PGX GRAPHITE

LOT NO: --
ORIENTATION: AX

LOG NO: 6484-74
LOCATION: END-ONE THIRD RADIUS

STRESS RATIO, R (MIN. STRESS / MAX. STRESS): .0

SPECIMEN NO.	DENSITY (MG/M**3)	MAX. STRESS (MPA)	MIN. STRESS (MPA)	CYCLES TO FAILURE
42B	1.765	5.1	.0	>122800 (RUNOUT)
16B	1.761	5.1	.0	>108800 (RUNOUT)
24A	1.764	5.1	.0	>111000 (RUNOUT)
52A	1.764	5.1	.0	>114700 (RUNOUT)
32C	1.762	5.1	.0	>159240 (RUNOUT)
58C	1.764	5.1	.0	>114400 (RUNOUT)
4C	1.762	5.1	.0	>120300 (RUNOUT)
70B	1.762	5.1	.0	>104500 (RUNOUT)
84C	1.759	5.1	.0	>121900 (RUNOUT)
78A	1.764	5.1	.0	>104100 (RUNOUT)
38B	1.758	5.9	.0	2
26C	1.765	5.9	.0	643
46A	1.760	5.9	.0	>105800 (RUNOUT)
52C	1.763	5.9	.0	305
72A	1.763	5.9	.0	11000
10B	1.745	5.9	.0	822
80C	1.766	5.9	.0	>117100 (RUNOUT)
64B	1.767	5.9	.0	92
20A	1.762	5.9	.0	572
90B	1.769	5.9	.0	572
56A	1.763	5.9	.0	< 1 (FIRST CYCLE)
40A	1.768	6.3	.0	91000
48C	1.761	6.3	.0	656
32B	1.764	6.3	.0	12226
14A	1.756	6.3	.0	451
58B	1.764	6.3	.0	79
6B	1.759	6.3	.0	1998
68A	1.763	6.3	.0	415
86B	1.759	6.3	.0	977
74C	1.763	6.3	.0	642
20C	1.758	6.3	.0	15672
22B	1.759	6.3	.0	< 1 (FIRST CYCLE)
80B	1.764	6.7	.0	11
68C	1.771	6.7	.0	49
88A	1.767	6.7	.0	85
36A	1.755	6.7	.0	4
42C	1.757	6.7	.0	2
26B	1.764	6.7	.0	6
16C	1.755	6.7	.0	< 1 (FIRST CYCLE)
8A	1.748	6.7	.0	< 1 (FIRST CYCLE)
54B	1.766	6.7	.0	25
62A	1.764	6.7	.0	129
30A	1.765	6.9	.0	< 1 (FIRST CYCLE)
48B	1.768	7.1	.0	< 1 (FIRST CYCLE)

TABLE A-13 (Continued)

36C	1.765	7.1	.0	<	1 (FIRST CYCLE)
10C	1.749	7.1	.0	<	1 (FIRST CYCLE)
64C	1.765	7.5	.0		15
4A	1.764	7.9	.0	<	1 (FIRST CYCLE)

TABLE A-14
FATIGUE TESTS ON PGX GRAPHITE

LOT NO: --

LOG NO: 6484-74

ORIENTATION: RADIAL

LOCATION: END-ONE THIRD RADIUS

CONTROL TENSILE TESTS

SPECIMEN NO.	DENSITY (MG/M**3)	DIA. (MM)	FRACTURE LOAD (KN)	TENSILE STRENGTH (MPA)
1A	1.760	12.69	1.21	9.6
3R	1.765	12.69	1.29	10.2
5C	1.762	12.70	1.37	10.8
7D	1.760	12.70	1.34	10.6
9A	1.761	12.70	1.26	10.0
11R	1.768	12.71	1.26	9.9
13C	1.763	12.71	1.16	9.1
15D	1.754	12.70	1.29	10.2
17A	1.761	12.70	1.21	9.5
19R	1.754	12.70	1.26	10.0
21C	1.756	12.70	1.31	10.4
23D	1.765	12.70	1.26	10.0
25A	1.745	12.70	1.05	8.3
27R	1.762	12.70	1.31	10.4
29C	1.756	12.70	1.21	9.5
31D	1.769	12.70	.79	6.2
33A	1.759	12.70	1.16	9.1
35R	1.762	12.70	1.24	9.8
37C	1.757	12.70	1.18	9.3
39D	1.770	12.70	1.00	7.9
41A	1.761	12.70	1.31	10.4
43R	1.762	12.70	1.34	10.6
45C	1.764	12.70	1.00	7.9
47D	1.757	12.70	1.31	10.4
49A	1.756	12.70	1.16	9.1
51R	1.772	12.68	1.18	9.4
53C	1.763	12.68	1.26	10.0
55D	1.760	12.68	1.31	10.4
57A	1.763	12.70	1.24	9.7
59R	1.758	12.70	1.16	9.1
61C	1.755	12.71	1.16	9.1
63D	1.769	12.68	1.10	8.7
65A	1.757	12.70	1.03	8.1
67R	1.770	12.68	1.21	9.6
69C	1.762	12.68	1.10	8.7
MEAN:	1.761		MEAN:	9.5 MPA (1376.PSI)
STD. DEV:	.006		STD. DEV:	1.0 MPA (139.PSI)

TABLE A-15
FATIGUE TESTS ON PGX GRAPHITE

LOT NO: --
ORIENTATION: RADIAL

LOG NO: 6484-74
LOCATION: END-ONE THIRD RADIUS

STRESS RATIO, R (MIN. STRESS / MAX. STRESS): -1.0

SPECIMEN NO.	DENSITY (MG/M**3)	MAX. STRESS (MPA)	MIN. STRESS (MPA)	CYCLES TO FAILURE
9C	1.759	5.6	-5.6	>143100 (RUNOUT)
57D	1.758	5.6	-5.6	>114200 (RUNOUT)
47A	1.761	5.6	-5.6	>106200 (RUNOUT)
41B	1.760	5.6	-5.6	>110300 (RUNOUT)
35C	1.767	5.6	-5.6	>109500 (RUNOUT)
29D	1.758	5.6	-5.6	>106600 (RUNOUT)
15B	1.757	5.6	-5.6	>123600 (RUNOUT)
21A	1.760	5.6	-5.6	>107500 (RUNOUT)
3D	1.764	5.6	-5.6	>155800 (RUNOUT)
63C	1.773	5.6	-5.6	>105400 (RUNOUT)
9B	1.763	6.8	-6.8	1300
57C	1.750	6.8	-6.8	27800
43A	1.768	6.8	-6.8	>127300 (RUNOUT)
25D	1.761	6.8	-6.8	>132200 (RUNOUT)
15A	1.764	6.8	-6.8	>100200 (RUNOUT)
37B	1.758	6.8	-6.8	2100
31C	1.766	6.8	-6.8	4000
3C	1.768	6.8	-6.8	>105800 (RUNOUT)
63B	1.770	6.8	-6.8	350
51D	1.772	6.8	-6.8	6700
11A	1.766	8.0	-8.0	32
57B	1.760	8.0	-8.0	4300
25C	1.762	8.0	-8.0	2987
37A	1.765	8.0	-8.0	6516
31B	1.764	8.0	-8.0	764
5B	1.768	8.0	-8.0	86
45D	1.757	8.0	-8.0	1052
19D	1.766	8.0	-8.0	1362
63A	1.764	8.1	-8.1	346
51C	1.772	8.1	-8.1	764
59A	1.758	8.8	-8.8	4
13D	1.765	8.8	-8.8	< 1 (FIRST CYCLE)
5A	1.758	8.8	-8.8	110
47C	1.754	8.8	-8.8	78
25B	1.761	8.8	-8.8	331
41D	1.759	8.8	-8.8	52
31A	1.767	8.8	-8.8	10
19C	1.761	8.8	-8.8	< 1 (FIRST CYCLE)
67D	1.767	8.9	-8.9	101
53B	1.771	8.9	-8.9	42

TABLE A-16
FATIGUE TESTS ON PGX GRAPHITE

LOT NO: -- LOG NO: 6484-74
ORIENTATION: RADIAL LOCATION: END-ONE THIRD RADIUS

STRESS RATIO, R (MIN. STRESS / MAX. STRESS): .0

SPECIMEN NO.	DENSITY (MG/M**3)	MAX. STRESS (MPA)	MIN. STRESS (MPA)	CYCLES TO FAILURE
13B	1.765	6.6	.0	>141200 (RUNOUT)
7C	1.759	6.6	.0	>123100 (RUNOUT)
59C	1.761	6.6	.0	>182700 (RUNOUT)
27D	1.756	6.6	.0	>145100 (RUNOUT)
45A	1.760	6.6	.0	>163300 (RUNOUT)
39B	1.760	6.6	.0	>121200 (RUNOUT)
33C	1.758	6.6	.0	>100400 (RUNOUT)
19A	1.756	6.6	.0	>135400 (RUNOUT)
1D	1.769	6.7	.0	>100400 (RUNOUT)
53D	1.770	6.7	.0	>118300 (RUNOUT)
13A	1.760	7.5	.0	3800
61B	1.761	7.5	.0	>102000 (RUNOUT)
7B	1.762	7.5	.0	>302700 (RUNOUT)
21D	1.763	7.5	.0	>337800 (RUNOUT)
27C	1.757	7.5	.0	>118500 (RUNOUT)
49D	1.757	7.5	.0	>101900 (RUNOUT)
39A	1.758	7.5	.0	>118300 (RUNOUT)
33B	1.770	7.5	.0	>109800 (RUNOUT)
1C	1.770	7.5	.0	>135600 (RUNOUT)
55C	1.767	7.5	.0	11600
7A	1.752	8.7	.0	170
61A	1.755	8.7	.0	746
17D	1.760	8.7	.0	29
35A	1.753	8.7	.0	1748
43D	1.758	8.7	.0	69
23C	1.764	8.7	.0	3
29B	1.761	8.7	.0	168
49C	1.754	8.7	.0	286
1B	1.762	8.7	.0	1165
55B	1.774	8.7	.0	48
65D	1.766	9.1	.0	2
29A	1.766	9.1	.0	< 1 (FIRST CYCLE)
3A	1.765	9.1	.0	< 1 (FIRST CYCLE)
11D	1.763	9.5	.0	1
17C	1.761	9.5	.0	75
23B	1.764	9.5	.0	27
43C	1.758	9.5	.0	9
37D	1.758	9.5	.0	36
49B	1.760	9.5	.0	29
55A	1.768	9.6	.0	3

TABLE A-17

CAPSULE IRRADIATION OG-1

FATIGUE TESTS ON H-451 GRAPHITE

LOT NO: 266

LOG NO: 5651-28

ORIENTATION: AXIAL

LOCATION: MIDLENGTH-CENTER

CONTROL TENSILE TESTS

SPECIMEN NO.	DENSITY (MG/M**3)	DIA. (MM)	FRACTURE LOAD (KN)	TENSILE STRENGTH (MPA)
F-22A	.000	5.08	.24	11.9
F-24A	.000	5.07	.25	12.1
F-26A	.000	5.08	.35	17.3
F-28A	.000	5.08	.32	15.9
F-30A	.000	5.07	.27	13.2
F-32A	.000	5.08	.32	15.9
F-34A	.000	5.07	.27	13.2
F-36A	.000	5.08	.28	13.8
F-38A	.000	5.07	.36	18.0
F-40A	.000	5.07	.28	13.9
MEAN:	.000		MEAN:	14.5 MPA (2105.PSI)
STD. DEV: ****			STD. DEV:	2.1 MPA (308.PSI)

TABLE A-18

CAPSULE IRRADIATION OG-1

FATIGUE TESTS ON H-451 GRAPHITE

LOT NO: 266

LOG NO: 5651-28

ORIENTATION: AXIAL

LOCATION: MIDLENGTH-CENTER

STRESS RATIO, R (MIN. STRESS / MAX. STRESS): -1.0

SPECIMEN NO.	DENSITY (MG/M ³)	MAX. STRESS (MPA)	MIN. STRESS (MPA)	CYCLES TO FAILURE
F-37A	.000	11.4	-11.7	>105700 (RUNOUT)
F-31A	.000	11.5	-11.5	8
F-25A	.000	11.5	-11.5	>102100 (RUNOUT)
F-27B	.000	11.6	-12.1	>104500 (RUNOUT)
F-34B	.000	11.7	-11.4	>100300 (RUNOUT)
F-28B	.000	11.7	-11.4	>112800 (RUNOUT)
F-40B	.000	11.8	-11.8	>102100 (RUNOUT)
F-23B	.000	11.8	-12.4	>111000 (RUNOUT)
F-39A	.000	12.2	-13.4	116
F-24B	.000	12.2	-12.2	56
F-42B	.000	12.6	-11.5	>305100 (RUNOUT)
F-22B	.000	12.6	-12.4	1845
F-33A	.000	12.7	-12.7	230
F-30B	.000	12.8	-12.6	2551
F-27A	.000	12.9	-11.6	>100100 (RUNOUT)
F-39B	.000	13.0	.0	< 1 (FIRST CYCLE)
F-36B	.000	13.2	-12.1	>110200 (RUNOUT)
F-29A	.000	13.8	-14.5	< 1 (FIRST CYCLE)
F-41A	.000	14.1	-13.4	< 1 (FIRST CYCLE)
F-32B	.000	14.5	-14.5	315
F-23A	.000	14.6	-14.6	657
F-35A	.000	14.7	-14.7	19713
F-38A	.000	14.7	-14.0	246
F-31B	.000	14.7	-11.5	210
F-33B	.000	14.7	-11.4	2
F-42A	.000	14.7	-13.4	175
F-37B	.000	14.8	-11.6	9
F-41B	.000	14.8	-11.7	39
F-35B	.000	14.9	-11.9	182
F-29B	.000	14.9	-11.9	2
F-25B	.000	14.9	-11.9	159
F-26B	.000	15.2	-14.5	< 1 (FIRST CYCLE)

TABLE A-19
CAPSULE IRRADIATIONS OG-1 AND OG-2

FATIGUE TESTS ON H-451 GRAPHITE

LOT NO: 266

LOG NO: 5651-28

ORIENTATION: RADIAL

LOCATION: MIDLENGTH-CENTER

CONTROL TENSILE TESTS

SPECIMEN NO.	DENSITY (MG/M**3)	DIA. (MM)	FRACTURE LOAD (KN)	TENSILE STRENGTH (MPA)
F-51A	.000	4.99	.43	22.2
F-53A	.000	4.99	.43	22.2
F-55A	.000	5.00	.50	25.4
F-57A	.000	5.01	.46	23.4
F-59A	.000	4.96	.41	21.1
F-61A	.000	5.01	.50	25.3
F-63A	.000	5.00	.42	21.5
F-65A	.000	5.04	.47	23.8
F-67A	.000	5.00	.45	22.8
F-69A	.000	5.03	.33	16.4
MEAN:	.000		MEAN:	22.4 MPA (3249.PSI)
STD. DEV: ****			STD. DEV:	2.6 MPA (373.PSI)

TABLE A-18

CAPSULE IRRADIATION OG-1

FATIGUE TESTS ON H-451 GRAPHITE

LOT NO: 266

LOG NO: 5651-28

ORIENTATION: AXIAL

LOCATION: MIDLENGTH-CENTER

STRESS RATIO, R (MIN. STRESS / MAX. STRESS): -1.0

SPECIMEN NO.	DENSITY (MG/M ³)	MAX. STRESS (MPA)	MIN. STRESS (MPA)	CYCLES TO FAILURE
F-37A	.000	11.4	-11.7	>105700 (RUNOUT)
F-31A	.000	11.5	-11.5	8
F-25A	.000	11.5	-11.5	>102100 (RUNOUT)
F-27R	.000	11.6	-12.1	>104500 (RUNOUT)
F-34R	.000	11.7	-11.4	>100300 (RUNOUT)
F-28R	.000	11.7	-11.4	>112800 (RUNOUT)
F-40R	.000	11.8	-11.8	>102100 (RUNOUT)
F-23R	.000	11.8	-12.4	>111000 (RUNOUT)
F-39A	.000	12.2	-13.4	116
F-24R	.000	12.2	-12.2	56
F-42R	.000	12.6	-11.5	>305100 (RUNOUT)
F-22R	.000	12.6	-12.4	1845
F-33A	.000	12.7	-12.7	230
F-30R	.000	12.8	-12.6	2551
F-27A	.000	12.9	-11.6	>100100 (RUNOUT)
F-39R	.000	13.0	.0	< 1 (FIRST CYCLE)
F-36R	.000	13.2	-12.1	>110200 (RUNOUT)
F-29A	.000	13.8	-14.5	< 1 (FIRST CYCLE)
F-41A	.000	14.1	-13.4	< 1 (FIRST CYCLE)
F-32R	.000	14.5	-14.5	315
F-23A	.000	14.6	-14.6	657
F-35A	.000	14.7	-14.7	19713
F-38A	.000	14.7	-14.0	246
F-31R	.000	14.7	-11.5	210
F-33R	.000	14.7	-11.4	2
F-42A	.000	14.7	-13.4	175
F-37R	.000	14.8	-11.6	9
F-41R	.000	14.8	-11.7	39
F-35R	.000	14.9	-11.9	182
F-29R	.000	14.9	-11.9	2
F-25R	.000	14.9	-11.9	159
F-26R	.000	15.2	-14.5	< 1 (FIRST CYCLE)

TABLE A-19
CAPSULE IRRADIATIONS OG-1 AND OG-2

FATIGUE TESTS ON H-451 GRAPHITE

LOT NO: 266

LOG NO: 5651-28

ORIENTATION: RADIAL

LOCATION: MIDLENGTH-CENTER

CONTROL TENSILE TESTS

SPECIMEN NO.	DENSITY (MG/M**3)	DIA. (MM)	FRACTURE LOAD (KN)	TENSILE STRENGTH (MPA)
F-51A	.000	4.99	.43	22.2
F-53A	.000	4.99	.43	22.2
F-55A	.000	5.00	.50	25.4
F-57A	.000	5.01	.46	23.4
F-59A	.000	4.96	.41	21.1
F-61A	.000	5.01	.50	25.3
F-63A	.000	5.00	.42	21.5
F-65A	.000	5.04	.47	23.8
F-67A	.000	5.00	.45	22.8
F-69A	.000	5.03	.33	16.4
MEAN:	.000		MEAN:	22.4 MPA (3249.PSI)
STD. DEV: ****			STD. DEV:	2.6 MPA (373.PSI)

TABLE A-20
CAPSULE IRRADIATIONS OG-1 AND OG-2

FATIGUE TESTS ON H-451 GRAPHITE

LOT NO: 266
ORIENTATION: RADIAL

LOG NO: 5651-28
LOCATION: MIDLENGTH-CENTER

STRESS RATIO, R (MIN. STRESS / MAX. STRESS): -1.0

SPECIMEN NO.	DENSITY (MG/M ³)	MAX. STRESS (MPA)	MIN. STRESS (MPA)	CYCLES TO FAILURE
F-54B	.000	14.3	-13.6	>118200 (RUNOUT)
F-60B	.000	14.5	-12.8	>121800 (RUNOUT)
F-58B	.000	14.7	-13.3	>110000 (RUNOUT)
F-62B	.000	14.8	-12.7	>112300 (RUNOUT)
F-69B	.000	16.2	-17.2	9500
F-68B	.000	16.3	-15.7	9350
F-63B	.000	16.6	-17.5	29
F-56B	.000	16.6	-17.3	1400
F-66A	.000	17.0	-17.0	19
F-66B	.000	17.4	-18.4	> 21000 (RUNOUT)
F-54A	.000	18.5	-17.9	359
F-64B	.000	18.6	-17.9	180
F-60A	.000	18.6	-18.6	32
F-57B	.000	18.7	-19.3	378
F-65B	.000	19.0	-22.4	< 1 (FIRST CYCLE)
F-52B	.000	19.5	-18.8	121
F-51B	.000	20.2	-20.8	6
F-68A	.000	20.6	-21.6	10
F-62A	.000	20.6	-21.3	364
F-56A	.000	20.8	-21.5	290
F-71A	.000	20.8	-21.5	< 1 (FIRST CYCLE)
F-59B	.000	20.9	-23.0	739
F-55B	.000	21.4	-22.1	< 1 (FIRST CYCLE)
F-67B	.000	22.1	-20.7	11
F-52A	.000	22.1	-22.8	< 1 (FIRST CYCLE)
F-53A	.000	22.6	-21.2	12
F-61B	.000	22.7	-21.3	7
F-64A	.000	22.8	-21.4	< 1 (FIRST CYCLE)
F-70A	.000	22.8	-21.4	92

TABLE A-21
CAPSULE (RRADIATIONS OG-1, 2 AND 3)

FATIGUE TESTS ON H-451 GRAPHITE

LOT NO: 266

LOG NO: 5651-28

ORIENTATION: AXIAL

LOCATION: MIDLENGTH-CENTER

CONTROL TENSILE TESTS

SPECIMEN NO.	DENSITY (MG/M ³)	DIA. (MM)	FRACTURE LOAD (KN)	TENSILE STRENGTH (MPA)
F-01A	.000	5.08	.37	18.4
F-03A	.000	5.06	.44	21.8
F-05A	.000	5.07	.37	18.5
F-07A	.000	5.07	.43	21.3
F-09A	.000	5.08	.46	22.6
F-11A	.000	5.08	.46	22.8
F-13A	.000	5.08	.42	20.8
F-15A	.000	5.08	.35	17.4
F-17A	.000	5.06	.37	18.4
F-19A	.000	5.03	.41	20.4
MEAN:	.000		MEAN:	20.2 MPA (2935.PSI)
STD. DEV: ****			STD. DEV:	1.9 MPA (281.PSI)

TABLE A-22
CAPSULE IRRADIATIONS OG-1, 2 AND 3

FATIGUE TESTS ON H-451 GRAPHITE

LOT NO: 266
ORIENTATION: AXIAL

LOG NO: 5651-28
LOCATION: MIDLENGTH-CENTER

STRESS RATIO, R (MIN. STRESS / MAX. STRESS): -1.0

SPECIMEN NO.	DENSITY (MG/M**3)	MAX. STRESS (MPA)	MIN. STRESS (MPA)	CYCLES TO FAILURE
F-03B	.000	13.5	-18.4	< 1 (FIRST CYCLE)
F-12B	.000	14.0	-14.4	89
F-04B	.000	14.1	-14.2	>101100 (RUNOUT)
F-18B	.000	14.1	-14.2	>103100 (RUNOUT)
F-10B	.000	14.1	-14.1	>106200 (RUNOUT)
F-20B	.000	14.1	-13.7	>115200 (RUNOUT)
F-16B	.000	14.4	-14.6	58
F-09B	.000	15.5	-20.1	< 1 (FIRST CYCLE)
F-06B	.000	16.0	-16.7	>113300 (RUNOUT)
F-04A	.000	16.1	-15.4	>102000 (RUNOUT)
F-02B	.000	16.1	-16.2	>106600 (RUNOUT)
F-10A	.000	16.1	-16.2	>113900 (RUNOUT)
F-13B	.000	16.1	-16.8	36
F-16A	.000	16.3	-17.2	>123000 (RUNOUT)
F-19B	.000	16.4	-17.2	200
F-06A	.000	17.9	-17.9	5928
F-15B	.000	18.1	-18.1	>109500 (RUNOUT)
F-12A	.000	18.1	-18.7	587
F-18A	.000	18.1	-18.1	24
F-01B	.000	18.2	-17.9	8
F-21B	.000	18.4	-17.9	35
F-02A	.000	18.7	-20.8	< 1 (FIRST CYCLE)
F-08A	.000	19.2	-20.1	< 1 (FIRST CYCLE)
F-11B	.000	19.4	-19.9	5
F-20A	.000	19.5	-20.1	75
F-17B	.000	19.5	-19.4	< 1 (FIRST CYCLE)
F-14A	.000	20.1	-19.4	2
F-21A	.000	20.1	-22.1	257
F-05B	.000	20.2	-20.2	76

Fig. A-5. Fatigue test data on H-451 graphite, axial orientation, quarter-length edge location, in air at ambient temperature. Log-log plot of normalized maximum stress versus number of cycles to failure with $R = -1$. Lower x/y tolerance limits represent the limits above which at least x% of all data would fall, with y% confidence.

Fig. A-6. Fatigue test data on H-451 graphite, axial orientation, quarter-length edge location, in air at ambient temperature. Log-log plot of normalized maximum stress versus number of cycles to failure with $R = -0.5$. Lower x/y tolerance limits represent the limits above which at least x% of all data would fall, with y% confidence.

Fig. A-7. Fatigue test data on H-451 graphite, axial orientation, quarter-length edge location, in air at ambient temperature. Log-log plot of normalized maximum stress versus number of cycles to failure with $R = 0$. Lower x/y tolerance limits represent the limits above which at least x% of all data would fall, with y% confidence.

Fig. A-8. Fatigue test data on H-451 graphite, axial orientation, quarter-length edge location, in air at ambient temperature. Log-log plot of normalized maximum stress versus number of cycles to failure with $R = 0.5$. Lower x/y tolerance limits represent the limits above which at least x% of all data would fall, with y% confidence.

Fig. A-9. Fatigue test data on H-451 graphite, radial orientation, quarter-length edge location, in air at ambient temperature. Log-log plot of normalized maximum stress versus number of cycles to failure with $R = -1$. Lower x/y tolerance limits represent the limits above which at least x% of all data would fall, with y% confidence.

Fig. A-10. Fatigue test data on H-451 graphite, radial orientation, quarter-length edge location, in air at ambient temperature. Log-log plot of normalized maximum stress versus number of cycles to failure with $R = -0.5$. Lower x/y tolerance limits represent the limits above which at least x% of all data would fall, with y% confidence.

Fig. A-11. Fatigue test data on H-451 graphite, radial orientation, quarter-length edge location, in air at ambient temperature. Log-log plot of normalized maximum stress versus number of cycles to failure with $R = 0$. Lower x/y tolerance limits represent the limits above which at least x% of all data would fall, with y% confidence.

Fig. A-12. Fatigue test data on H-451 graphite, radial orientation, quarter-length edge location, in air at ambient temperature. Log-log plot of normalized maximum stress versus number of cycles to failure with $R = 0.5$. Lower x/y tolerance limits represent the limits above which at least x% of all data would fall, with y% confidence.

Fig. A-13. Fatigue test data for PGX graphite, axial orientation, end - one-third radius location, in air at ambient temperature. Log-log plot of normalized maximum stress versus number of cycles to failure with stress ratio $R = -1$. Lower x/y tolerance limits represent the limits above which at least x% of all points would fall, with y% confidence. Open circles represent run-outs.

Fig. A-14. Fatigue test data for PGX graphite, axial orientation, end - one-third radius location, in air at ambient temperature. Log-log plot of normalized maximum stress versus number of cycles to failure with stress ratio $R = 0$. Lower s/y tolerance limits represent the limits above which at least x% of all points would fall, with y% confidence. Open circles represent run-outs.

Fig. A-15. Fatigue test data for PGX graphite, radial orientation, end - one-third radius location, in air at ambient temperature. Log-log plot of normalized maximum stress versus number of cycles to failure with stress ratio $R = -1$. Lower x/y tolerance limits represent the limits above which at least x% of all points would fall, with y% confidence. Open circles represent run-outs.

Fig. A-16. Fatigue test data for PGX graphite, radial orientation, end - one-third radius location, in air at ambient temperature. Log-log plot of normalized maximum stress versus number of cycles to failure with stress ratio $R = 0$. Lower x/y tolerance limits represent the limits above which at least x% of all points would fall, with y% confidence. Open circles represent run-outs.

Fig. A-17. Ambient temperature fatigue test data for H-451 graphite, axial orientation, irradiated to $3.8 \times 10^{25} \text{ n/m}^2$ (equivalent fission fluence) at 1173 K (900°C). Log-log plot of normalized peak stress versus number of cycles to failure, with stress ratio, $R = -1$. Lower x/y tolerance limits represent the limits above which x% of all observations would fall, with y% confidence. Open circles represent run-outs.

Fig. A-18. Ambient temperature fatigue test data for H-451 graphite, radial orientation, irradiated to $5.7 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 1223 to 1263 K (950° to 990°C). Log-log plot of normalized peak stress versus number of cycles to failure, with stress ratio, $R = -1$. Lower x/y tolerance limits represent the limits above which x% of all observations would fall, with y% confidence. Open circles represent run-outs.

Fig. A-19. Ambient temperature fatigue test data for H-451 graphite, axial orientation, irradiated to $8.5 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR} at 1223 to 1263 K (950° to 990°C). Log-log plot of normalized peak stress versus the number of cycles to failure, with stress ratio, $R = -1$. Lower x/y tolerance limits represent the limits above which x% of all observations would fall, with y% confidence. Open circles represent run-outs.

Fig. A-20. Constant life fatigue diagram (Goodman diagram) for H-451 graphite, axial orientation, tested in air at ambient temperature

Fig. A-21. Constant life fatigue diagram (Goodman diagram) for H-451 graphite, radial orientation, tested in air at ambient temperature

Fig. A-22. Constant life fatigue diagram (Goodman diagram) for PGX graphite, axial orientation, tested in air at ambient temperature

Fig. A-23. Constant life fatigue diagram (Goodman diagram) for PGX graphite, radial orientation, tested in air at ambient temperature