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O.E.C.D. HIGH TEMPERATURE REACTOR PROJECT

DRAGON

**Dragon Project Report**

# A HIGH TEMPERATURE GRAPHITE IRRADIATION CREEP EXPERIMENT IN THE DRAGON REACTOR

by


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MAY 1971


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## ABSTRACT

The irradiation induced creep of pressed Gilsocarbon graphite under constant tensile stress has been investigated in an experiment carried out in FE 317 of the OECD High Temperature Gas Cooled Reactor "Dragon" at Winfrith (England). The experiment covered a temperature range of 850°C to 1240°C and reached a maximum fast neutron dose of $1.19 \times 10^{21}$ n $cm^{-2}$ NDE (Nickel Dose DIDO Equivalent). Irradiation induced dimensional changes of a string of unrestrained graphite specimens are compared with the dimensional changes of three strings of restrained graphite specimens stressed to 40%, 58% and 70% of the initial ultimate tensile strength of pressed Gilsocarbon graphite. Total creep strains ranging from 0.18% to 1.25% have been measured and a linear dependence of creep strain on applied stress was observed. Mechanical property measurements carried out before and after irradiation demonstrate that Gilsocarbon graphite can accommodate significant creep strains without failure or structural deterioration. Total creep strains are in excellent agreement with other data, however the results indicate a relatively large temperature dependent primary creep component which at 1200°C approaches a value which is three times larger than the normally assumed initial elastic strain. Secondary creep constants derived from the experiment show a temperature dependence and are in fair agreement with data reported elsewhere. A possible interpretation of the results is given.

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A HIGH TEMPERATURE GRAPHITE IRRADIATION CREEP

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## 1. INTRODUCTION

Irradiation induced plasticity in graphite is a technologically important phenomenon for the design of High Temperature Gas Cooled Reactors since it provides a mechanism for the relief of stresses generated in the graphite structure during reactor operation. These stresses arise from differential dimensional changes caused by flux and temperature gradients within the graphite core. The creep behaviour of graphite under fast neutron irradiation has been studied by several experimenters [1-10] over a wide range of irradiation conditions. Most of these experiments were carried out using the restrained shrinkage method [1-6] first described by Losty et al., [1].

The work presented in this paper studies the creep behaviour of pressed Gilsocarbon graphite irradiated under constant tensile stress over a temperature range of 850°C to 1240°C. The experiment was conducted in FE 317 of the OECD High Temperature Reactor "Dragon" at Winfrith (England) [11] for 198 full power days resulting in a maximum fast neutron dose of $1.19 \times 10^{21}$ n $cm^{-2}$ NDE (Nickel Dido Equivalent) as shown in Fig. 1.

## 2. EXPERIMENTAL

Graphite creep assemblies were irradiated in a Dragon fuel element of the Metallurgical III Series. The experiment essentially consisted of three strings of twelve tensile type specimens (dumb-bells, see Fig. 2) each manufactured from the pressed Gilsocarbon graphite No. 95 [12]. The twelve graphite specimens were connected together by threaded end portions and positioned within the 22.987 mm internal diameter of the annular fuel compacts in the centre of a fuel rod [13]. The upper end of the string of specimens was screwed into a modified upper end plug of the fuel rod. The lower end of the specimens was attached to a stainless steel bellows. To minimise the neutron dose and temperature to which the bellows was subjected it was located by a nut in the specially bored out lower reflector end piece of the fuel tube. A simple electrical contact in the base of the fuel rods below the bellows provided a means by which failure of specimens or bellows could be detected under reactor operation. A fourth string of unrestrained tensile type specimens made from the pressed Gilsocarbon graphite No. 95 and an anisotropic fine grain material G5 [12] was irradiated as a series of control specimens in the same fuel element.

### 2.1 Graphite Specimens

All graphite specimens were cut from a block of pressed Gilsocarbon graphite (production quality) axially with respect to the axis of pressing. Length measurements between the shoulders of a specimen were made at room temperature before and after irradiation. The specimens were rotated in a transducer comparator jig and the maximum and minimum deviation from an Invar Standard were measured to an accuracy of ±0.0005 in. The results are recorded in Table 1. Initial physical and mechanical properties were

Table 1

Dimensional and Property Changes of Restrained and Unrestrained Gilsocarbon Graphite No. 95

| | Specimen Number | Length of Specimens in Units of 0.001 in on the Standard Length: Pre-Irradiation | | | Post-Irradiation | | | Difference in Gauge Readings (0.001 in) | Gauge Difference Plus Correction for Standards (0.001 in) | Length Change % | Young's Modulus ($10^4$ Kp cm$^{-2}$) Irradiation Pre- | Post- | Electrical Resistivity (m Ω cm) Irradiation Pre- | Post- | Ultimate Tensile Strength (Kp cm$^{-2}$) Irradiation Pre- | Post- |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| STRESSED | A1 | -2.7 | | -2.4 | + 4.5 | B | + 6.2 | + 7.90 | + 7.90 | +0.20 | | 11.3 | | 1.66 | | 218 |
| | A2 | +1.3 | | +1.6 | -13.0 | 2 | -12.3 | -14.10 | +14.90 | +0.37 | | 9.4 | | 1.89 | | |
| | A3 | -1.4 | | -1.0 | -12.0 | 2 | -11.5 | -10.55 | +18.40 | +0.46 | | 8.7 | | 1.93 | | |
| | A4 | -2.0 | | -1.8 | + 8.5 | B | + 9.3 | +10.80 | +10.80 | +0.27 | | 8.7 | | 1.81 | | |
| | A5 | -2.2 | | -1.9 | + 1.2 | B | + 1.7 | + 3.45 | + 3.45 | +0.09 | | 8.7 | | 1.81 | | |
| | A6 | -1.7 | B | -1.1 | - 9.3 | B | - 8.6 | - 7.55 | - 7.55 | -0.19 | 7.9 ± 0.64 | 9.4 | 1.00 ± 0.04 | 1.58 | 152 ± 13.1 | |
| | A7 | -1.6 | | -1.0 | - 7.1 | B | - 6.0 | - 5.25 | - 5.25 | -0.13 | | 8.7 | | 1.70 | | 162 |
| | A8 | -1.6 | | -1.1 | - 9.8 | B | - 9.3 | - 8.20 | - 8.20 | -0.20 | | 9.4 | | 1.58 | | |
| | A9 | -2.2 | | -1.7 | - 8.3 | B | - 6.9 | - 5.65 | - 5.65 | -0.14 | | 9.4 | | 1.54 | | |
| | A10 | -2.0 | | -0.7 | - 0.3 | B | + 1.0 | + 1.70 | + 1.70 | +0.04 | | 9.4 | | 1.58 | | |
| | A11 | -1.6 | | -1.0 | + 5.7 | B | + 6.4 | + 7.65 | + 7.65 | +0.19 | | 8.7 | | 1.66 | | |
| | A12 | -1.9 | | -1.6 | + 5.6 | B | + 6.4 | + 7.75 | + 7.75 | +0.19 | | 9.2 | | 1.58 | | |
| STRESSED | B1 | -1.5 | | 0.0 | +10.2 | B | +11.5 | +11.60 | +11.60 | +0.29 | | 10.3 | | 1.84 | | 194 |
| | B2 | -1.6 | | 0.0 | -14.1 | 2 | -15.0 | -13.75 | +15.25 | +0.38 | | 9.4 | | 1.79 | | |
| | B3 | -0.9 | | +0.6 | - 5.3 | 2 | + 6.1 | - 5.55 | +23.45 | +0.59 | | 8.7 | | 1.95 | | |
| | B14 | -0.1 | | +1.3 | - 9.2 | 2 | -10.2 | -10.30 | +18.70 | +0.47 | | 8.7 | | 1.87 | | |
| | B5 | -1.2 | | -0.1 | + 9.6 | B | +10.6 | +10.75 | +10.75 | +0.27 | | 9.4 | | 1.77 | | |
| | B6 | -1.3 | B | +0.1 | + 8.9 | B | + 9.8 | +10.05 | +10.05 | +0.25 | 7.9 ± 0.64 | 8.7 | 1.00 ± 0.04 | 1.79 | 152 ± 13.1 | |
| | B17 | -0.4 | | +0.9 | + 5.1 | B | + 5.8 | + 5.10 | + 5.10 | +0.13 | | 8.7 | | 1.74 | | |
| | B8 | -1.1 | | +0.4 | + 4.8 | B | + 5.6 | + 5.55 | + 5.55 | +0.14 | | 8.3 | | 1.69 | | |
| | B9 | -1.3 | | +0.1 | +10.3 | B | +10.8 | +11.15 | +11.15 | +0.28 | | 8.7 | | 1.71 | | 158 |
| | B10 | -0.7 | | +0.1 | + 8.4 | B | + 9.1 | + 9.05 | + 9.05 | +0.23 | | 9.4 | | 1.64 | | |
| | B11 | -1.0 | | -0.3 | + 8.3 | B | + 8.8 | + 9.20 | + 9.20 | +0.23 | | 9.4 | | 1.51 | | |
| | B12 | -1.6 | | +0.5 | + 8.0 | B | + 9.1 | + 9.60 | + 9.60 | +0.24 | | 9.4 | | 1.46 | | |
| STRESSED | C1 | -0.1 | | +0.7 | -14.3 | 2 | -13.2 | -13.35 | +15.65 | +0.39 | | 10.9 | | 1.75 | | 214 |
| | C2 | -0.7 | | +1.1 | - 5.8 | 2 | - 4.6 | - 4.90 | +24.10 | +0.60 | | 9.4 | | 1.79 | | |
| | C3 | -1.3 | | -0.8 | + 1.7 | 2 | + 3.4 | + 3.60 | +32.60 | +0.82 | | 9.4 | | 1.79 | | |
| | C4 | -1.6 | | -1.3 | - 0.4 | 2 | + 1.3 | + 1.90 | +30.90 | +0.77 | | 9.4 | | 1.73 | | |
| | C5 | -1.5 | | +0.9 | - 6.7 | 2 | - 5.8 | - 5.95 | +23.05 | +0.58 | | 8.7 | | 1.79 | | |
| | C6 | -2.1 | B | 0.0 | -11.1 | 2 | - 9.5 | - 8.75 | +20.25 | +0.51 | 7.9 ± 0.64 | 8.7 | 1.00 ± 0.04 | 1.73 | 152 ± 13.1 | |
| | C7 | -0.8 | | +1.2 | - 9.8 | 2 | - 8.4 | - 9.30 | +19.70 | +0.49 | | 8.7 | | 1.77 | | |
| | C8 | -1.1 | | +0.5 | - 9.6 | 2 | - 8.6 | - 8.80 | +20.20 | +0.50 | | 8.7 | | 1.73 | | 172 |
| | C9 | -2.4 | | -1.9 | -13.4 | 2 | -12.1 | -10.60 | +18.40 | +0.46 | | 9.4 | | 1.66 | | |
| | C10 | +0.5 | | +3.0 | - 8.0 | 2 | - 6.2 | - 8.65 | +20.15 | +0.50 | | 9.4 | | 1.64 | | |
| | C11 | -1.1 | | +0.5 | -12.0 | 2 | -11.5 | -11.45 | +17.55 | +0.44 | | 9.4 | | 1.58 | | |
| | C12 | -1.5 | | -1.1 | -14.7 | 2 | -11.9 | -12.00 | +17.00 | +0.43 | | 9.4 | | 1.55 | | |
| NON-STRESSED | A24 | -3.8 | | -3.3 | - 2.3 | B | - 3.6 | + 0.80 | + 0.80 | +0.02 | | 10.3 | | 1.78 | | 179 |
| | A25* | +2.4 | | +2.9 | + 7.6 | 1 | + 6.3 | + 4.30 | -24.30 | -0.58 | | | | | | |
| | A13 | -2.3 | | -1.7 | - 7.6 | B | - 9.1 | - 6.35 | - 6.35 | -0.16 | | 10.3 | | 1.93 | | |
| | A26* | +0.1 | | +0.5 | ≠ 3.937 | | | | -64.70 | -1.60 | | | | | | |
| | A14 | +1.4 | | +2.3 | ≠ 3.980 | | | | -23.30 | -0.58 | | 9.4 | | 1.77 | | |
| | A27* | +1.5 | B | +2.3 | ≠ 3.919 | | | | -84.30 | -2.10 | | | | | | |
| | A15 | -2.5 | | -2.0 | - 3.2 | 1 | - 4.3 | - 1.60 | -30.20 | -0.76 | 7.9 ± 0.64 | 8.6 | 1.00 ± 0.04 | 1.66 | 152 ± 13.1 | 129 |
| | A17 | -3.1 | | -2.4 | - 1.3 | 1 | - 2.3 | + 0.95 | -27.50 | -0.69 | | 8.5 | | 1.74 | | |
| | A28* | -0.8 | | 0.0 | ≠ 3.927 | | | | -74.00 | -1.90 | | | | | | |
| | A16 | -1.2 | | -1.0 | ≠ 3.981 | | | | -22.80 | -0.57 | | 9.2 | | 1.70 | | |
| | A18 | -2.1 | | -1.6 | -12.3 | B | -13.2 | -10.90 | -10.90 | -0.27 | | 9.4 | | 1.70 | | |
| | A19 | +0.2 | | +1.0 | - 4.3 | B | - 4.8 | - 5.10 | - 5.10 | -0.13 | | | | | | |

*G5 Graphite Specimens

Standard Length: B = 4.0014 in
1 = 3.9728 in
2 = 4.0304 in
3 = 4.0563 in

≠ Length measured with Vernier

determined on spare graphite specimens of identical type and material, whereas post-irradiation measurements were carried out on individual creep specimens. A summary of all pre- and post-irradiation measurements is given in Table 1. The error in mechanical property measurements is estimated to ±10%. All creep specimens were subjected to a load of 70 Kp to eliminate weak or cracked specimens before irradiation. In order to achieve different stress levels in the experiment the diameter of the specimens varied as shown in the following table.

Table 2

Diameter of Creep Specimens

| Type | Diameter (cm) | Cross-Sectional Area ($cm^2$) |
|---|---|---|
| A | 1.1087 ± 0.0008 | 0.9650 |
| B | 0.9047 ± 0.0009 | 0.6425 |
| C | 0.8285 ± 0.0011 | 0.5388 |

## 2.2 Bellows

The stainless steel bellows of seamed double-wall type are approximately 16 cm long and have an effective cross sectional area of 3.29 $cm^2$. They were evacuated and filled with helium at 1 atm at room temperature (20°C). Each individual bellows was leak tested by mass-spectrometer and calibrated before assembly. The bellows was introduced into a specially designed test rig and subjected to an external pressure of up to 20 atm, whilst the force generated by the bellows was recorded [13].

The differential pressure on the bellows at 370°C to 400°C in the reactor at power was 20 atm - 2.3 atm = 17.7 atm. If the bellows was restrained to its original length a pull of 17.7 x 1.033 x 3.29 = 60.2 Kp would have been exerted. Because of thermal expansion, irradiation shrinkage and creep of the graphite components the bellows increased or decreased in length during irradiation and a spring rate effect altered the effective pull on the specimens.

The spring rate of the bellows was determined before irradiation at room temperature and differential operating pressure (17.7 atm). The following table shows the results of this test [12].

| Table 3<br>Spring Rate of Bellows at Operating Pressure | | |
|---|---|---|
| Bellows No. | Expansion Rate | Compression Rate |
| 1 | 2.72 Kp/0.635 cm<br>5.89 Kp/1.27 cm | 2.26 Kp/0.635 cm<br>3.17 Kp/1.27 cm |
| 3 | 2.72 Kp/0.635 cm<br>5.89 Kp/1.27 cm | 2.26 Kp/0.635 cm<br>3.17 Kp/1.27 cm |
| 4 | 2.26 Kp/0.635 cm<br>5.44 Kp/1.27 cm | 1.81 Kp/0.635 cm<br>2.72 Kp/1.27 cm |

## 2.3 Bellows Length Change During Irradiation

Due to differential thermal expansion, irradiation induced shrinkage and elastic and plastic strains between graphite specimens and fuel tube the bellows decreased in length during reactor operation. Using the materials data given in Table 4 the approximate movement of the bellows has been determined:

Start of irradiation: (N = 0, T = operating temperature)

$$\Delta L = L_1 \left( \alpha_1 T_1 + \frac{\delta}{E_1} \right) - L_2 \alpha_2 T_2 - L_3 \alpha_3 T_3$$

(for list of symbols see P17)

with

$$L_1 = \sum_{n=1}^{n=12} l_n$$

End of irradiation*: ($N = 1 \times 10^{21}$ n cm$^{-2}$ NDE, T = operating temperature)

$$\Delta L = L_1^* \left( \alpha_1^* T_1 + \frac{\delta}{E^*} \right) - L_1 - L_1^* - \left( L_2^* \alpha_2^* T_2 - L_2 - L_2^* \right) - \left( L_3^* \alpha_3^* T_3 - L_3 - L_3^* \right)$$

with

$$L_1^* = \sum_{n=1}^{n=12} l_n^*$$

Positive movement $\Delta L$ of the bellows indicates compression of the bellows whereas a negative $\Delta L$ refers to expanding bellows. The calculations were carried out on the assumption that the elastic and plastic strains in the fuel tube and end plugs are negligible because of the large cross sectional area of these parts.

Table 4

Fuel Element Materials Data

| Type | Material | Length (cm) | Average Temperature (°C) | Pre-Irradiation Data | | Post-Irradiation Data | | |
|---|---|---|---|---|---|---|---|---|
| | | | | Mean CTE $10^{-6}\ ^{o}C^{-1}$ | Young's Modulus $Kp/cm^2$ | Dimensional Changes % | Mean CTE $10^{-6}\ ^{o}C^{-1}$ | Young's Modulus $Kp/cm^2$ |
| Dumb-bell | Graphite 95 | 13.65 | 1130 | 6.2 (20-1130°C) | $7.9 \times 10^4$ | See Table 1 | 6.2 (20-1130°C) | $8.7 \times 10^4$ |
| Fuel Tube | Graphite 87 | 165 | 800 | 5.0* (20-800°C) | - | 0.10 | 5.5 (20-800°C) | - |
| Fuel Element End Plug | Graphite 87 | 42 | 350 | 4.0 (20-400°C) | - | 0.20* | 4.5* (20-800°C) | - |

*Estimated values based on similar graphite

Table 5 summarises the results of this calculation and shows the variation of stresses in the specimens due to the spring rate of the bellows.

The straight line stress-strain relationship in itself indicates that the bellows worked properly during irradiation and no failure should have occurred. However the integrity of the bellows after irradiation has been tested in the Hot Cell by subjecting the bellows to an external pressure of 20 atm and measuring the pull generated. The bellows were maintained at pressure for several days and the leak tightness has been demonstrated.

### 2.4 Instrumentation

A limited number of Tungsten-Tungsten/Rhenium thermocouples were mounted in the centre of three fuel rods of this Metallurgical III fuel element. These thermocouples indicated a relatively constant temperature in the spine of an annular fuel compact throughout the time of irradiation. Based on additional information of graphite surface thermocouples from other identical fuel elements in the Dragon core, an axial temperature profile has been established [14]. Temperatures quoted in this report are accurate within $\pm 50^{\circ}C$. Fig. 1 shows the mean axial temperature profile, corresponding to a position inside the annular fuel compact together with the axial distribution of fast neutron doses. Fast neutron doses were obtained from the activation of nickel (fast flux) and cobalt (thermal flux) monitors in ceramic form, encapsulated in silica [12]. Four sets of flux monitors each set in a miniature graphite sub-container have been inserted in the end sections of the unrestrained G5 specimens. The error in flux monitor measurements for this relatively short time irradiation is of the order of ±10% [15]. Fast fluxes are expressed in terms of an equivalent fission flux Ni-Dido.

## 3. RESULTS

The dimensional changes of restrained and unrestrained graphite specimens are plotted in Fig. 2 as a function of core position. Using the temperature and fast neutron dose profiles given in Fig. 1 it is possible to allocate a mean temperature and fast neutron dose to each individual specimen as shown in Table 6. The total creep strain was calculated by taking the actual difference between the change in length of the stressed specimen and the change in length of the unstressed specimen at the same position. Total creep strains ranging between 0.18% and 1.25% have been achieved without any sign of deterioration of the material. In confirmation, measurements of Young's Modulus and strength (Table 1) show a similar increase in these properties for both restrained and unrestrained specimens. Young's Modulus measurements are in fair agreement with the results reported by Blackstone et al., [16] for unrestrained graphite specimens of identical material. Fig. 3a shows the Young's Modulus of restrained and unrestrained graphite specimens as function of core position. It is thought that the scatter in the data is due to inaccuracy of the measurements (error on irradiated specimens ±10%) rather than to any systematic difference between restrained and unrestrained specimens. This view is supported by the fact that the electrical resistivity is equal for both restrained and unrestrained specimens as shown in Fig. 3b. It should be noted that the electrical resistivity has been calculated using the mean initial diameter of the specimens. This could result in an error of about +1.5% for specimens with the highest shrinkage in diameter. Diameter measurements have been carried out on a small number of specimens only and the results are given in Table 7. The measurements indicate a larger decrease in diameter of restrained specimens compared to unrestrained

Table 5

Variation of Applied Stress

| Specimen Type | Bellows Movement (cm) | | Stress in Specimen No. 1 (Kp/cm$^2$) | | | |
|---|---|---|---|---|---|---|
| | Start | End | Start | End | Mean | % of UTS* |
| A | 0.56** | 0.86** | 60.350 | 60.250 | 60.300 | 39.7 |
| B | 0.62** | 1.38** | 90.300 | 88.400 | 89.350 | 58.8 |
| C | 0.66** | 1.72** | 108.300 | 106.500 | 107.400 | 70.6 |

*UTS = unirradiated ultimate tensile strength

** = bellows go into compression

Table 6

Tensile Creep - Summary of Results on Pressed Gilsocarbon Graphite No. 95

| Specimen Number | Irradiation Data: Mean Temperature °C | Irradiation Data: Fast Neutron Dose $10^{21}$ n $cm^{-2}$ NDE | Length Changes: Unrestrained Control Specimens % | Length Changes: Restrained Specimens % | Creep Strain % | Mean Stress** $10^6$ dyne $cm^{-2}$ | Total Creep Constant K $10^{-12}$ (dyne $cm^{-2})^{-1}$ ($10^{20}$ n $cm^{-2})^{-1}$ | Primary*** Creep Strain % | Secondary Creep Strain % | Secondary Creep Constant K II $10^{-12}$ (dyne $cm^{-2})^{-1}$ ($10^{20}$ n $cm^{-2})^{-1}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| A1 | 850 | 0.87 | +0.02 | +0.20 | +0.18 | 59.15 | 3.66 | 0.11 | 0.07 | |
| A2 | 940 | 1.00 | -0.05* | +0.37 | +0.42 | 59.19 | 7.10 | 0.13 | 0.29 | 4.91 |
| A3 | 1020 | 1.11 | -0.16 | +0.46 | +0.62 | 59.23 | 9.44 | 0.17 | 0.45 | 6.85 |
| A4 | 1100 | 1.18 | -0.38* | +0.27 | +0.65 | 59.27 | 9.30 | 0.21 | 0.44 | 6.29 |
| A5 | 1160 | 1.19 | -0.57 | +0.09 | +0.66 | 59.31 | 9.35 | 0.24 | 0.42 | 5.95 |
| A6 | 1210 | 1.13 | -0.69* | -0.19 | +0.50 | 59.35 | 7.08 | 0.27 | 0.23 | 3.43 |
| A7 | 1240 | 1.03 | -0.76 | -0.13 | +0.63 | 59.39 | 10.30 | 0.29 | 0.34 | 5.56 |
| A8 | 1240 | 0.92 | -0.69 | -0.20 | +0.49 | 59.43 | 8.96 | 0.29 | 0.20 | 3.66 |
| A9 | 1230 | 0.80 | -0.65* | -0.14 | +0.51 | 59.47 | 10.75 | 0.29 | 0.22 | 4.63 |
| A10 | 1210 | 0.67 | -0.57 | +0.04 | +0.61 | 59.51 | 15.30 | 0.27 | 0.34 | 8.53 |
| A11 | 1170 | 0.54 | -0.27 | +0.19 | +0.46 | 59.55 | 14.30 | 0.24 | 0.22 | 6.94 |
| A12 | 1130 | 0.38 | -0.13 | +0.19 | +0.32 | 59.59 | 14.10 | 0.22 | 0.10 | |
| B1 | 850 | 0.87 | +0.02 | +0.29 | +0.27 | 87.66 | 3.54 | 0.16 | 0.11 | |
| B2 | 940 | 1.00 | -0.05* | +0.38 | +0.43 | 87.71 | 4.91 | 0.21 | 0.22 | 2.51 |
| B3 | 1020 | 1.11 | -0.16 | +0.59 | +0.75 | 87.76 | 7.70 | 0.25 | 0.50 | 5.14 |
| B14 | 1100 | 1.18 | +0.38* | +0.47 | +0.85 | 87.81 | 8.12 | 0.31 | 0.54 | 5.22 |
| B5 | 1160 | 1.19 | -0.57 | +0.27 | +0.84 | 87.86 | 8.04 | 0.36 | 0.48 | 4.60 |
| B6 | 1210 | 1.13 | -0.69* | +0.25 | +0.94 | 87.91 | 9.47 | 0.41 | 0.53 | 5.35 |
| B17 | 1240 | 1.03 | -0.76 | +0.13 | +0.89 | 87.96 | 9.83 | 0.44 | 0.45 | 4.98 |
| B8 | 1240 | 0.92 | -0.69 | +0.14 | +0.83 | 88.01 | 10.25 | 0.44 | 0.39 | 4.82 |
| B9 | 1230 | 0.80 | -0.65* | +0.28 | +0.93 | 88.06 | 13.18 | 0.44 | 0.49 | 6.96 |
| B10 | 1210 | 0.67 | -0.57 | +0.23 | +0.80 | 88.11 | 13.54 | 0.41 | 0.39 | 6.61 |
| B11 | 1170 | 0.54 | -0.27 | +0.23 | +0.50 | 88.16 | 10.50 | 0.36 | 0.14 | 2.95 |
| B12 | 1130 | 0.38 | -0.13 | +0.24 | +0.37 | 88.21 | 11.02 | 0.33 | 0.04 | |
| C1 | 850 | 0.87 | +0.02 | +0.39 | +0.37 | 105.50 | 4.03 | 0.20 | 0.17 | |
| C2 | 940 | 1.00 | -0.05* | +0.60 | +0.65 | 105.56 | 6.15 | 0.25 | 0.40 | 3.79 |
| C3 | 1020 | 1.11 | -0.16 | +0.82 | +0.98 | 105.62 | 8.36 | 0.30 | 0.68 | 5.80 |
| C4 | 1100 | 1.18 | -0.38* | +0.77 | +1.15 | 105.68 | 9.22 | 0.37 | 0.78 | 6.25 |
| C5 | 1160 | 1.19 | -0.57 | +0.58 | +1.15 | 105.74 | 9.14 | 0.44 | 0.71 | 5.65 |
| C6 | 1210 | 1.13 | -0.69* | +0.51 | +1.20 | 105.80 | 10.04 | 0.50 | 0.70 | 5.85 |
| C7 | 1240 | 1.03 | -0.76 | +0.49 | +1.25 | 105.86 | 11.48 | 0.54 | 0.71 | 6.51 |
| C8 | 1240 | 0.92 | -0.69 | +0.50 | +1.19 | 105.92 | 12.21 | 0.54 | 0.65 | 6.67 |
| C9 | 1230 | 0.80 | -0.65* | +0.46 | +1.11 | 105.98 | 13.10 | 0.53 | 0.58 | 6.84 |
| C10 | 1210 | 0.67 | -0.57 | +0.50 | +1.07 | 106.04 | 15.05 | 0.50 | 0.57 | 8.00 |
| C11 | 1170 | 0.54 | -0.27 | +0.44 | +0.71 | 106.10 | 12.39 | 0.44 | 0.27 | 4.71 |
| C12 | 1130 | 0.38 | -0.13 | +0.43 | +0.56 | 106.16 | 13.85 | 0.40 | 0.16 | |

*From Fig. 2

**Including weight of the specimens

***From Fig. 6

Table 7

Diameter of Restrained Dumb-Bell Specimens

| Specimen No. | $D_o$ (cm) | $D^*$ (cm) | $D_o - D^*$ (cm) | $\frac{D_o - D^*}{D_o}$ (%) | $\frac{\Delta D}{D_o}$ Max. Min. (%) |
|---|---|---|---|---|---|
| A1 | +1.1087 −0.0008 | 1.1082 | −0.0005 | −0.045 | −0.117 +0.027 |
| A3 | | 1.1046 | −0.0041 | −0.37 | −0.44 −0.30 |
| A7 | | 1.0952 | −0.0135 | −1.22 | −1.29 −1.15 |
| A12 | | 1.1067 | −0.0020 | −0.18 | −0.25 −0.11 |
| B1 | +0.9047 −0.0009 | 0.9055 | +0.0008 | +0.088 | −0.011 +0.18 |
| B3 | | 0.9007 | −0.0040 | −0.44 | −0.54 −0.34 |
| B17 | | 0.8954 | −0.0093 | −1.03 | −1.13 −0.93 |
| B12 | | 0.9020 | −0.0027 | −0.30 | −0.40 −0.20 |
| C1 | +0.8285 −0.0011 | 0.8285 | ±0.0000 | ±0.00 | −0.13 +0.13 |
| C3 | | 0.8252 | −0.0033 | −0.40 | −0.53 −0.27 |
| C7 | | 0.8202 | −0.0083 | −1.00 | −1.13 −0.87 |
| C12 | | 0.8270 | −0.0015 | −0.18 | −0.31 −0.05 |
| DIAMETER OF UNRESTRAINED SPECIMENS | | | | | |
| A24 | +1.1087 −0.0008 | 1.1087 | ±0.0000 | ±0.00 | −0.07 +0.07 |
| A13 | | 1.1057 | −0.0030 | −0.27 | −0.34 −0.20 |
| A15 | | 1.0986 | −0.0101 | −0.91 | −0.98 −0.84 |
| A19 | | 1.1069 | −0.0018 | −0.16 | −0.23 −0.09 |

$D_o$ = Diameter before irradiation

$D^*$ = Diameter after irradiation

specimens. However the limited accuracy of the measurements in which a micrometer has been used, and the lack of pre-irradiation data on individual specimens do not allow one to draw a conclusion on the volume changes of stressed graphite specimens. Fig. 4 shows the relationship between irradiation induced creep strain and stress of pressed Gilsocarbon graphite. Data points were taken from the smoothed curves of Fig. 2. However there is still some scatter in the data of Fig. 4 and it is suggested that surface defects in the rather coarse grain graphite have reduced the effective diameter of the specimens. Such a reduction leads to a decrease in the effective cross sectional area of a specimen and this effect is most pronounced for specimens with the smallest diameter. Total creep strains as a function of fast neutron dose have been plotted in Fig. 5 for two temperature ranges. This plot is based on a number of systematised points derived from the stress-strain relationship in Fig. 4 and from Table 3.

Investigations of irradiation induced creep in graphite have shown that the creep process can be separated into primary and secondary components [7, 9, 17]. The primary creep has been estimated by extrapolation of the secondary creep curve in Fig. 5 to zero dose. The zero intercept values (primary creep strains) are plotted in Fig. 6 as a function of irradiation temperature, and Fig. 7 compares the elastic strains of unirradiated Gilsocarbon graphite with zero intercept strains of irradiated material. Fig. 8 shows the secondary creep constant $K_{II}$ as a function of irradiation temperature.

## 4. DISCUSSION

Examination of the present data gives further evidence for the existence of a relatively large primary creep component followed by a period of continuous secondary creep. It is interesting to note that if the total creep strains are adjusted for primary creep using the initial elastic strain, the secondary creep coefficients obtained agree excellently with those of Blackstone [6] (cf. Fig. 8) who makes this assumption in his restrained shrinkage experiments at Petten. However the results in Fig. 6 indicate a temperature dependence for primary creep in the range of 1000°C to 1240°C and it is evident from Fig. 7 that the primary creep strains are significantly larger than the initial elastic strain. J. E. Brocklehurst et al., [10] reported primary creep strains of the order of 0.1% in compression for an isotropic graphite irradiated at about 400°C under a constant stress of 63 Kp/cm$^2$, but other workers have reported much smaller values in tension, comparable to the elastic strain [3, 7, 8]. It is difficult in many cases to compare the present results with other data since the dose scales are different and primary creep is estimated by extrapolation of the secondary creep curve (Fig. 5) to zero dose; also temperatures in other experiments were generally lower. The results in Fig. 5 show that a mechanism of continuous secondary creep exists which is capable of producing strains in excess of the elastic strain. Several mechanisms by which such creep takes place have been suggested by G. K. Williamson et al., [18] and an analysis of possible processes is given by Kelly et al., [19]. None of those theories at present is able to fully explain irradiation creep.

Discrepancies have been observed in the property changes of restrained graphite specimens. It was reported by Blackstone et al., [6] and Gray et al., [9] that tensile creep retards changes in the coefficient of thermal expansion (CTE). On the other hand no difference in the changes of Young's Modulus were reported in the literature [10] and this has also been observed in the present experiment. Furthermore no differences between electrical resistivity of unrestrained and restrained graphite specimens have been found. All these observations lead to the suggestion of grain boundary sliding as a contributory mechanism for irradiation creep. This idea was first put forward by Losty [17] and a similar suggestion was made by Brocklehurst et al., [10] who found a correlation of creep and elastic deformation. Such a correlation appears to involve not only the crystallite phase of polycrystalline graphite but also the disordered binder phase.

Graphite specimens in the Dragon experiment were irradiated at three different stress levels of 40%, 58% and 70% of their unirradiated ultimate tensile strength and the results shown in Figs. 4 and 5 confirm the usual assumption [4, 6, 9, 10] that secondary creep strain $\Sigma_{II}$ is linearly proportional to stress $\Sigma$ and fast neutron dose N, thus

$$\Sigma_{II} = K \, \delta \, N \qquad (1)$$

where K is the creep constant. The secondary creep strain has been calculated using the following equation

$$\Sigma_{II} = \Sigma - \Sigma_{I} \qquad (2)$$

where $\Sigma$ is the total measured creep strain and $\Sigma_{I}$ is the primary creep strain plotted in Fig. 6. The measurements have been analysed on the basis of the above equations and a secondary creep constant $K_{II}$ has been calculated. The calculations are summarised in Table 6 and the secondary creep constants are plotted in Fig. 8 as a function of irradiation temperature. It should be noted that results of the two specimens irradiated at the bottom and top end of the core have been omitted because of larger uncertainties in dose and temperature in these regions. The quoted creep constants are likely to be correct within 15 to 20%, the largest contribution to this error arises from uncertainties in primary creep strain and fast neutron dose. The value of the secondary creep constant $K_{II}$ increases by a factor of two with irradiation temperature in the range 900°C to 1240°C as shown in Fig. 8. The results are compared with irradiation creep constants published by Blackstone et al., [6] for a wide range of graphites. These data were derived from a restrained shrinkage experiment and the fair agreement with the present data confirms the validity of an experiment of this type.

## 5. SUMMARY

Pressed Gilsocarbon graphite specimens have been irradiated under constant tensile stresses over a temperature range of 850°C to 1240°C up to a fast neutron dose of $1.19 \times 10^{21}$ n $cm^{-2}$ NDE.

The graphite specimens were subjected to stresses of 40%, 58% and 70% of their unirradiated ultimate tensile strength and total creep strains of up to 1.25% have been achieved without any sign of mechanical deterioration in the material.

Young's Modulus and strength measurements on restrained and unrestrained Gilsocarbon graphite specimens show an increase in both properties and reveal no difference between restrained and unrestrained specimens.

A linear dependence of irradiation creep on stress has been observed.

The data indicate the existence of a large and temperature dependent primary creep component which at 1200°C approaches a value three times larger than the initial elastic strain, followed by a period of continuous secondary creep. The secondary creep constants are in fair agreement with values obtained from the restrained shrinkage experiments of Blackstone et al., [6].

## 6. ACKNOWLEDGMENTS

Acknowledgment is made to the Chief Executive of the Dragon Project for permission to publish this paper. The work originated from a proposal made by Mr. E. H. Voice to carry out an experiment of this type in the Dragon Reactor. The assistance of Mr. A. Kingsbury in the pre- and post-irradiation work is gratefully acknowledged.

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## LIST OF SYMBOLS

Dumb-bell Specimens

$l_n$ = length of an individual specimen n

$L_1$ = overall length

$\alpha_1$ = mean CTE

$T_1$ = average operating temperature

$E_1$ = Young's Modulus

$\delta$ = applied stress

Graphite Fuel Tube

$L_2$ = active length

$\alpha_2$ = mean CTE

$T_2$ = average operating temperature

Fuel Element End Plug

$L_3$ = active length

$\alpha_3$ = mean CTE

$T_3$ = average operating temperature

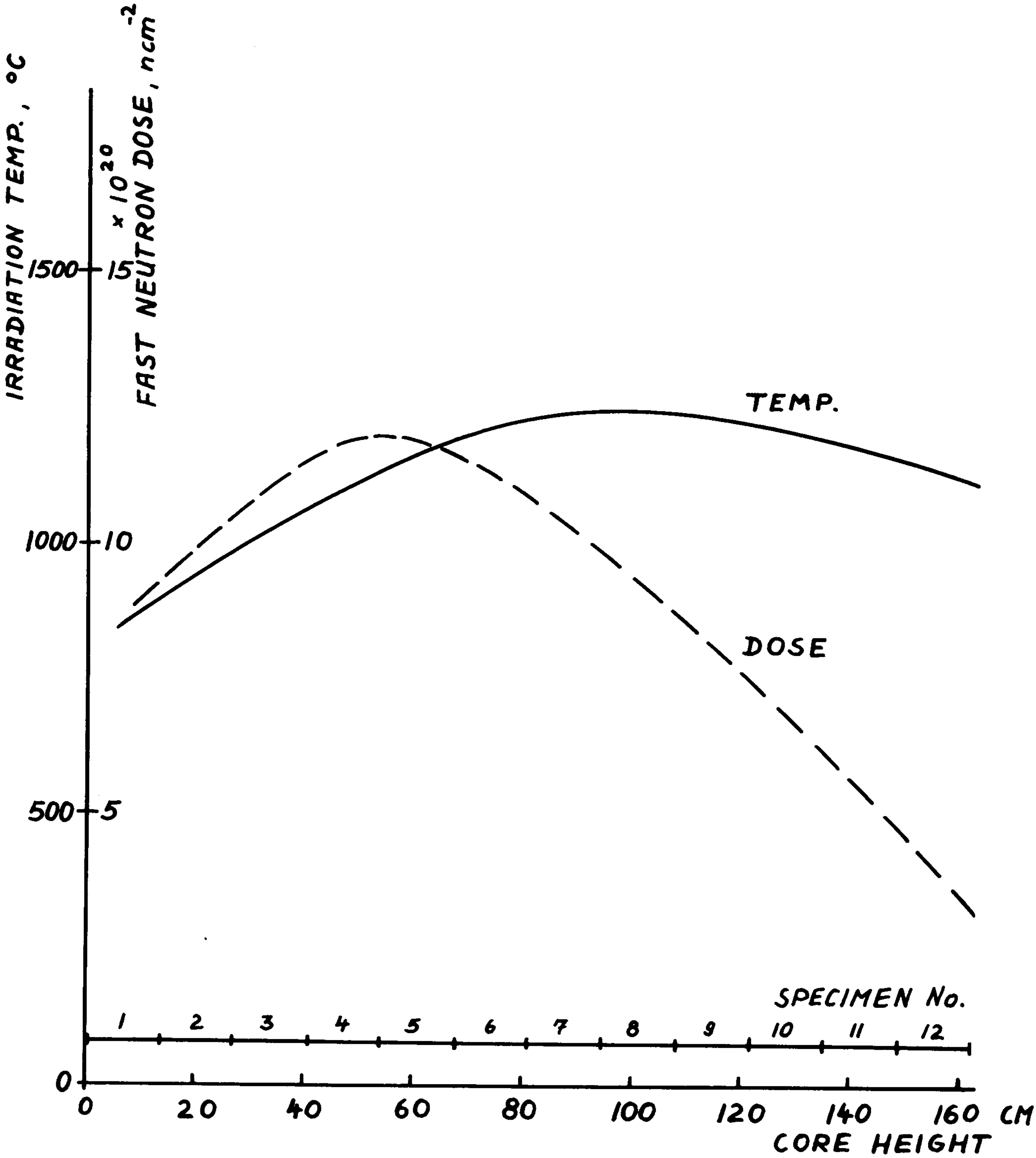


Fig.1 AXIAL DISTRIBUTION OF FAST NEUTRON DOSE (NDE) AND IRRADIATION TEMPERATURE.

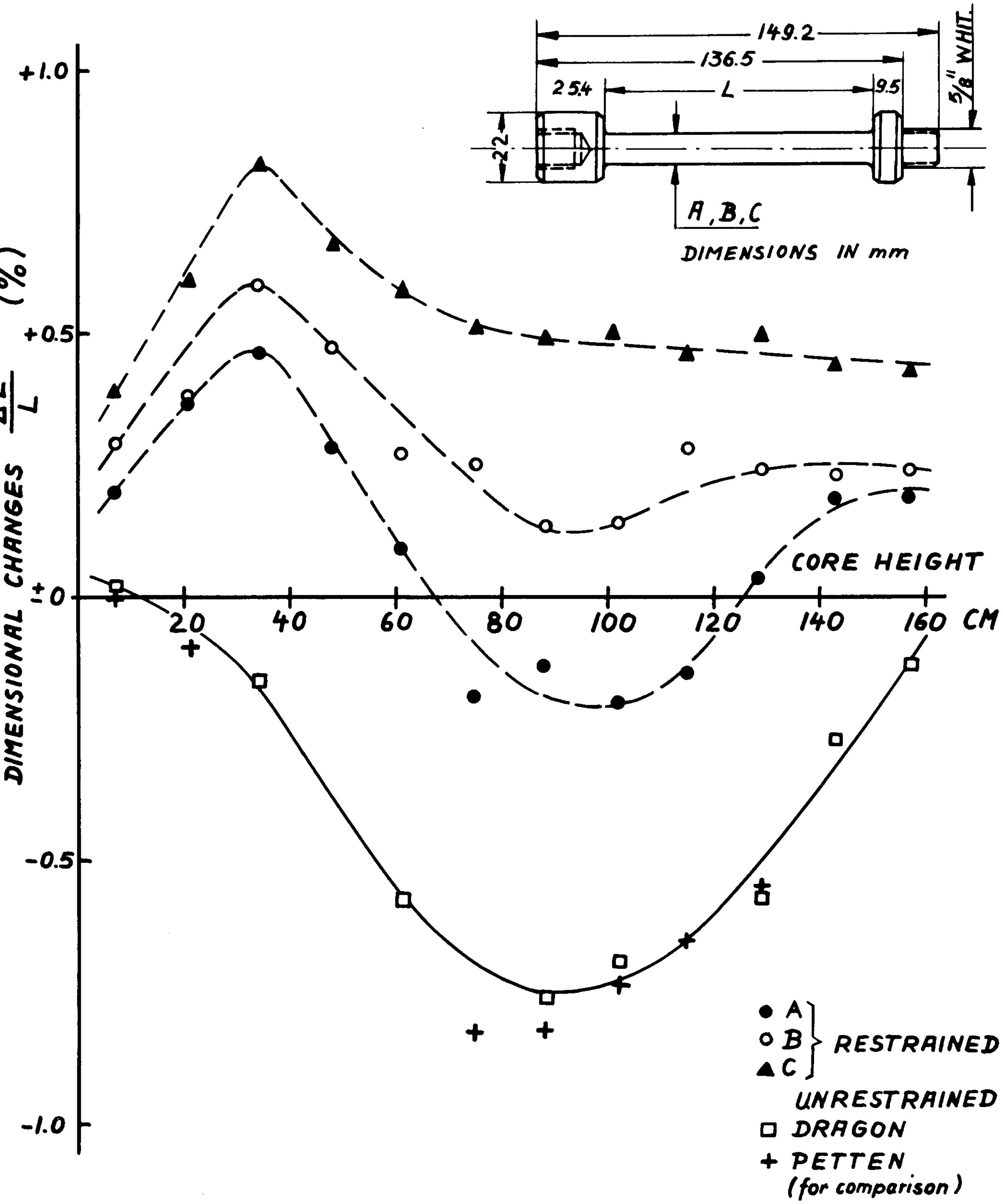


Fig. 2 DIMENSIONAL CHANGES OF GRAPHITE CREEP SPECIMENS VS. POSITION IN THE CORE.

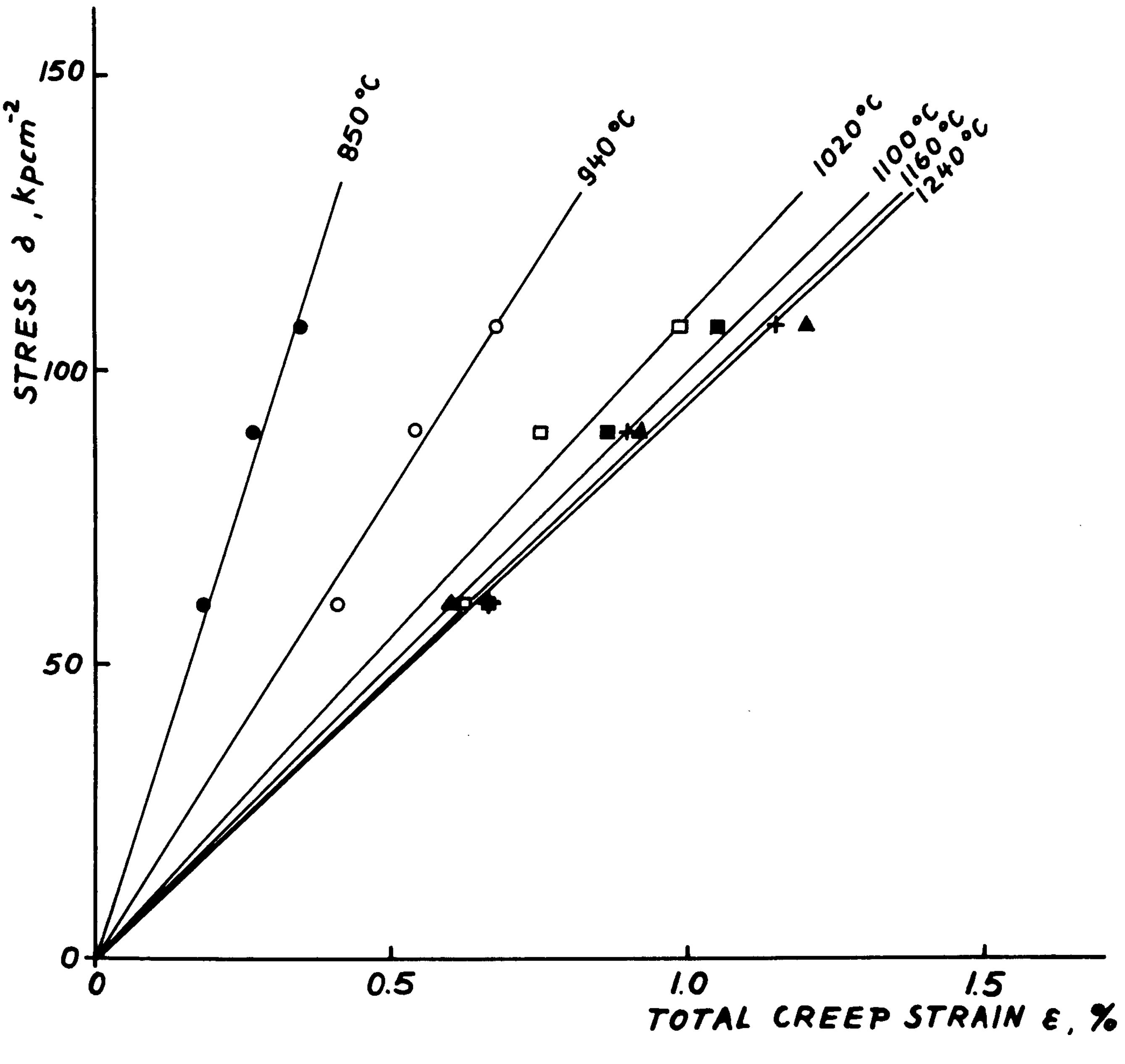


FIG.4 RELATION BETWEEN TOTAL CREEP STRAIN AND STRESS OF PRESSED GILSOCARBON GRAPHITE IRRADIATED TO FAST NEUTRON DOSES OF 0.87–1.19 x $10^{21}$ n $cm^{-2}$ NDE TEMPERATURES: ● 850°C; ○ 940°C; □ 1020°C; ■ 1100°C; + 1160°C; ▲ 1240°C.

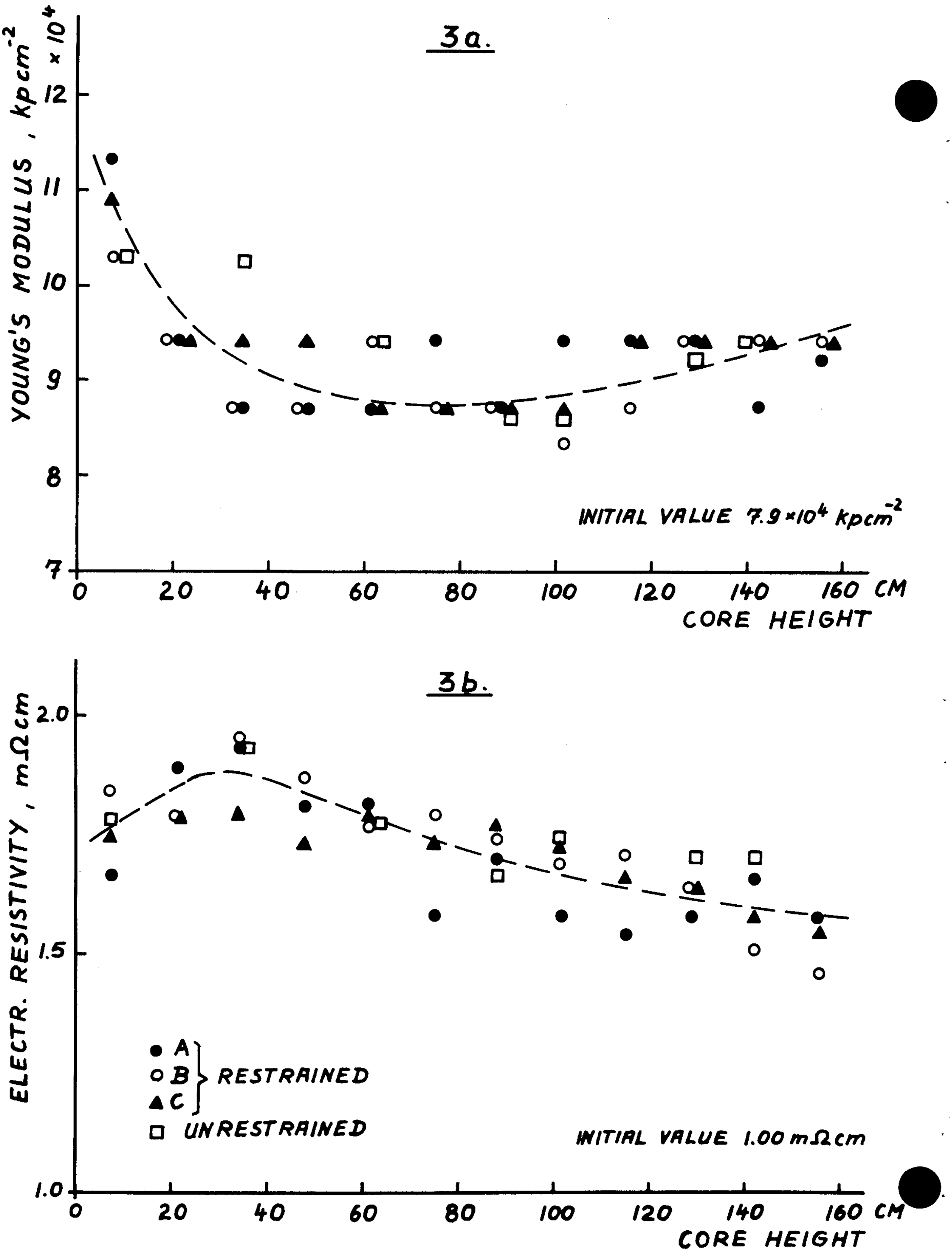


FIG. 3 PROPERTY CHANGES OF GRAPHITE CREEP SPECIMENS VS. POSITION IN THE CORE

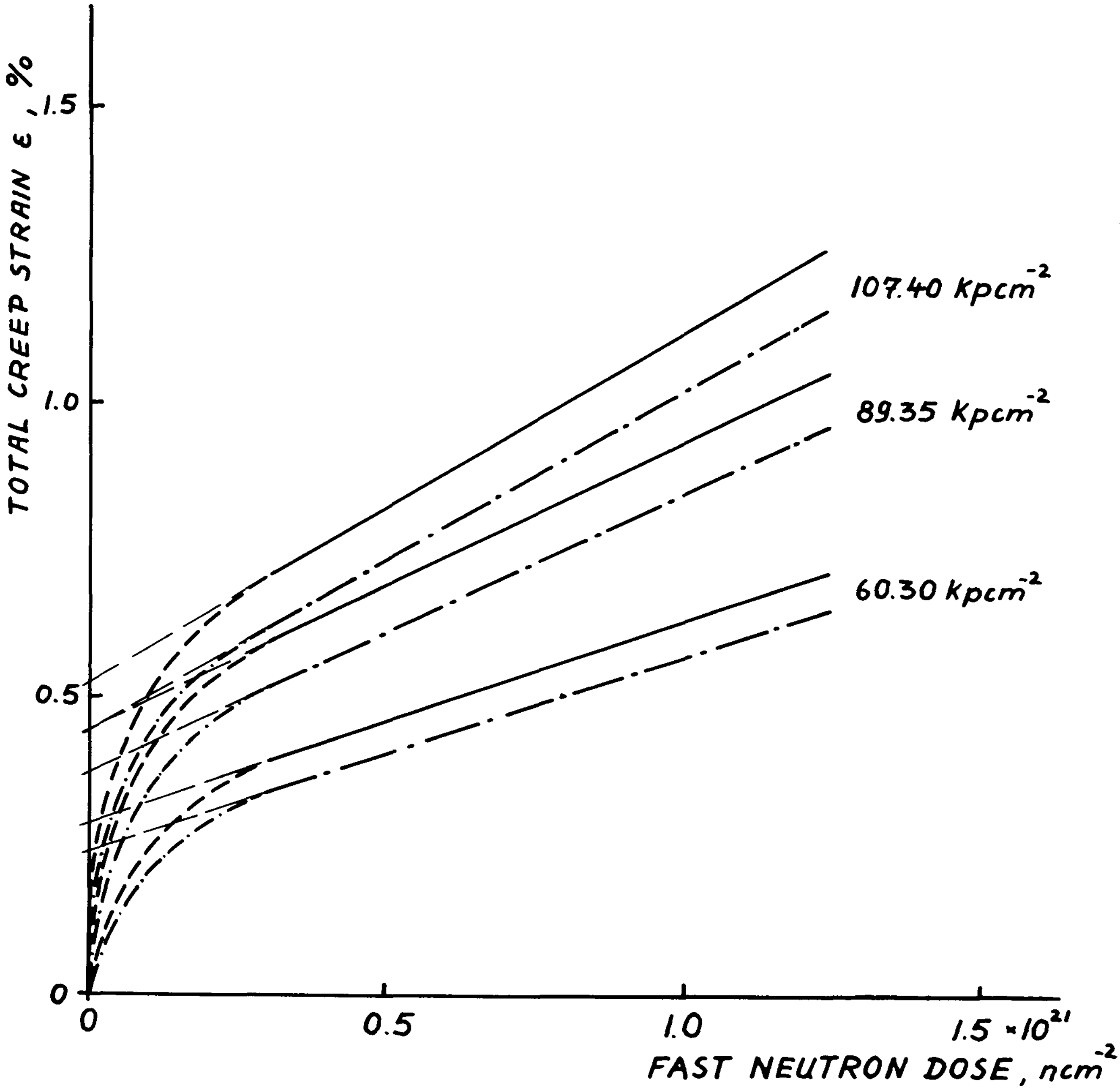


FIG.5 IRRADIATION INDUCED CREEP STRAINS FOR PRESSED GILSOCARBON GRAPHITE NO.95
TEMPERATURES: —— 1210–1240°C
—·— 1160–1170°C

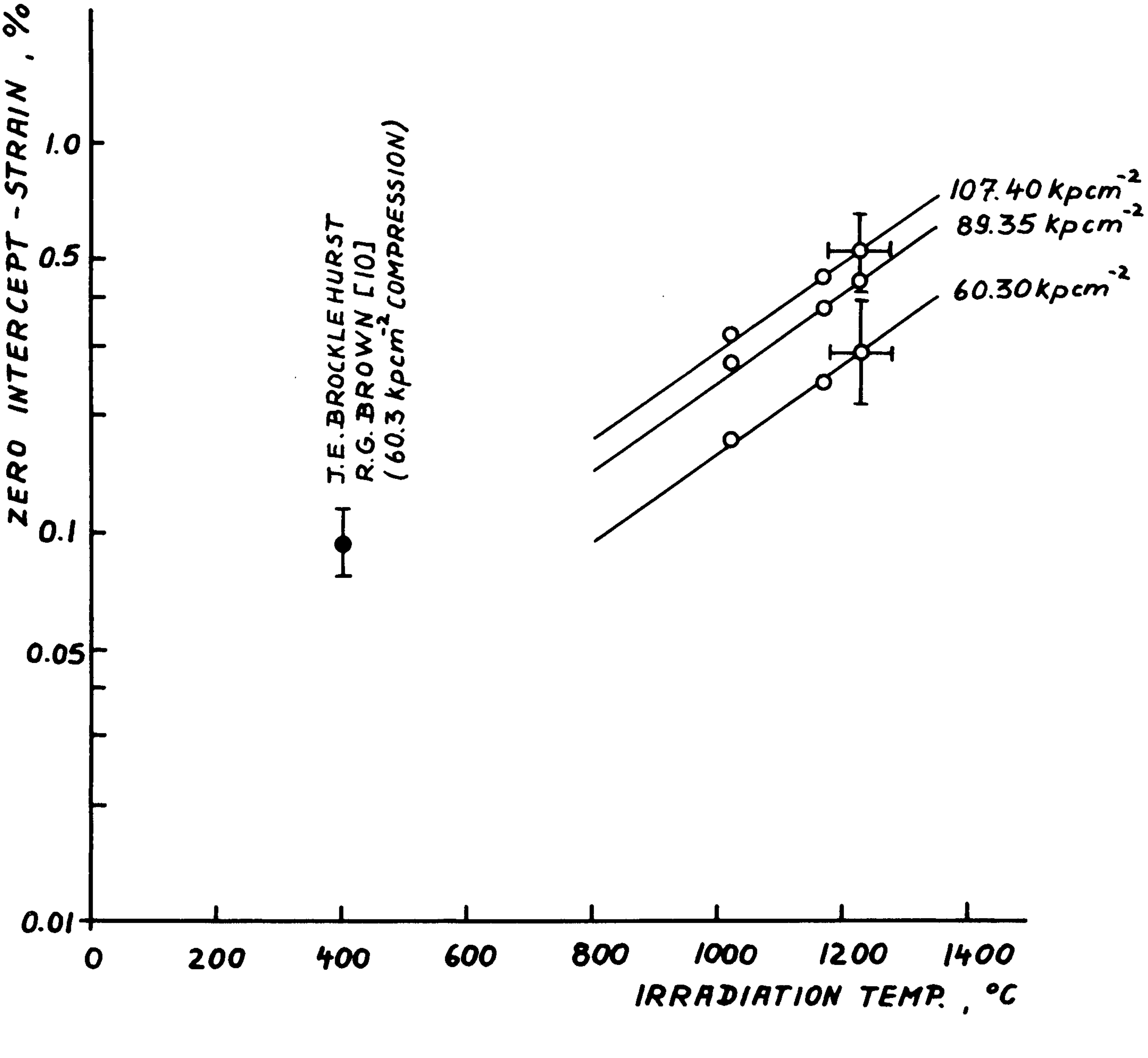


FIG. 6 ZERO INTERCEPT (TENSILE PRIMARY CREEP STRAINS) AS A FUNCTION OF IRRADIATION TEMPERATURE.

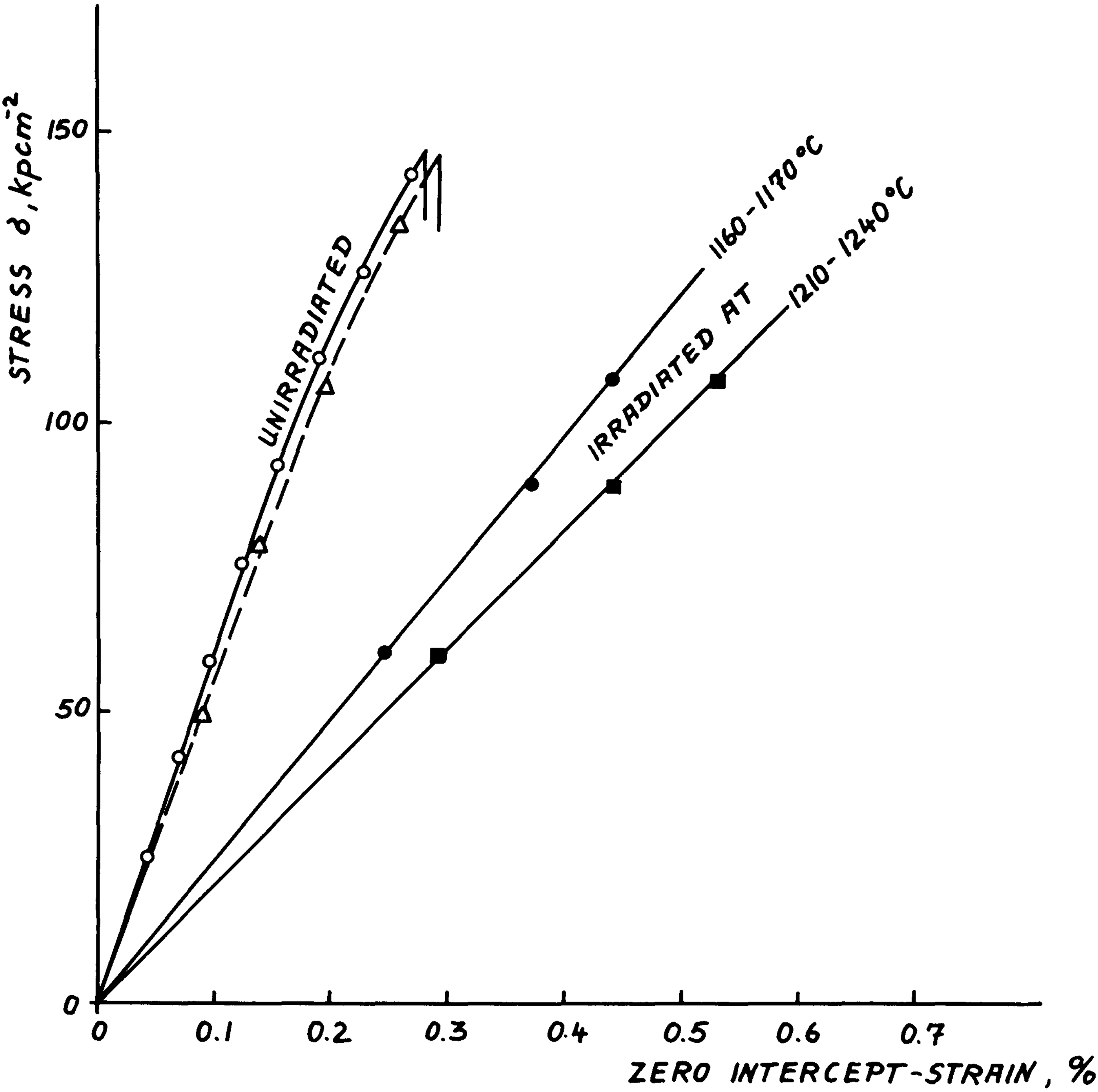


FIG. 7 EFFECT OF IRRADIATION ON ZERO INTERCEPT-STRAIN.

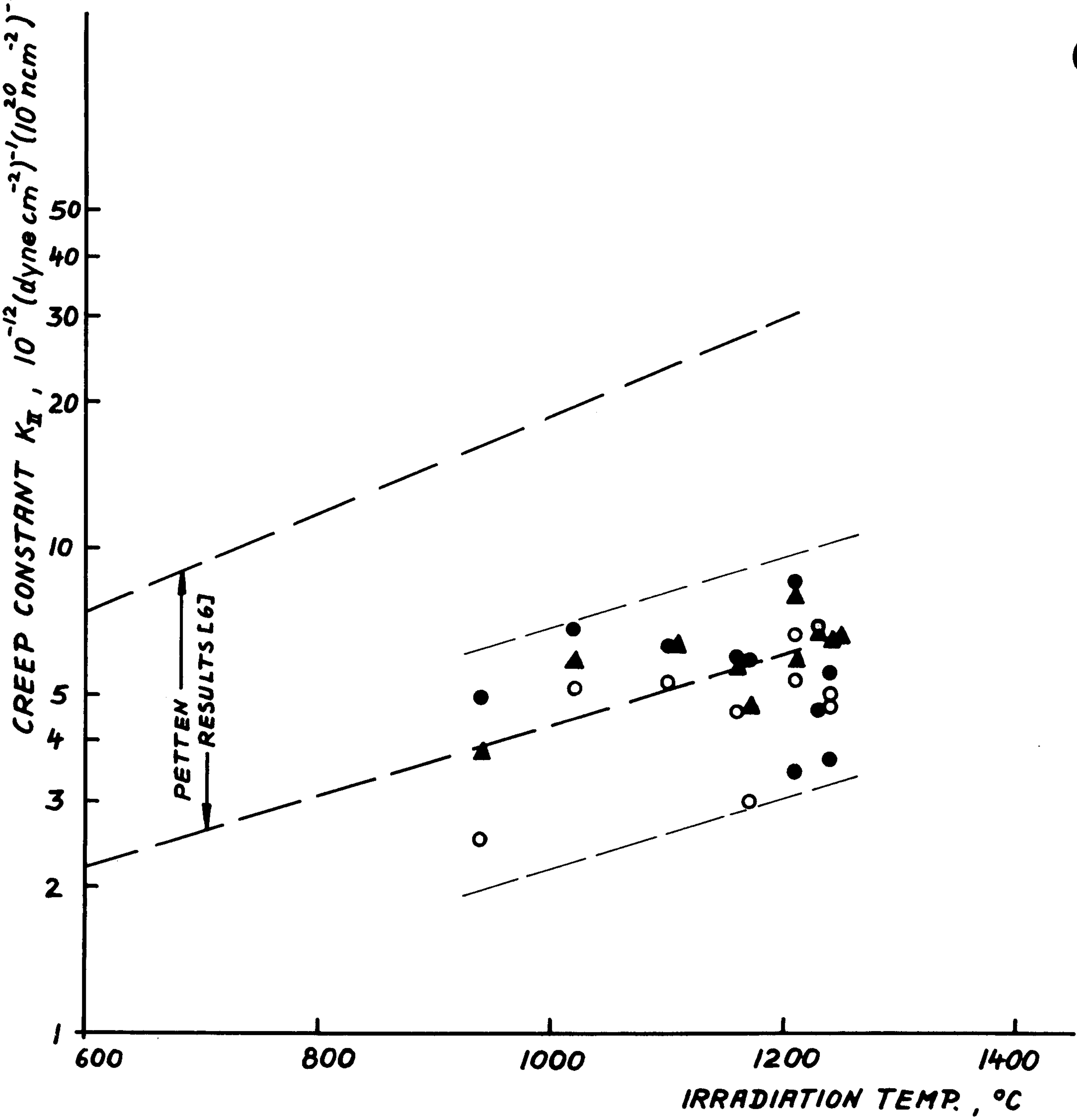


FIG. 8 SECONDARY CREEP CONSTANT (TENSION) AS FUNCTION OF IRRADIATION TEMPERATURE FOR PRESSED GILSOCARBON GRAPHITE NO.95. SPECIMEN TYPE: ● A; ○ B; ▲ C.