# The origins and use of the equivalent temperature concept

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## ABSTRACT

In some graphite research fields, it is accepted practice to apply an equivalent temperature correction when using graphite data from facilities with differing fast neutron fluxes. The origins of the equivalent temperature hypothesis are described, including the data and theory originally used to justify the approach, and some reservations that have been expressed by various authors are discussed. Relevant findings of recent statistically based work on Gilsocarbon materials irradiated in test reactors at differing flux are presented. The data originally used for justifying the approach and the more recent data analyses both suggest that the use of equivalent temperatures may be justified at low temperatures but not at temperatures above about 300–350 °C. Unfortunately the quantity and quality of the data does not allow for a more exact temperature to be defined.

## 1. Introduction

When graphite is used in a nuclear reactor, it will undergo significant dimensional and material properties changes due to the combined effect of fast neutron dose, temperature changes, and in some gas-cooled reactors, radiolytic oxidation. These changes are complex and difficult to predict. Although there have been and are ongoing studies into understanding the changes from a microstructural level, historically the most practicable method to determine the changes over the life of the graphite or component has been to irradiate graphite samples and measure the desired properties. In order to obtain the data before the reactor's end-of-life, material test reactors (MTRs) having an accelerated fast neutron flux compared to power-producing reactors, were used. Although this provided the required data within a reasonable time, the differences between the MTR and power-producing reactor in question had to be taken into account. An accepted difference and conversion is the difference in neutron energy spectra and the use of an equivalent damage dose; this concept is not examined in detail here. A rather more contentious concept is that of the equivalent temperature, which is held to account for the difference in the dose rates of the reactors. Examining the equivalent temperature concept is the objective of this paper.

## 2. Origins of equivalent temperature

Bell et al. [1] first hypothesised that when two irradiations to the same dose were carried out at different fluxes or rates, the subsequent property changes were different, even if the neutron energy spectra had been the same. The reasoning was that in a reactor, graphite would undergo a form of annealing, with the net rate of damage (rate of damage minus the rate of annealing) in the graphite being not only a function of irradiation dose but also a function of temperature and irradiation time. A reduction in either temperature or irradiation time would cause a reduction in the amount of annealing. In order to arrive at this hypothesis, two assumptions were made.

The first assumption was that when graphite was irradiated at the same temperature for the same time in two neutron fluxes with different energy spectra, the samples would be damaged identically if the ability of the neutron fluxes to cause damage were the same. This so-called damage flux could be expressed by

$$\phi_d \int_0^\infty \Psi(\varepsilon)\phi(\varepsilon)\mathrm{d}\varepsilon, \tag{1}$$

where $\phi(\varepsilon)\mathrm{d}\varepsilon$ is the flux of neutrons with energies between $\varepsilon$ and $\varepsilon + \mathrm{d}\varepsilon$, and $\Psi(\varepsilon)$ is the ability of the neutrons of different energies to produce damage. This leads to the concept of equivalent dose.

The second assumption was that if the damage flux increased and at the same time the temperature was raised, the rate of displacement and the rate of annealing would increase equally. The time-dependent component of the damage processes in graphite

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is held to be such that equivalence of net damage at different fluxes (atomic displacement rates) in samples taken to the same total dose could be achieved only when the higher flux was experienced at a higher temperature to compensate for the shorter time. The relationship between equivalent temperatures $T_1$ and $T_2$ for fluxes $\phi_1$ and $\phi_2$ is given by

$$\frac{1}{T_1} - \frac{1}{T_2} = \frac{k}{E} \ln\left(\frac{\phi_2}{\phi_1}\right), \tag{2}$$

where $k$ is Boltzmann's constant ($8.616 \times 10^{-5}$ eV K$^{-1}$) and $E$ is an activation energy characterising the damage process and its annealing.

This relationship is attributed to Kinchin in the 1950s, although a reference giving the exact derivation has not been traced. The assumptions behind the expression is that the atomic displacement rate $dc/dt$ is proportional to the flux and inversely proportional to thermal annealing described by an Arrhenius equation as given below:

$$\frac{dC}{dt} \propto \frac{\phi}{\exp(\frac{E}{kT})}. \tag{3}$$

If this expression is related to positions in two different reactors, Eq. (2) can then be simply derived.

The use of a simple Arrhenius equation with a single activation energy implies that annealing is purely thermal and that there is only one process involved, i.e. only one type of defect is being annealed, or the relationship is capable of describing the annealing of all types of defects. In addition the possibility of irradiation annealing is ignored. During the 1950s and 1960s there was an effort to try to gain further understanding of these processes, due to issues surrounding stored energy and irradiation growth in low temperature graphite reactors. A significant amount of interest was focussed on thermal annealing, and to some extent irradiation annealing, of irradiated graphite, and this work is briefly discussed below.

### 2.1. Thermal annealing of defects in graphite

The thermal annealing kinetics for simple defects in graphite such as those associated with stored energy, decrease in thermal conductivity or increase in modulus are usually described by using simple Arrhenius models developed by Vand [2] and Primak [3] for annealing defects in metals:

$$\frac{dS}{dT} = f(S)e^{-\frac{E(S)}{kT}}, \tag{4}$$

where $dS/dT$ is the annealing rate of some property (in this case stored energy) $S$, $f(S)$ is known as the characteristic equation, as it characterises the graphite sample being annealed, and $E$ is an activation energy, or activation function, discussed further below. Whilst this simple relationship can, with constant activation energy, describe the initial annealing of 'point' defects, with increasing annealing temperature the 'annealed defects' combine to form more complex and more stable defect configurations. These will require higher activation energies to anneal out. Thus the activation energy $E$ becomes a function of the remaining, and newly formed, lattice defects and annealing temperature leading to a reduced annealing rate as the temperature increases. This behaviour is typical of the release of stored energy in which the rate of release reduces significantly above 200 °C and only starts to increase again at temperatures in excess of 1200 °C, as discussed by Rapenaux et al. [4]. Thus the form and solution of Eq. (4) becomes more complex involving variable activation energies (or a spectrum of independent [5] activation energies) each of which is a function of stored energy released and annealing temperature. Clearly similar argu-

ments could be attributed to continuous annealing in-reactor with the added complication that point defects are constantly being generated by atomic displacements. However, a further complication is that thermal annealing in a reactor has been shown to be different to thermal annealing outside a reactor as discussed below.

### 2.2. Radiation annealing

Early experiments indicated that graphite anneals to a greater extent when held in a reactor than would be the case at the same temperature outside a reactor. The most significant study is still probably that by Nightingale [6], who irradiated graphite samples at 30 °C and then thermally annealed the samples at ~350 °C for several days outside the reactor, until equilibrium was reached, before again annealing them in a reactor. He measured the change in total stored energy, thermal conductivity, lattice spacing and linear dimensional change and showed that there is a significant difference in annealing behaviour in a reactor compared to annealing outside a reactor. When annealed outside the reactor there was a rapid recovery in the particular property which appeared to saturate at some percentage of the virgin value. However, on further annealing in-reactor the rate of annealing increased, with the property approaching the virgin value at an annealing temperature well below the temperature that would be required to thermally anneal the sample (which is greater than 1300 °C). Nightingale sought to explain this through a dynamic equilibrium between irradiation damage, thermal annealing and irradiation annealing. In thermal annealing he deduced that only a narrow band of activation energies was involved. However, he found that a wide range of activation energies applied to irradiation annealing. Unfortunately this work was not pursued further to investigate graphite irradiated at the higher temperatures that are of interest in modern graphite moderated reactors. However, the complexity of the annealing mechanisms involved is clearly demonstrated. This called into question the application of the simple relationship given by Eq. (2) to a broad range of irradiation temperatures and reactor environments. Furthermore, the higher activation energies required to thermally anneal (and probably irradiation anneal) the more complex defects associated with graphite irradiated at higher temperatures, above 300 °C, imply that the difference between an equivalent temperature and actual temperature is likely to be small.

### 2.3. Practical application of EDT

In practice when using Eq. (2), an attempt has been made to calibrate $E$ empirically from experimental observations. The accuracy and range of applicability of $E$ will therefore depend on the quality and quantity of data from which values for $E$ are derived. It is clear from the description above that the proposed mechanism has been derived to describe the behaviour of the graphite crystallites and therefore its application to dimensional and property changes in polycrystalline graphite implies that the bulk property changes in nuclear graphite can be directly related to the irradiation-induced changes to the graphite crystals. This leads to the following questions as outlined below:

- Is the equivalent temperature relationship directly applicable to all property changes, e.g. stored energy, electrical resistivity, dimensional change, coefficient of thermal expansion, thermal conductivity, Young's modulus and strength?
- When high dose microstructural changes caused by large irradiation crystal deformations start to take place is the equivalent temperature relationship still directly applicable or does the relationship require modification for each property under consideration?

- How should the equivalent temperature relationship be applied to graphite undergoing combined fast neutron damage and radiolytic oxidation?

The use of Eq. (2) has another disadvantage; the expression breaks down if the ratio between the flux in the two reactors is large. It breaks down at a ratio greater than 20:1 according to Simmons [7] who acknowledges that the arguments given in deriving Eq. (1) are 'not rigorous and the method is not always valid'. He gives no data to justify this ratio or statement, but the arguments presented above support his comments. In practice if large ratios are used in Eq. (2), such as those appropriate to treat graphite damage in high temperature reactor (HTR) reflector blocks, the difference between EDT and the actual reactor temperature becomes very large. The application of this expression for the structural integrity assessment of nuclear graphite components has only gained acceptance by workers in the UK, and has not gained acceptance in the USA, Russian and Japan, although it is interesting to note that workers in the latter countries are generally interested in higher temperature nuclear graphite applications.

### 2.4. Experimental evidence

Bell et al. [1] applied the equivalent temperature theory, and the equivalent dose theory, to experimental data from monitoring samples taken from the Calder Hall production and power-producing reactors and samples irradiated in higher flux material test reactors (BEPO, DIDO or PLUTO, see Table 1) to study the stored energy in Pile Grade A (PGA) graphite. To use equivalent temperature, the activation energy $E$ had to be determined. Therefore, samples were irradiated in PLUTO for three hours at 150 °C with the reactor running at 7.5 MW. The dose and change in electrical resistivity of the samples were measured, and by making equivalent measurements when the reactor was running at 300 kW, a mean activation energy of 1.58 eV was determined.

The data presented by Bell et al. [1] were for the rate of release of stored energy at 400 °C for graphite samples irradiated in MTRs and for graphite monitoring samples removed from Calder Hall during routine shutdowns. The samples were irradiated between 155 and 355 °C; examples of the data are presented in Figs. 1 and 2. The data was compared using the calculated equivalent temperatures, i.e. the samples from the MTR rig irradiated at 205 °C were calculated to be at an equivalent temperature of 180 °C, and compared with Calder Hall samples irradiated at an equivalent temperature of 180 ± 10 °C. The reason for the ±10 °C in the Calder Hall data was to give a reasonable number of points for comparison. In the figures presented here, the Calder Hall data at the actual temperature of the MTR data has also been included in order to highlight the effect of using equivalent temperature.

At actual irradiation temperatures of 255 °C and below, the data from Calder Hall were found to be in better agreement with the MTR data when the equivalent temperature conversion was applied. At actual irradiation temperatures of 305 and 355 °C, there were insufficient data to state confidently whether the equivalent

temperature was appropriate or not. Therefore, the work by Bell et al. [1] only supports the equivalent temperature concept at lower temperatures (255 °C and below) within the relatively low dose range ($\sim$6.5 × 10$^{20}$ n/cm$^2$ equivalent DIDO nickel dose or $\sim$0.9 dpa).

Work by Bridge et al. [8] further supported the use of equivalent temperatures at lower temperatures (150–219 °C) and doses ($\sim$4 × 10$^{19}$ n/cm$^2$ nickel or $\sim$0.05 dpa). In an experiment to examine the effect of flux level, and thus the equivalent temperature hypothesis, samples of PGA graphite were irradiated in a Danish MTR (DR3) at different temperatures (150, 182, 210, and 219 °C) at different power levels (1 and 10 MW). The electrical resistivity, thermal conductivity, Young's modulus, and dimensional changes of the samples were measured and examined to identify any flux level effect. By applying the equivalent temperature concept, it was demonstrated that there was good agreement in the data from irradiations of similar equivalent temperatures. However, in this instance the activation energy $E$ used in the conversion was 1.2 eV, a value chosen by the authors based upon a value reported by Kinchin [9] for annealing of resistivity changes in graphite.

A later study by Martin and Price [10] provided further support for the use of equivalent temperature at lower temperatures and to a higher dose ($\sim$53 × 10$^{20}$ n/cm$^2$ equivalent DIDO nickel or $\sim$7 dpa). This investigation examined the determination of doses and temperatures of experiments conducted in Dounreay fast reactor (DFR) by comparing dimensional and thermal conductivity changes in PGA graphite irradiated in DFR or DIDO (Figs. 3–6). At temperatures of 350 °C and below, data that applied the equivalent temperature conversion (using an activation energy $E$ of 1.2 eV) showed improved agreement over the data that did not use the conversion. At temperatures above this (450 and 650 °C), neither set of data exhibited better agreement than the other. Thus, the
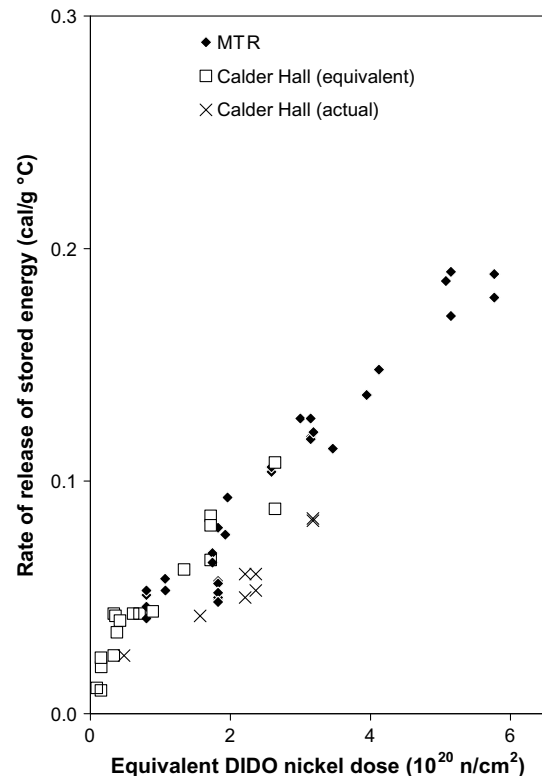


**Fig. 1.** Comparison of stored energy release rate data from MTR experiments at 205 °C actual (180 °C equivalent) irradiation temperature and Calder Hall monitoring samples at 205 ± 10 °C actual (180 ± 10 °C equivalent) irradiation temperature.

**Table 1**
The effect of using EDT on temperature prediction for various reactor systems

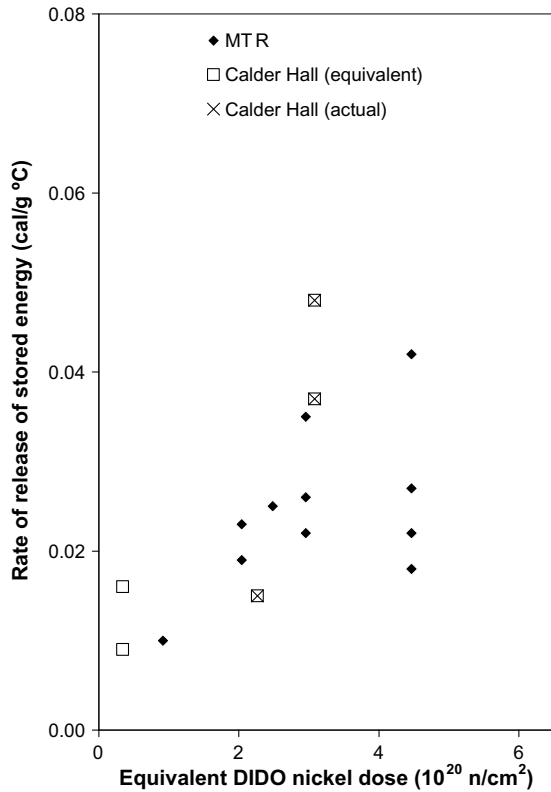| Reactor | Flux $\phi$ (n/cm$^2$ s) | Activation energy $E$ (eV), temperatures (°C) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 1.2 | 3 | 1.2 | 3 | 1.2 | 3 | 1.2 | 3 |
| DIDO | 4.00 × 10$^{13}$ | 300 | 300 | 400 | 400 | 600 | 600 | 900 | 900 |
| PLUTO | 1.40 × 10$^{14}$ | 272 | 288 | 362 | 384 | 536 | 573 | 788 | 852 |
| BR-2 | 6.20 × 10$^{14}$ | 242 | 275 | 321 | 366 | 472 | 544 | 680 | 801 |
| DFR | 8.50 × 10$^{14}$ | 236 | 273 | 313 | 362 | 460 | 538 | 660 | 790 |
| Typical thermal reactor | 1.00 × 10$^{13}$ | 335 | 313 | 448 | 419 | 683 | 631 | 1055 | 957 |

Fig. 2. Comparison of stored energy release rate data from MTR experiments at 305 °C actual (269 °C equivalent) irradiation temperature and Calder Hall monitoring samples at 305 ± 10 °C actual (269 ± 10 °C equivalent) irradiation temperature.
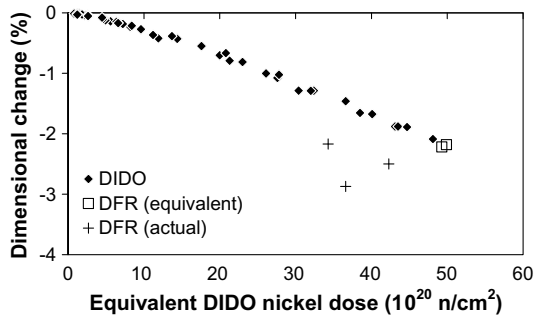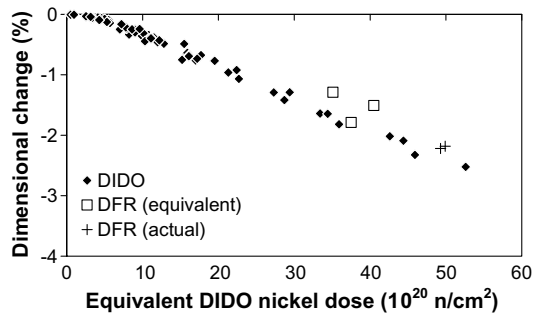


Fig. 3. Comparison of dimensional change data from DIDO experiments at 350 °C actual irradiation temperature and DFR experiments at 350 ± 20 °C actual irradiation temperatures and 350 ± 20 °C equivalent DIDO irradiation temperatures.



Fig. 4. Comparison of dimensional change data from DIDO experiments at 450 °C actual irradiation temperature and DFR experiments at 450 ± 20 °C actual irradiation temperatures and 450 ± 20 °C equivalent DIDO irradiation temperatures.
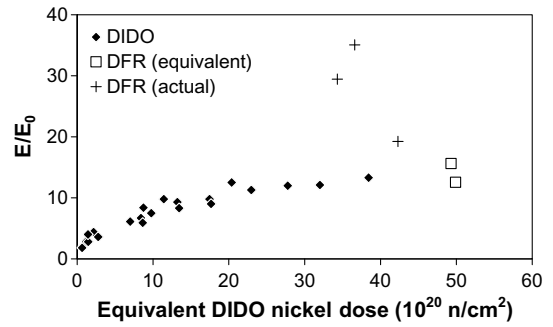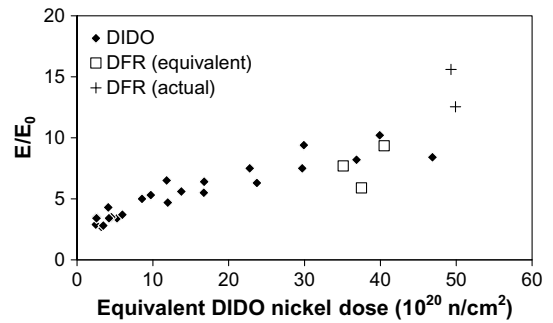


Fig. 5. Comparison of thermal conductivity data from DIDO experiments at 350 °C actual irradiation temperature and DFR experiments at 350 ± 20 °C actual irradiation temperatures and 350 ± 20 °C equivalent DIDO irradiation temperatures.



Fig. 6. Comparison of thermal conductivity data from DIDO experiments at 450 °C actual irradiation temperature and DFR experiments at 450 ± 20 °C actual irradiation temperatures and 450 ± 20 °C equivalent DIDO irradiation temperatures.

equivalent temperature concept was again supported at lower temperatures and neither proved nor disproved at higher temperatures.

It was upon such evidence that some accepted the use of the equivalent temperature conversion. However, there have been a number of concerns with its use ever since it was first hypothesised.

## 3. Significance of the choice of activation energy

A range of activation energies is used with the equivalent temperature concept, and the question arises as to which value is correct. Different values have been reported [1,8,9,11] varying from 1.2 to 1.58 to 2.0 eV. Modern day analyses use either 1.2 or 3.0 eV depending upon the material property and dose under examination. A recent investigation [12] that uses first principles to examine the atomistic processes in the radiation damage of graphite offered a scientific basis for an activation energy of 1.2 eV. However, in practice the activation energy is derived empirically from experimental observations. Its accuracy therefore, is dependent upon the quality of data from which it has been derived. From Table 1 below it can be seen that the use of EDT can make a significant difference in temperature prediction. This is important in the prediction of the life of graphite components as temperature differences of these magnitudes can significantly change the stress distribution in a typical graphite component.

## 4. Acceptance of the EDT concept in graphite

Equivalent temperature has not been accepted by all workers in the graphite research field. At the 19th International Carbon

Conference, held in Philadelphia in 1981, two papers with opposing views were presented. Brocklehurst et al. [13] presented Gilsocarbon data for dimensional change and thermal conductivity which they claimed to show no flux effect for dimensional change up to turnaround (at that time they had no low flux data beyond turnaround) alongside thermal resistivity data which was purported to show a flux effect. At the same conference Kennedy and Eartherly [14] presented a significant amount of data (dimensional change and Young's modulus) for various types of graphite irradiated in the range 400–900 °C in a high flux reactor (HFR) and lower flux thermal reactor (N-reactor); none of these showed any discernable flux effect. This is also reported by Kennedy and Eatherly in Ref. [15]. However, in the latter reference the temperature of the irradiation data is not stated (presumably it is the same as in the previous Ref. [14], 400–900 °C) and this is important because of the next reservation.

The data originally used to support the equivalent temperature concept, as described earlier, do not demonstrate that the concept is applicable across all of the temperature ranges examined (150–650 °C). Reynolds and Thrower [16] had raised this point after examining irradiation-induced defects in graphite crystals using transmission electron microscopy (TEM). The authors stated that their findings were consistent with the use of equivalent temperature up to 300 °C but a flux effect was not expected at higher temperatures. It is upon this last point that recent work has provided further insight.

## 5. Statistical evaluation of UK graphite data

There is ongoing work [17] to re-examine the dimensional and material properties data for a grade of graphite used in the UK called Gilsocarbon (so named due to the name of the coke source, Gilsonite). The main aim of this work is to use modern statistical tools to develop models for the behaviour of irradiated Gilsocarbon (in inert and oxidising atmospheres) and to compare these new models with the existing relationships.

The first stage of the effort was to collect all of the relevant data. In total, approximately 22 000 data points were collected that included 17 material properties over a temperature range of 150–1500 °C and to a dose of $367 \times 10^{20}$ n/cm$^2$ equivalent DIDO nickel (48 dpa). It should be noted that although all doses were stated as or converted to an equivalent dose (equivalent DIDO nickel or EDN), all of the temperatures were tabulated as actual irradiation temperature rather than the equivalent temperature (Equivalent DIDO Temperature or EDT). The reasons for not converting to EDT were (1) the flux of the MTR at the time of the experiment was often not reported, and (2) the concerns previously reported for the equivalent temperature concept. The Gilsocarbon in the database has different codes that identify who made the graphite, when it was made, the batch number etc., so the data can be analysed for specific codes of Gilsocarbon. A limited quantity of data was identified where the same Gilsocarbon graphite (same code) had been irradiated in different MTRs at varying flux levels but at approximately the same irradiation temperature. By comparing dimensional or material property changes for the same Gilsocarbon graphite code irradiated in different MTRs at the same temperature, it is possible to directly measure the flux effect relevant to each dimensional or material property change.

Comparison of the dimensional changes of the same Gilsocarbon graphite irradiated in PLUTO and DFR (quoted historically as having fluxes of $1.4 \times 10^{14}$ n/cm$^2$ s and $10 \times 10^{14}$ n/cm$^2$ s, respectively) showed general agreement using actual irradiation temperature, without using the equivalent temperature conversion (Figs. 7–9). However, this observation is based on limited data, often over different dose ranges. It was not possible in many cases to compare the dimensional changes at comparable equivalent temperatures (EDT) because of insufficient data. In addition, the experimental temperatures in DFR are known to have had significant uncertainty (up to ±70 °C in extreme cases [18]) that could hide any flux effect in the comparison. Thus, direct comparisons of specific datasets as in Figs. 7–9 should be interpreted as suggesting that there is little or no flux effect on dimensional changes over the temperature range considered (430–780 °C).

The statistical analyses reported in [17] are based in part on a Transformation Analyses Code which identifies the mean trends of data without having to assume a fitting function. The technique has the ability to identify correlations between variables (numeric) and factors (non-numeric), allowing the analyst to develop a model for the examined behaviour based upon the trends and correlations. After characterising key trends, a property change model was developed and calibrated by least squares. After the model
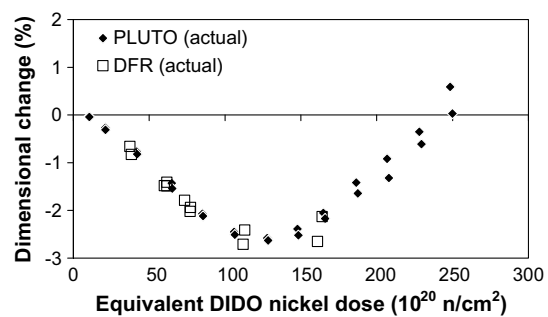


**Fig. 7.** Comparison of dimensional change data from PLUTO experiments at 430 °C actual irradiation temperature and DFR experiments at 430 and 435 °C actual irradiation temperatures.
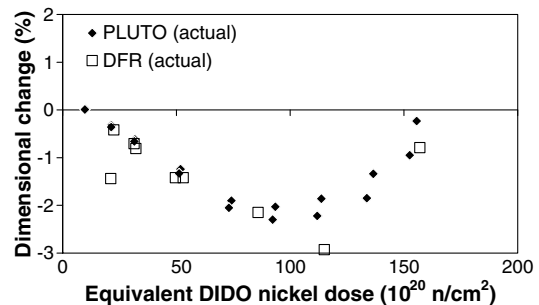


**Fig. 8.** Comparison of dimensional change data from PLUTO experiments at 600 °C actual irradiation temperature and DFR experiments at 600 and 620 °C actual irradiation temperatures.
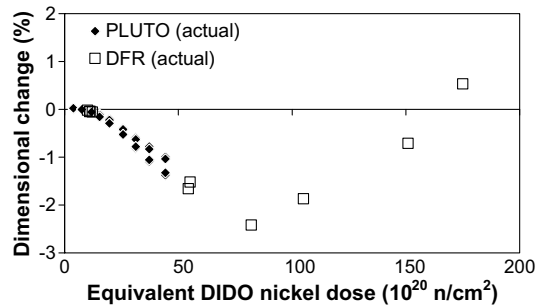


**Fig. 9.** Comparison of dimensional change data from PLUTO experiments at 780 ± 10 °C actual irradiation temperature and DFR experiments at 780 ± 10 °C actual irradiation temperature.
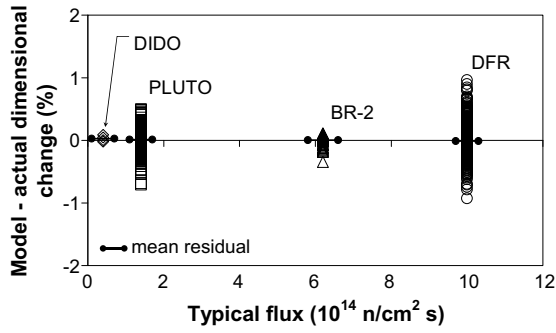
**Fig. 10.** Residual analysis with respect to MTR flux for dimensional changes of Gilsocarbon irradiated in an inert atmosphere at ~300–650 °C.
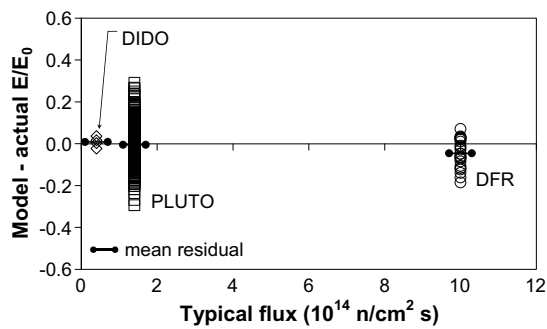


**Fig. 11.** Residual analysis with respect to MTR flux for Young's modulus changes of Gilsocarbon irradiated in an inert atmosphere at ~300–650 °C.

was developed, the quality of fit was analysed in a number of ways. One of these was a residual analysis, where the difference between the model estimate of property change and the actual measured property change was plotted against variables or factors used in the model and others that were not used in the model. The residual plots can be used to help identify any variable trends that are omitted from or inaccurately characterised by the model. The actual irradiation temperature was used in the model, rather than equivalent temperature, and flux is not in the model at all, so the residual plots for flux and irradiation temperature should reveal an un-modelled flux trend if flux should be considered and an inaccurate temperature trend if equivalent temperature should have been used. Instead, the residual analysis is consistent with no flux effect and using actual irradiation temperature.

Two irradiation effects models have been completed and undergone a residual analysis to date; a dimensional change model of Gilsocarbon irradiated in an inert atmosphere in the approximate temperature range 300–650 °C [17], and a Young's modulus ratio model (irradiated modulus divided by unirradiated modulus or $E/E_0$) of Gilsocarbon irradiated in an inert atmosphere in that same temperature range [19]. In the dimensional change case (Fig. 10) data are available from four MTRs (DIDO, PLUTO, BR-2, and DFR) and the mean residual calculated for all the data on each MTR is essentially zero, showing no overall flux effect. In the Young's modulus analysis (Fig. 11) data are available from three different MTRs (DIDO, PLUTO, and DFR), and in the two MTRs with the lowest fluxes (DIDO and PLUTO) the mean residuals were approximately zero. The mean residual for the highest flux MTR (DFR) is slightly off the zero line, by about 1–3% of the estimated $E/E_0$ value. Therefore, in the Young's modulus data there is also little or no flux effect in the approximate temperature range 300–650 °C.

## 6. Revisit of the UK PGA data

An attempt has also been made to revisit the UK Pile Grade A (PGA) MTR graphite irradiation database. Unfortunately there appears not to be the quantity of data as for the UK Gilsocarbon data with the most complete compendium being that by Birch and Brocklehurst [20]. The data has much more scatter than the Gilsocarbon data. However for irradiation temperatures above 300 °C the dimensional change and thermal resistivity data has been plotted in Figs. 12 and 13, respectively. Note some of the lower temperature DFR data which exhibited significant scatter, including swelling, have been omitted because, as previously discussed, these DFR data are for a broad temperature range with up to ±70 °C uncertainty on the irradiation temperature. The extent, dose and temperature ranges of the PGA dimensional change data are given in Table 2.

Attempts to fit statistical models to both the dimensional change and thermal resistivity data were unsuccessful due to insufficient data from some of the reactors and because the data did not cover the same temperature ranges. However, from Fig. 12 it can be seen by inspection that within the scatter there is no indication that a flux correction factor is required. Brocklehurst et al. [13] have suggested that EDT may not be applicable to dimensional change but would be applicable to a direct 'crystal' effect. To see if this was the case thermal resistivity for PGA is plotted in Fig. 13. However, again within the significant scatter there is no indication that this is the case.

## 7. Discussion

A more realistic theoretical EDT model would have to consider the variety of defects produced by atomic displacements in the particular radiation flux. At any one time the total observed number present could be considered as the sum of the numbers in various different defect configurations:
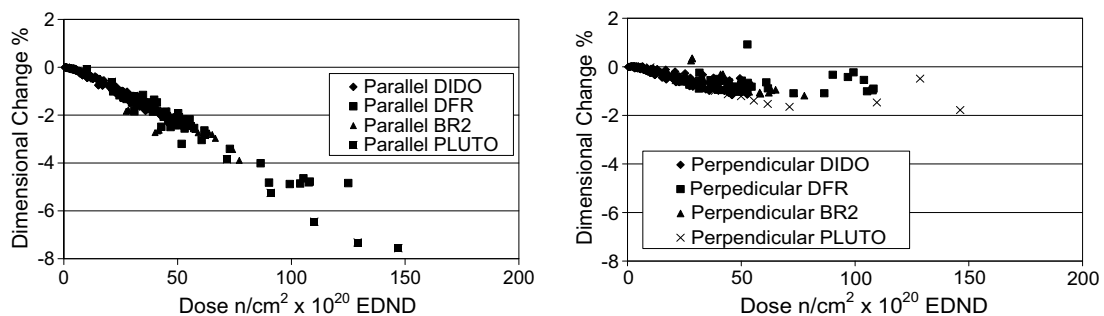


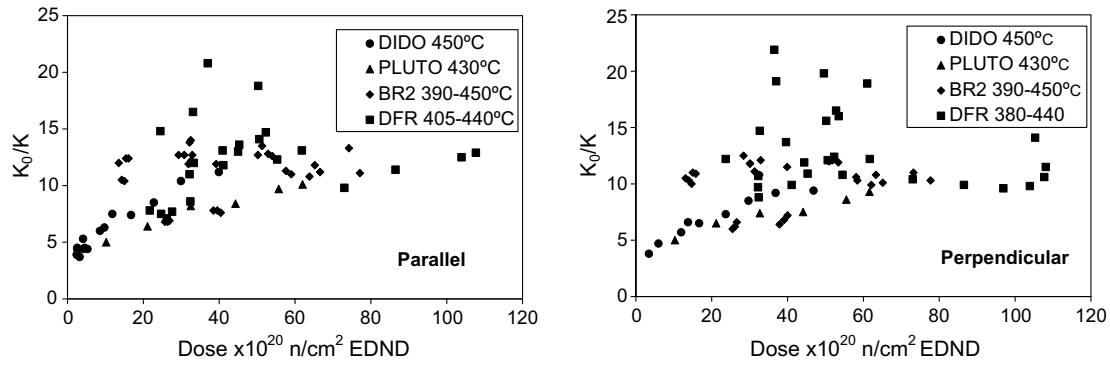**Fig. 12.** Dimensional changes in PGA graphite.

**Fig. 13.** Thermal resistivity change in PGA graphite.

**Table 2**
PGA dimensional change data, number of data points, dose and temperature ranges

| Reactor | | Parallel | | Perpendicular | |
|---|---|---|---|---|---|
| | | Temperature (°C) | Dose | Temperature (°C) | Dose |
| DIDO | Maximum | 650.0 | 52.6 | 650.0 | 52.6 |
| DIDO | Minimum | 300.0 | 0.5 | 300.0 | 0.5 |
| DIDO | N | 212 | 212 | 207 | 207 |
| PLUTO | Maximum | 600.0 | 147.0 | 600.0 | 146.2 |
| PLUTO | Minimum | 430.0 | 10.1 | 430.0 | 10.0 |
| PLUTO | N | 16 | 16 | 16 | 16 |
| BR-2 | Maximum | 450.0 | 77.1 | 450.0 | 77.7 |
| BR-2 | Minimum | 300.0 | 13.5 | 300.0 | 13.1 |
| BR-2 | N | 34 | 34 | 25 | 25 |
| DFR | Maximum | 790.0 | 125.0 | 790.0 | 108.1 |
| DFR | Minimum | 335.0 | 21.7 | 335.0 | 23.7 |
| DFR | N | 67 | 67 | 46 | 46 |

$$C_{obs} = C_1 + C_2 + C_3 + \cdots + C_T + \cdots + C_n. \tag{5}$$

These will exhibit (and are arranged in) an ascending range of stabilities depending on the local environment. Those in energy wells of the same order as $kT$ are those up to $C_T$: beyond $C_T$ only energetic particles have sufficient energy to remove the defect from its energy well. For simplicity it is assumed that incident fast neutrons have sufficient energy to anneal any defect which they have created. Conversion of one defect type into another more stable form will also be an added complication. However, with such a model the net rate of defect accumulation can be given by an equation of the form:

$$\frac{dC_{obs}}{dt} = \Psi\phi - k_{ra}\phi \sum_0^n C_n \sum_0^{n_t} C_n A_n \exp\left(-\frac{E_n}{kT}\right), \tag{6}$$

where $\Psi\phi$ is the instantaneous rate of defect production due to the flux $\phi$ and the second term is the rate of radiation annealing of defects, which is proportional to the product of flux and total defect concentration present. The third term is the rate of thermal annealing which is restricted to those defects in energy wells comparable in magnitude to $kT$.

Now as the irradiation temperature is raised, a point will be reached for those defects capable of thermal activation where the rate of thermal annealing will be much greater than the rate at which that category of defect is being formed by the neutron flux and their standing concentration will then be quite low. Beyond that temperature the main defects present will consist of defect types which can only be removed by energetic radiation and the standing net concentration will depend only on the relative rates of radiation production and annealing – a factor which will remain constant with flux.

Based on the above alternate derivation it is *physically* reasonable that there should be a temperature correction for flux effects at lower temperatures which disappears as the temperature is raised.

Unfortunately there is insufficient data to define the many constants required in the relationships given above, and in any case, so many constants would be involved that the relationship could be empirically fitted to any data set. It is clearly a balance between thermal annealing and irradiation annealing, and in general, one can expect a range of different types of 'damage'. In metals, these might be classified as various types of 'clusters' of point defects, 'Frenkel pairs' (of 'self' interstitial-vacancy pairs), enhanced lattice vibrations (heat), etc. However, there is insufficient understanding of the nature of such phenomena in graphite, or of the energies associated with any one form of 'damage'; hence, the ability of any one such form to be annealed-out by thermal or irradiation annealing. Therefore, a pragmatic approach needs to be taken through examination of the existing data. Over the higher temperature range above 350 °C, analysis of data does not support any effect of flux that needs to be addressed by an EDT correction. However, at lower temperatures below a temperature between 300 and 350 °C there appears to be need for correction, unfortunately the quantity and quality of the data does not allow for an exact temperature to be defined.

## 8. Conclusions

The origins of the equivalent temperature concept have been presented. Experimental data support the concept at temperatures of 350 °C and below, but show no consistent trends at higher temperatures in the range 350–650 °C.

For temperatures greater than 350 °C, there are technical reservations regarding the derivation and applicability of the equivalent temperature concept and of the use of a single activation energy across the temperature range of interest to modern graphite moderated reactors.

Comparison of data collected for ongoing statistical work did not identify any substantial flux effect when examining the dimensional and Young's modulus changes of Gilsocarbon graphite at 430–780 °C, in those cases where the graphite was irradiated in different MTR at similar actual temperature and a factor seven difference in flux Thus, an equivalent temperature conversion to account for flux would not be necessary.

The overall conclusion of this investigation is that equivalent temperature may be a credible method of accounting for flux and temperature effects at relatively low actual irradiation temperatures ($T_i < 350$ °C), but there is little or no clear evidence to support its use in the range 350–650 °C.

Analysis of the UKAEA PGA data for irradiation temperatures above 300 °C did not show any clear evidence of a flux effect although there is significant scatter in the data.

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