Failure probability study of HTR graphite component using microstructure-based model

Suyuan Yu, Xiang Fang, Haitao Wang, Chenfeng Li

Abstract

Nuclear graphite is widely used as in-core structural material in the high temperature gas-cooled reactors (HTRs). As mechanical properties of graphite change with neutron irradiation and temperature, the reliability evaluation of graphite internals of a HTR is commonly accomplished by the finite element analysis using various constitutive creep models and the following structural failure prediction with introduction of failure models that have essential impact on the final evaluation result. In this paper, a microstructure-based failure model proposed by Burchell in 1996 in conjunction with the finite element code INET-GRA3D of INET is used to study failure probability of a graphite side reflector design in the pebble-bed HTR during its entire service life from the microstructural view. The corresponding irradiation-induced creep stress analysis is carried out using both the UKAEA model and the Kennedy model. H-451 graphite is selected as material input since its irradiation material data from both macrostructure tests and microstructure observation is available. The results are compared with those using the macrostructure-based Weibull model commonly accepted in the engineering field and consistent trends are observed. Moreover, the Burchell model leads to the failure probability more sensitive to stress levels than the Weibull model.

1. Introduction

Nuclear graphite serves as reflector, neutron moderator as well as major structure material in high temperature gas-cooled reactors (HTRs). It is well known that fast neutron irradiation leads to both dimensional and material property changes of graphite, and that significant creep happens when graphite is stressed under such circumstance (Birch and Bacon, 1983; Blackstone, 1977). For the in-core graphite components, stresses are generated due to the non-uniformity of temperature and irradiation (Burchell and Sneed, 2007; Engle and Kelly, 1984). Considering that high stress concentration can significantly influence the structural integrity and service lives of graphite components, it is essential that stress distributions of graphite components are obtained and then properly evaluated. Over the last several decades, various constitutive creep models and failure models have been proposed and developed (Kelly, 1982). Such models are commonly integrated into the finite element code via user subroutines in order to carry out irradiation stress analysis and reliability evaluation of graphite components. Numerical evaluation of an irradiated graphite component using the finite element modeling technique consists of two steps, namely (1) irradiation-induced stress analysis: by establishing a three-dimensional graphite model, finite element meshing, inputting graphite properties (Young's modulus, CTE, thermal conductivity, dimensional change, etc.) as functions of both irradiation and temperature, generating creep parameters according to creep models, and applying boundary conditions (including temperature distribution and neutron irradiation distribution during the entire service life), a finite element analysis is carried out and stress distributions are readily obtained (Tsang and Marsden, 2005, 2007; Berre et al., 2008). (2) Reliability analysis: stresses at all integration points...
of the finite element model are used as input following certain deterministic or probabilistic failure model to evaluate structural integrity at each time point (e.g., each year) of the service life (Schubert et al., 1991; Oku and Ishihara, 2004).

There are several creep models available for the irradiation-induced stress analysis, like the UKAEA model (Kelly and Brocklehurst, 1977) and the Kennedy model (Kennedy et al., 1980), which establish a relationship between creep and other irradiation properties of graphite such as elastic modulus and dimensional information. These models have been verified by irradiation tests of stressed nuclear graphite specimens and good agreement was reported (Kelly and Burchell, 1994a). For the failure models, both deterministic and probabilistic models are accepted in the engineering standards and codes. The probabilistic method is commonly regarded as a more suitable tool to evaluate brittle materials like graphite. As an example of application, one can find the Weibull model used in the German HTR code draft KTA-3232 (KTA, 1992) to generate a value of failure probability for graphite components in HTRs. Parameters of the Weibull model come from the tensile tests of graphite specimens, which show direct but macro-structural information of failure. On the other hand, a microstructure-based failure model initially proposed by Burchell in 1996 attributes structural failure of stressed graphite to the microstructural fracture-induced failure of graphite particles. This model establishes a mechanism to evaluate structural integrity of graphite components from the microstructural view. Compared with frequent studies on the failure probability of graphite using the Weibull model (Schubert et al., 1991; Wang and Yu, 2008; Fang et al., 2011), there is little report on the application of the Burchell model to evaluate pebble-bed HTR graphite components.

In the present paper, the Burchell model is applied in conjunction with the finite element code INET-GRASD of INET to numerically study the failure probability of pebble-bed HTR graphite components from a microstructural view during the entire reactor service life. The idea of microstructural fracture-induced particle failure mode is extended to establish a failure mechanism at each integration point of the finite element model, thereby making it possible to evaluate failure probability of a graphite component with arbitrary shape. A candidate design of graphite side reflector in the pebble-bed HTR is selected to develop a three-dimensional model to be investigated. The following sections are organized as follows. In Section 2, the constitutive law of irradiation-induced creep of graphite is briefly reviewed and several classical creep models are summarized. In Section 3, detailed formula of probabilistic failure models including macrostructure-based Weibull model and microstructure-based Burchell model are listed, with a focus on their extension to be combined with the finite element modeling technique. In Section 4, a three-dimensional finite element model of one candidate design of the pebble-bed HTR graphite side reflector is established and analyzed using different creep model/failure model combinations. Stress distributions and the corresponding failure probabilities along with the entire reactor service life are calculated and compared among creep/failure models. In Section 5, conclusions are given.

2. Review of the constitutive creep law of irradiated graphite and creep models

2.1. Constitutive law of irradiate graphite

The constitutive law for nuclear graphite under high temperature and fast neutron irradiation condition is (Tsang and Marsden, 2008; Wang and Yu, 2008)

\[
\sigma = D(T, \gamma)\varepsilon^f = D(T, \gamma)(\varepsilon - \varepsilon^e - \varepsilon^R - \varepsilon^m)
\]

where \(\sigma\) is the stress tensor, \(D(T, \gamma)\) is the elastic matrix as a function of temperature \(T\) and neutron dose \(\gamma\). The total strain tensor \(\varepsilon\) is composed of the elastic strain \(\varepsilon^e\), thermal strain \(\varepsilon^T\), irradiation-induced strain \(\varepsilon^R\), and creep strain \(\varepsilon^m\). Generally speaking, the irradiation-induced creep strain is divided into two phases: the primary creep strain \(\varepsilon^C\) and the secondary creep strain \(\varepsilon^SC\). \(\varepsilon^C\) is commonly approximated as \(\varepsilon^C = \frac{\sigma}{E_0} + k_0\gamma\). Where \(E_0\) is the Young’s modulus of virgin graphite and \(k\) is the secondary creep coefficient. Therefore, \(\varepsilon^C\) in Eq. (1) is expressed as (Yao et al., 2007)

\[
\varepsilon^C = \varepsilon^PC + \varepsilon^SC = \frac{\sigma}{E_0} + k_0\gamma
\]

(2)

2.2. Creep models for stress analysis

The secondary creep coefficient \(k\) is a key factor in Eq. (2) as the value of \(k\) changes along with variations of temperature, neutron dose and stress loaded. In the classical visco-elastic model, \(k\) comes from the test data of irradiated graphite specimens under tensile or compressive load. However, such irradiation test of stressed graphite is very complicated, time-consuming and very limited data are available at the end. In order to overcome such drawback, several creep models such as the UKAEA model and Kennedy model have been developed to predict the creep according to the test data of other more easily obtained properties under irradiation.

In the UKAEA model, Young’s modulus is selected as the substitute of \(k, \ v\) at a neutron dose \(\gamma\) can be written as a function form as (Kelly and Brocklehurst, 1977)

\[
k(\gamma) = k_p \left[ \int \frac{E^*}{E(\gamma)} d\gamma \right] = k_p S(\gamma)^{-1}
\]

(3)

where \(k_p\) is the secondary creep coefficient in some specific region, \(E^*\) is the corresponding Young’s modulus. \(S\) is a structural factor. The creep strain in Eq. (2) by UKAEA model is rewritten as,

\[
\varepsilon^C = \varepsilon^PC + \varepsilon^SC = \frac{\sigma}{E_0} + k_p \int_0^\gamma S(\gamma)^{-1} d\gamma
\]

(4)

In the Kennedy model, the data of the percentage volume change \(\Delta V/V\) is applied instead of the data of \(k, v\) is rewritten as (Kennedy et al., 1980)

\[
k(\gamma) = k_p \left[ 1 - \mu \frac{(\Delta V/V)(T, \gamma)}{(\Delta V/V)_m} \right]
\]

(5)

\(\Delta V/V\) is a function of temperature \(T\) and neutron dose \(\gamma\) \((\Delta V/V)_m\) is the maximum volume shrinking of the graphite, and \(\mu\) is empirical constant, \(\mu = 0.75\). The creep strain in Eq. (2) is rewritten by Kennedy model as

\[
\varepsilon^C = \varepsilon^PC + \varepsilon^SC = \frac{\sigma}{E_0} + k_p \int_0^\gamma \sigma \left[ 1 - \mu \frac{(\Delta V/V)(\gamma)}{(\Delta V/V)_m} \right] d\gamma
\]

(6)

3. Probabilistic failure models

According to the finite element modeling, a graphite component can be divided into many integration points in the calculation. Each integration point refers to a calculated stress level and thus possesses an independent failure probability according to the probabilistic failure models. The total failure probability of a graphite component is a composite of all integration points’ failure probabilities. For the Weibull model and Burchell fracture model, the seeking law of one integration point’s failure probability as well as the synthesis artifice of the total failure probability are totally different. In addition, parameters of the two models have different physical meanings.
3.1. Weibull model

Parameters in the Weibull model are mainly obtained from the experimental test of uniradiated graphite specimens. To integrate this model to the finite element method, the probability density function \( f(x) \) at each integration point is determined by the following two-parameter Weibull distribution (KTA, 1992; Yu et al., 2004):

\[
f(x) = \left( \frac{x}{S_c} \right)^{m-1} \frac{m}{S_c} \exp \left[ - \left( \frac{x}{S_c} \right)^m \right]; \quad x > 0
\]

where \( m \) is a shape parameter, \( S_c \) is characteristic strength value. Both \( m \) and \( S_c \) arise from the fitting experimental curves. If \( \sigma \) represents the variable \( x \) in Eq. (7), failure probability \( P_i \) at an integration point can be designated as

\[
P_i = \int_0^\sigma f(x)dx = 1 - \exp \left[ - \left( \frac{\sigma}{S_c} \right)^m \right].
\]

The survival probability is then deduced as,

\[
1 - P_i = \exp \left[ - \left( \frac{\sigma}{S_c} \right)^m \right].
\]

The survival probability of the graphite component is

\[
P_i = \exp \left\{ - \sum_i \left( \frac{\sigma}{S_c} \right)^m \times \frac{V_i}{V} \right\},
\]

with \( V_i \) defined as the representative volume of the integration point and \( V \) the total volume of the graphite component, \( V = \sum_i V_i \).

The failure probability of the graphite component is then expressed as (Yu et al., 2004),

\[
P_{tot} = 1 - P_i = 1 - \exp \left\{ - \sum_i \left( \frac{\sigma}{S_c} \right)^m \times \frac{V_i}{V} \right\}.
\]

3.2. Burchell fracture model

The basic idea of the Burchell fracture model (Burchell, 1996) is reviewed and summarized below and integrated into the framework of the finite element method. The corresponding formulae are also referred to the literature (Burchell, 1996). In the finite element model, each integration point is considered to be a small representative volume element (cm magnitude). The integration points are comprised of a pile of graphite particles (mm magnitude or less). Each particle contains a so-called “weakness plane” which parallels to the \( a \)-axis of the particle and is oriented at angle \( \theta \) to the fracture exposure. A great deal of pores are randomly distributed in the graphite matrix. The pores are recognized as the starting point of the microstructural fracture occurred. Cracks extend by tearing the particles on its way along with the weakness planes. Fig. 1 shows the microstructure of a graphite representative volume containing particles and pores. Herein \( a \) and \( c \) are the mean filler particle size and pore radius respectively. When stressed at a level of \( \sigma \), a particle’s probability of fracture along the weakness plane is (Burchell, 1996),

\[
P_i = \frac{4}{\pi} \cos^{-1} \left( \frac{K_{pi}}{K_c} \right)^{1/3},
\]

where \( K_{pi} \) is a critical stress intensity factor which may reflect the resistance capacity of a particle against cracks. \( K_c \) is a stress intensity factor associated with a pore. \( K_i \) is defined as,

\[
K_i = \sigma \sqrt{\pi \varepsilon}
\]

According to Eq. (12), the limits of particle fracture probability can be defined. When \( K_i \leq K_c \), \( P_i = 0 \), indicating that the particle cannot be broken. When \( K_i > 2 \sqrt{\pi} K_c \), \( P_i = 1 \), indicating that the particle will certainly break. When \( K_{pi} < K_i < 2 \sqrt{\pi} K_c \), the corresponding probability of fracture is \( P_i \) if there are \( n \) particles along the crack path, the failure probability of the whole row is

\[
P_n = (P_i)^n = \left[ \frac{4}{\pi} \cos^{-1} \left( \frac{K_{pi}}{K_c} \right) \right]^{1/n).
\]

where \( n \) can be regarded as \( n = b/a \), \( b \) is the representative size of integration point.

With the crack propagating, the crack size will increase from \( c \) to \( c + dc \), \( i = 1, 2, 3 \ldots \). The probability of crack extending \( i \) rows of particles can be derived based on multiplication principle as

\[
P_a = \prod_{i=0}^\infty \left[ \frac{4}{\pi} \cos^{-1} \left( \frac{K_c}{\sigma \sqrt{\pi (c + ia)}} \right) \right]^{1/3} \left( \frac{b}{a} \right).
\]

Let \( a \) and \( K_c \) are constants for a particular kind of graphite, but \( c \) inevitably is distribution data. A probability function \( f(c) \) is defined as

\[
f(c) = \text{const} x \exp \left[ - \frac{1}{2} \left( \frac{\ln 2c - \ln S_0}{\ln S_d} \right)^2 \right].
\]

The probability that the size of a pore falls between \( c \) and \( c + dc \) is \( f(c)dc \). \( S_0 \) is the mean pore size and \( S_d \) is a statistical parameter reflecting the spread of \( c \)'s distribution. The probability that a single pore will destroy a whole integration point under stress \( \sigma \) is

\[
P_k = \int_0^\infty f(c)P_n(c, \sigma)dc.
\]
### Table 1

Table 1 Parameters for creep models.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>1</th>
<th>2</th>
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<tr>
<td>Primary creep ratio</td>
<td>Same as elastic (&lt;0.5)</td>
<td>Same as elastic (&lt;0.5)</td>
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<tr>
<td>Secondary creep ratio</td>
<td>Same as elastic (&lt;0.5)</td>
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The survival probability of the integration point is then expressed as,

$$P_j = (1 - P_k)^2 = \left[ 1 - \int_0^\infty f(c)P_n(\sigma, c)\,dc \right]^2$$  \hspace{1cm} (18)

As each pore has two sides, there is a square in the right side of Eq. (18).

If $N$ is defined as the number of pores per unit volume and $V$ is volume of the integration point, $NV$ is the amount of pores in the part. The total fracture probability of the part is

$$P_{tot} = 1 - P_{tot}^{NV} = 1 - \left[ 1 - \int_0^\infty f(c)P_n(\sigma, c)\,dc \right]^{2NV}$$  \hspace{1cm} (19)

The graphite component possesses many integrals whose volume and stress levels vary significantly. Therefore the survival probability of the component is (Ishihara et al., 2001)

$$P_j = \prod_j \left[ 1 - \int_0^\infty f(c)P_n(\sigma(j), c)\,dc \right]^{2NV(j)}$$  \hspace{1cm} (20)

The total fracture probability of the graphite component is

$$P_{tot} = 1 - P_{tot} = 1 - \prod_j \left[ 1 - \int_0^\infty f(c)P_n(\sigma(j), c)\,dc \right]^{2NV(j)}$$  \hspace{1cm} (21)

### 4. Numerical results

In the following, a three-dimensional finite element model is established according to a candidate design of the pebble-bed HTR graphite side reflector. Nuclear graphite H-451 is selected as material input since its irradiation material data from both macrostructure tests and microstructure observation is available. Stress analysis is carried out using both the UKAEA model and the Kennedy model in order to obtain stress distributions of the entire graphite component during its service life. The corresponding failure probability is deduced according to the microstructure-based Burchell fracture model, and the results are compared with those from the Weibull model.

#### 4.1. Finite element model and material data

The finite element is carried out using the three-dimensional finite element code INET-GRA3D developed by INET. The code is based on user subroutines of the commercial software MSC.MARC. Algorithms for various creep models and failure models are integrated into the code. Besides, some uncertainties must be taken into consideration in the analysis (Kelly and Burchell, 1994b). Two cases of different creep ratio are considered. The primary creep ratio must be the same as the elastic ratio (<0.5), while the secondary creep ratio is either the same as the elastic ratio (<0.5) or the same as the plastic case (0.5). The two cases and parameters are listed in Table 1. Both cases are calculated using various creep models and failure models.

A modified equivalent stress $\sigma_{eq}$ is used to evaluate service life of graphite component in reliability analysis defined as (Schubert et al., 1991),

$$\sigma_{eq} = \sqrt{\frac{\sigma_1^2 + \sigma_2^2 + \sigma_3^2 - 2\nu(\sigma_1\sigma_2 + \sigma_2\sigma_3 + \sigma_3\sigma_1)}{\bar{\sigma}}}$$

where $\nu$ is Poisson’s ratio, $\sigma_i$ ($i=1, 2, 3$) are modified principal stresses which are defined as:

$$\bar{\sigma}_i = \begin{cases} \sigma_i, & \sigma_i \geq 0 \\ \sigma_t, & \sigma_i < 0 \end{cases}$$

$\sigma_t$ ($i=1, 2, 3$) are principal stresses, $\sigma_t$ and $\sigma_c$ are the tensile and compressive stress, respectively.

Fig. 2 shows a 1/4 model with symmetric conditions of a candidate design of the pebble-bed HTR graphite side reflector. There are two circular holes, one for the control rod and the other serves as helium path. The left side of the brick faces to reactor core while the right side neighbors the peripheral carbon bricks. Fig. 3 shows the temperature distribution at the end of 30 years’ service life (EOL). The temperature of the core side is 450 °C while the other side is 280 °C. There exists a large temperature gradient around the control rod hole. The maximum fast neutron dose at the core side reaches $1 \times 10^{22}$ n cm$^{-2}$ (EDN) at EOL and decreases in a radial direction toward the outside, following an exponential law.

Young’s modulus is the key information in the UKAEA model as the Young’s modulus is selected as the substitute of the secondary creep coefficient. Fig. 4 shows the Young’s modulus’ curves for H-451 graphite versus neutron dose at 600 °C (Burchell, 2008).
Young's modulus sustains growth until $8 \times 10^{21} \text{n cm}^{-2} \text{(EDN)}$, followed by a constant phase and a re-increasing phase. The Young's modulus curve begins to decline after about $13 \times 10^{21} \text{n cm}^{-2} \text{(EDN)}$.

The Kennedy model uses the dimensional change as the substitute of the secondary creep coefficient. Fig. 5 shows the $a$-direction and $c$-direction percentage dimensional change for H-451 graphite versus neutron dose at 600°C and 900°C (Burchell, 2008). The shrinkage in $c$-direction is always smaller than the shrinkage in $a$-direction, indicating the expansion in $c$-direction will be much greater. The extreme shrinkage value at 600°C is greater than the value at 900°C. With the temperature rising, the initiation of shrinking and expanding occurs earlier, indicating that the graphite component will degrade sooner in high temperature.

For the failure model, parameters of the Burchell model come from the microstructure information of both unirradiated and irradiated graphite, while parameters of the Weibull model are commonly deduced from the tensile test data of unirradiated graphite. Table 2 lists major parameters of H-451 graphite for the Burchell model (Burchell, 1996). In order to make comparison, parameters of H-451 graphite for the Weibull model are calculated by fitting the probabilistic test data (Burchell, 1996) using the least squares fitting method and appended in Table 2.

Fig. 6 shows the prediction of the two models against the test result. Good agreement is observed. The maximum predicted deviation of both models is about 1 MPa. The experimental curve and two predicted curves are at the nearest at the mean strength point (50% failure probability, 16–17 MPa). On the left-half of Fig. 6, the failure probability of Weibull model prediction is the maximum, while failure probability of Burchell model prediction is the minimum. On the right-half, the state is just the opposite. That indicates the curve of Burchell model is “steeper” and more sensitive to the stress than Weibull model in a stress range near the mean strength point. When the stress changes, the variation of failure probability by Burchell model is expected to be greater than the variation by Weibull model.

In the presence of the fast neutron irradiation, most parameters in Table 2 change, except mean particle size $a$, bulk density $\rho$ and Statistical Parameter $S_d$, $K_i$ increases rapidly in the early irradiation, and reaches a saturation value of 0.42 MPa m$^{1/2}$ at dose of $10^{20} \text{n cm}^{-2} \text{(EDN)}$. Specimen volume $V$ and breadth $b$ are real-time obtained from FEM calculation. The neutron dose dependency of mean pore size $S_p$, mean pore area $P_a$, pore density $N$ and porosity are figured in Fig. 7 (Burchell, 1996). All modified parameters are adopted in Burchell fracture model reliability analysis.

![Fig. 4. Young's modulus development for H-451 at 600°C.](image1)

![Fig. 5. Dimensional change for H-451 at 600°C and 900°C.](image2)

![Fig. 6. Prediction and experimental results of tensile strength of H-451 graphite.](image3)

<table>
<thead>
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<th>Parameter</th>
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<td>Burchell model</td>
<td></td>
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<tr>
<td>Mean particle size, $a \text{(\mu m)}$</td>
<td>500</td>
</tr>
<tr>
<td>Bulk density, $\rho \text{(g/cm}^3\text{)}$</td>
<td>1.79</td>
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<td>Mean pore size, $S_p \text{ (\mu m)}$</td>
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<td>Statistical parameter, $S_d$</td>
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<td>Mean pore area, $P_a \text{(\mu m}^2\text{)}$</td>
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<tr>
<td>Number of pores per m$^2$, $N \text{(m}^{-2}\text{)}$</td>
<td>$2.97 \times 10^8$</td>
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<tr>
<td>Specimen volume, $V \text{(m}^3\text{)}$</td>
<td>$3.17 \times 10^{-6}$</td>
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<tr>
<td>Specimen breadth, $b \text{(mm)}$</td>
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<tr>
<td>Particle critical stress intensity factor, $K_i \text{(MPa m}^{1/2}\text{)}$</td>
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<td>Weibull parameter, $m$</td>
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<td>Weibull parameter, $S_i \text{(MPa)}$</td>
<td>16.86</td>
</tr>
</tbody>
</table>
4.2. Results and discussion

The modified equivalent stress distributions at beginning and end of life (BOL and EOL) in case 2 using the Kennedy model are shown in Figs. 8 and 9, respectively. The stress is concentrated in two areas, both of which move gradually to the outside over time. \( P_1 \) and \( P_2 \) are chosen as the stress concentration points at BOL. However, at EOL, the stress concentration areas move and make the two selected points displace to \( P_3 \) and \( P_4 \), respectively.

The curves of \( P_1 \) and \( P_2 \)'s modified equivalent stresses are shown in Fig. 10 with case 1 and Fig. 11 with case 2. It is shown that the stress at \( P_1 \) rises to peak value in the first 10 years, and drops down to origin in the later 15 years. The stress increases again to 2 MPa near EOL. The peak values in various cases are quite different. In case 1, the peak values are 3.1 MPa and 3.6 MPa under the UKAEA model and the Kennedy model respectively. But in case 2, the peak values are much higher and reach to 5 MPa and 5.6 MPa. In both cases, the stress result by the Kennedy model is always a little larger than the result by the UKAEA model.

At point \( P_2 \), the stress slightly increases then decreases in the first 20 years, and rises rapidly thereafter. The maximum value keeps on 5–6 MPa among various cases and models. The trends between cases have small differences. The stress of case 1 reaches the minimum value faster. In addition, similar results are obtained by different creep models.

Figs. 12 and 13 show \( P_3 \) and \( P_4 \)'s modified equivalent stress prediction in case 1 and case 2, respectively. The gap between the
predicted stress curves in the two cases is negligible, indicating that the choice of secondary creep ratio affects the stresses at $P_3$ and $P_4$ very little in the chosen temperature and irradiation range. The stresses at both points rise simultaneously and rapidly in the first 20 years, but diverge thereafter. The stress at $P_3$ falls while the stress at $P_4$ keeps on increasing throughout the life time except at EOL. The peak values at $P_3$ appear near 20 service year and reach 7 MPa and 7.9 MPa under the UKAEA model and the Kennedy model. The peak values at $P_4$ under various models appear near EOL and reach 8.6 MPa and 9.7 MPa. The stress result by the Kennedy model is also larger than the result by the UKAEA model with a largest deviation of 1.1 MPa.

The failure probability reflects the structural integrity and life sensitivity of graphite component. As the most important HTR core structural component, the graphite side reflector belongs to the first Structural Reliability Class (SRC-1) in the German HTR code draft KTA-3232 (KTA, 1992) with the allowable value of failure probability derived from stress distribution to be $10^{-4}$. The predicted failure probabilities of various creep and failure models in case 1 are shown in Fig. 14. The trends of all curves are the same although there are differences on the specific values. The failure probability increases continually in the whole lifetime except near EOL. The results obtained with Weibull distribution model reaches $1 \times 10^{-7}$ to $1.2 \times 10^{-7}$. The failure probability calculated with stress result of Kennedy model is greater since the Kennedy model gives greater stress result than the UKAEA model.

It is clearly shown in Fig. 14 that the failure probability obtained with Burchell model changes much faster. The results of Burchell model calculated with Kennedy model stress is an order of magnitude greater than the results calculated with UKAEA model stress. That indicates the Burchell fracture model is more sensitive to stress and neutron dose than the Weibull model. When the stress or neutron dose change, the changing rate of the Burchell model result is obviously faster than the Weibull model result. However, in the selected temperature and irradiation range, the failure probability values of both models are always comparable. This observation is consistent with the previous discussion in Section 4.1. The failure probability obtained with Burchell model is much lower than that of the Weibull model at BOL but increases rapidly and reaches peak value near 25 years, and the value is close to (calculated with UKAEA model) or even exceed (calculated with Kennedy model) the results of Weibull model.

Fig. 15 shows the failure probability curves in case 2. It is shown that the results in case 1 and case 2 are very close. The maximum failure probability appears near 25 years of service life. The peak value is $3 \times 10^{-8}$ to $1 \times 10^{-7}$ for Weibull model, and $5 \times 10^{-8}$ to $1 \times 10^{-6}$ for Burchell model.
5. Conclusions

Nuclear graphite is the key in-core structural material of the pebble bed HTRs. When subjected to high temperature as well as fast neutron irradiation, significant dimensional and property changes happen to the graphite, and creep occurs with load. The finite element method in conjunction with constitutive creep laws is commonly used to study structural integrity of the graphite components taking into account the above-mentioned irradiation behavior of graphite. Among numerous failure models developed to evaluate graphite components, the Burchell model gives a probabilistic prediction based on the microstructural characteristics of graphite. In this paper, the Burchell model has been integrated into the framework of the finite element code INET-GRA3D of INET and used to study failure probability of a pebble-bed HTR graphite component from the microstructural view. Both the UKAEA model and the Kennedy model have been adopted to generate creep in the stress analysis. H-451 graphite is selected as material input due to its available data from both macro- and microstructural views. The results have been summarized and compared with those using the Weibull model commonly accepted in the engineering field.

It is clearly shown that numerical results of the failure probabilities arising from the two failure models are in satisfactory agreement in the developing trends although there are discrepancies on the specific values. None of the predictions exceeds the criteria requirement $10^{-8}$. In addition, the Burchell model leads to the failure probability more sensitive to the stress and neutron dose than that of the Weibull model, indicating that stress concentrations play an important role in the Burchell model. This conclusion is consistent with the fact that Burchell focuses on the contribution of the peak stresses rather than the average contributions of all stresses as the Weibull model does.

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