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THE CALCULATION OF THE STRESS-STRAIN STATE OF GRAPHITE BRICKS OF THE URANIUM-GRAPHITE REACTORS AND THE PROGNOSIS OF THE DESTRUCTION OF THE GRAPHITE STACK RBMK-REACTORS

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The operation of RBMK-1000 and RBMK-1500 reactors has put on the agenda a number of tasks of prolongation service life for components of these reactors. They include computations to determine the shrinkages of graphite brick and motion of the pressure tube hole as well as their mechanical interaction after the tube-to-graphite gap has been used up or in accident conditions. A solution of these problems calls for determining the stress-strain state of the graphite block, with provision for radiation-induced creep and anisotropic dimensional change. One aspect of this problem is treated here, namely, the effect of the physical model of graphite as a continuous medium on the result of calculations. This work is deemed necessary due to widely known fact of inconsistency between calculations and the actually measured graphite brick hole motion [1]. The experimental data received from operation of uranium-graphite reactors of various types differ of 50 % or even more from the experimental data; in some cases the difference may reach a few hundred per cent. A comparison of calculation and experimental data is shown in fig. 1. This divergence is so large that it can not be eliminated by the introduction of corrections for the uncertainty of irradiation conditions (temperature or fluence) or through allowing for the non-linearity of the strain-stress loading diagram, for the effect of cyclic loading, creep anisotropy or material texture. The magnitude of the possible error was determined by varying the values of creep, elasticity modulus and scatter of the dimensional change properties. The contribution of above mentioned factors is estimated to be no more than 25 %. This is attributed to the inadequate representation of the graphite material as a deformed medium in the employed model compared with the properties of real-life material.

1. THE TRADITIONAL MODEL OF GRAPHITE AS A CONTINUOUS DEFORMED MEDIUM

The graphite structural model as a mechanics model of deformable body for the anisotropic material can be described by equations, typical for the deformed media, while the parameters of this model, namely mechanical properties like elasticity modulus, thermal expansion coefficient and others, including radiation-induced dimensional changes may be studied by traditional methods using radiation specimens data [2]. If cylindrical anisotropy, usually employed in calculations, is assumed, these equations look as follows:

$$\varepsilon_r = \frac{1}{E}(\sigma_r - \nu\sigma_\vartheta) - \frac{\nu_1}{E_1}\sigma_z + \alpha_r t + \chi_r + \varepsilon_r^v$$

$$\varepsilon_\vartheta = \frac{1}{E}(\sigma_\vartheta - \nu\sigma_r) - \frac{\nu_1}{E_1}\sigma_z + \alpha_\vartheta t + \chi_\vartheta + \varepsilon_\vartheta^v \qquad (1)$$

$$\varepsilon_z = \frac{1}{E_1}\sigma_z - \frac{\nu}{E_1}(\sigma_r + \sigma_\vartheta) + \alpha_z t + \chi_z + \varepsilon_z^v$$

These formulas use the following notation: σ-are components of the stress tensor, ε - components of the deformation tensor,E-is an elasticity modulus in the normal direction, E_1 - elasticity modulus in the parallel direction, ε^v - creep deformation, α - thermal expansion coefficients, t - temperature, ν - Poisson coefficient,χ - radiation dimensional change, r,ϑ,z -coordinates. It was proposed [3] to consider the dimensional change χ as if the temperature strain. There's a sufficient experimental basis for this, since it is possible to differentiate between the temperature, radiation-induced deformations and creep strains from specimen irradiation experiments. For example one may point out the results of the calculation of the radiation-induced dimentional change of the graphite brick of the RBMK-reactors. These calculations are based on three main hypotheses of the elastic theory: hypothesis of the preservation of the angles and sides of the simple element under thermal expansions (hypothesis of F.Neumann) and also by neutron irradiation, hypothesis of the stress-strain tensor connection, and the hypothesis of the continuous area (Saint-Vennant equation of continuity). As we propose these tree hypotheses must be reconsidered under graphite specific radiation initiated conditions. Also the balance. equations (Cauchy equation) must be modify for account of radiation induced volume force. We suggest a new model as the model of area with subelements. We supposed that more correct results of the calculation of the radiation induced dimensional changes of the graphite brick may be received if we consider not one but several sublevels of the mechanical interaction between elements of the graphite structure under irradiation. It is known from [2],[3], that graphite is a policrystallite material, and its components pass throw very complicated examinations under irradiation such as change of the crystalls sizes, their bending and splitting, subgrain pore criation and so on. Down we consider some assumptions which are used in a new macromechanical model of the graphite.

1.The Saint-Vennant equation of continuity (3), (4) in graphite is not correct as well as hypothesis of the preservation of the angles (hypothesis of F.Neumann) under the neutron irradiation. Equation of continuity are satisfy only in the resulting model.

2.As a corollary, Cauchy equation must be modify with allowance for of radiation induced volume force and they accept in the form:

$$\frac{\partial\sigma_{ij}}{\partial x_{ij}} - F_i^m = 0 \qquad (2)$$

Here F_i - is a set of distributed forces having the same effect as volume force in the elastic theory.

3.We supposed, that the different levels of interactions between crystallites may be modulated with the specific models, which of them consider only one principal side of the process.

4.The balance equations are correct for each models.

5.The based mechanical parameters such as elastic modulus, radiation induced creep and so on in each kind of elements may be differ.

6.The boundary condition in each kind of subelements are identical.

7.The radiation dimensional change in everyone subelements except specimental subelements is not take into account in the Saint-Vennant equation of continuity. So let's write it as

$$\frac{\partial^2 \varepsilon^{sum}_{xx}}{\partial y^2} + \frac{\partial^2 \varepsilon^{sum}_{yy}}{\partial x^2} = \frac{\partial^2 \varepsilon^{sum}_{xy}}{\partial x\, \partial y} \qquad (3)$$

for first group of equation and

$$2\frac{\partial^2 \varepsilon^{sum}_{xx}}{\partial y\, \partial z} = \frac{\partial}{\partial x}\left(-\frac{\partial \varepsilon^{sum}_{yz}}{\partial x} + \frac{\partial \varepsilon^{sum}_{zx}}{\partial y} + \frac{\partial \varepsilon^{sum}_{xy}}{\partial z}\right) \qquad (4)$$

for second group, where

$$\varepsilon^{sum}_{ij} = \varepsilon^{(s)}_{ij} + \varepsilon^{(r)}_{ij} + \varepsilon^{(c)}_{ij} \qquad (5)$$

The rest of the equation of continuity can be obtained with permutation of index x,y,z. Here

ε^{sum}_{ij} - are the deformation of the resulting model,

$\varepsilon^{(s)}_{ij}$ - deformation of the the specimental subelement,

$\varepsilon^{(r)}_{ij}$ - deformation of the rotate subelement,

$\varepsilon^{(c)}_{ij}$ - deformation of the compression subelement,

such that $\varepsilon^{(s)}_{ij}$ is defined by equation (1), $\varepsilon^{(r)}_{ij}$ and $\varepsilon^{(c)}_{ij}$ is defined only creep deformation in that subelements. It is assumed that another deformation in that subelements are insignificantly.

2. BASE SUBELEMENTS OF THE NEW MODEL

The number of subelements in this model must be in correlation with the number of specific elements of the graphite microstructure. The traditional model of the graphite as a continuous deformed medium is considered as a spacimental subelement with attribute (1). The characteristics of the other subelements are set according to the best correlation with experimental results.

2.1. Rotate subelement

We supposed that in graphite there are uniform distribution rotate elements which arise under irradiation and they create uniform rotation moment load. The arising of such load may be connected with unisotropic orientation of crystalline in graphite and nonunion of their dimensional changes under irradiation. The rotation deformation may be characterized with rotating moments M_k and torsional modulus B_k :

$$\omega_k = \frac{M_k}{B_k}; \qquad m_k = m_k(Q, t, \Delta t, \ldots\ ) \qquad (6)$$

Mean volume properties of the graphite under such moments may be character ed with the intensity of uniform distributed moments. We supposed that the moment magnitude is defined with the neutron flux intensity and some temperature function :

$$M_k = A_k \varphi f(t), \qquad (7)$$

where A -is a constant defined from experiment, φ - neutron flux intensity, f(t)- is a temperature function.

Under rotation moments action the balance equation became as

$$\frac{\partial \sigma_{ij}}{\partial x_{ij}^{m}} - F_i^{m} = 0$$

where F_i - is a system of distributed forces which is equivalent to volume moments defining from (4):

$$\int F_i^{m} r\, dr = \int M_i^{m} r\, dr \qquad (8)$$

The dependence between stress and strain is the same (1).

2.2. Compression subelement

Compression strains appear in bricks due to radiation induced and thermal dimensional changes of isolated crystallites. However as we supposed the properties of subelements may differ greatly the strains which appear in compression subelements due to some kinds of rotation may be essentially smaller then the creep deformations in the spacimental subelement. So if the magnitude of such moment is equal zero (or very small) the result of rotation may be approximate with some kinds action of the radiation induced dimensional strains indicated in equation (1) with the parameter χ. For the calculation of such subelements we may use Cauchy balance equation without distributed forces - that is in formula (2) F=0. Hypothesis of the preservation of the angles (hypothesis of F. Neumann) is satisfy.

3. THE DEFINITION OF THE PARAMETER OF THE PHENOMENOLOGICAL MODEL AND THE RESULTS OF CALCULATIONS

To determine the parameters of subelements one may use the experimental result of the radiation shrinkage of graphite bricks of the atomic power station [1] and the result of the investigations of properties of different kind graphite samples under irradiation. The magnitude of parameter χ of the compression subelement need for calculation of the shrinkage and destruction of the bricks not more than radiation induced radiation dimensional change of the separate crystallites of the graphite structure. The magnitude of parameter A of the rotate subelement is selected according to appearance of sufficient compression stress. Defined from this calculating parameters of subelements are closely spaced for graphite grade GR-280 and B-15. This model was used to create the mathematical correct method of calculation of the stress-strain state of the graphite bricks of RBMK - reactors. This method uses three subelements but after the choosing of parameters of subelements it became clear that for the essential increasing of the calculation precision of the radiation induced shrinkage of the graphite brick and the time to the brick crack it is quite enough only two subelements. The verification of this method at the graphite bricks of uranium-graphite reactors shows good agreement for the time of the brick failure and of magnitude of its shrinkage. The prognosis of the brick shrink was verificated according two results - the maximum shrink of the inner diameter of the brick and neutron fluence which corresponds to the maximum shrink (fig.1). The most important parameter of the strain-stress state of the graphite brick is the magnitude of the tension stresses in the tangential direction . Its changes over the neutron fluence is shown in fig. 2. As it clear from the calculation brick will develop cracks at the fluence about (1.6-1.7) 10 neutrons/cm (En > 0.18 MeV) when stress will exceed the breaking strength. Fig. 3 illustrates the difference in time upto the crack creation calculated from new and previous methods. The difference is very essential. As the concluding we consider that it is possible to improve this method essentially and create 2 - or 3 - dimentional method of the calculation due to take into consideration such parameters as neutron flux intensity, irradiation temperature and so on. However, it is not jet obviously what is better for mechanical model to use the rotate subelement or compression subelement.

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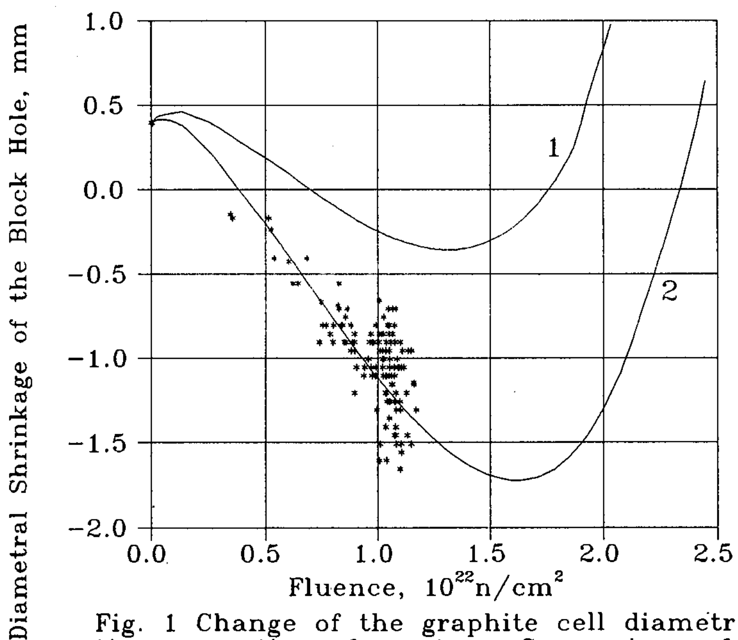

Fig. 1 Change of the graphite cell diametr vs. time operation of reactor. Comparison of the experimental (143 points, *) and calculation data. 1 - routine model, 2 - new model.

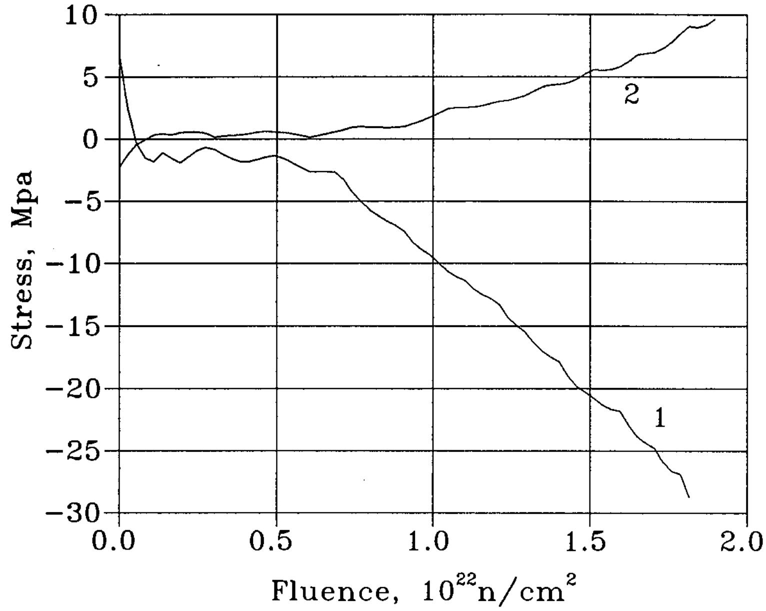

Fig.2 Change of the tensile or compression stresses on the inner (1) or external (2) surface of the graphite block vs. time operation of reactor.

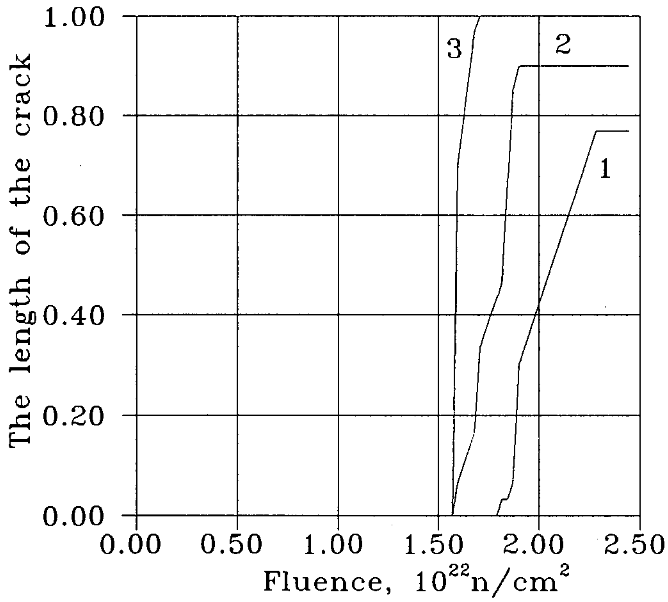

Fig.3 A forecast of the rupture of graphit blocks vs. time operation of reactor: 1-routine model, fail under allowable stress; 2 - new model, fail under allowable stress; 3-new model, fail under achievment critical value of intensity factor. The length of the crack in relation units.