SECTION 1
PHYSICS OF RADIATION DAMAGES AND EFFECTS IN SOLIDS

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EFFECT OF IRRADIATION AND THERMO-INDUCED PROCESSES ON REACTOR IN VESSEL ELEMENTS DURING LONG-TERM OPERATION

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A method for determining the effect of inhomogeneous temperature distribution, irradiation damage, irradiation swelling, irradiation creep of the material on the long-term strength of reactor in vessel internals and their deformation has been developed. The deformed state of the WWER type nuclear reactor baffle was determined. Constitutive equations taking into account the hidden damage of the material are proposed. According to the results of computer simulations, the strain fields of the section of the baffle during its operation for 60 years were analyzed, the place of possible occurrence of a macroscopic defect was determined.

INTRODUCTION

Continuation of the operation life of WWER reactors requires substantiation of the reliability of operation of reactor in-vessel internals (RVI), made of stainless steels type Kh18N10T. To solve this problem the data on the behavior of the materials of the RVI (primarily – baffles and shafts of the reactor) with long-term irradiation and the development of complex, significantly nonlinear processes are required.

The baffle of the WWER-1000 reactor (Fig. 1) is a monolithic cylindrical structure with an outer diameter of 3470 mm, the inner surface of which in cross section repeats the configuration of the core. It has 90 longitudinal channels for cooling. The total height of the reactor baffle, which consists of five elements in height, is 4070 mm. The height of each element is 814 mm [1].

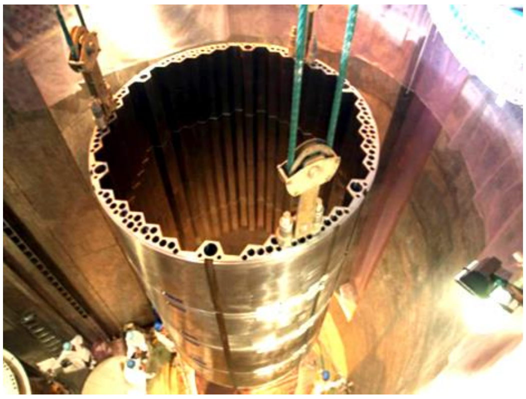


Fig. 1. Appearance of the WWER reactor baffle

For mathematical modeling of temperature modes and stress-strain state in structural elements of complex geometry, which is the baffle of a nuclear reactor, the Finite Element Method (FEM) is practically unalterable [2–4]. Two approaches are used to evaluate physically nonlinear processes, which include deformation under the action of radiation, both of which are based on FEM algorithms.

The first of them is formulated based on the approaches of the theories of elasticity and plasticity [5], considering a number of states of a deformed solid with different values of the yield stress. Radiation creep and swelling strains are taken into account for each, individually selected, time. Damage to the material is not taken into account in the general system of equations.

The second approach to the analysis of long-term deformation processes is to formulate and solve boundary- initial value problems, which from the point of view of the FEM theory are reduced to systems of nonlinear differential equations [3, 4].

The first approach is developed by B.Z. Margolin and co-authors [6, 7]. With the help of engineering software packages, in which the FEM is implemented, the results of the baffle’s calculation as a sequence of elastic-plastic problems with additional strains caused by inhomogeneous heating in cross section and irradiation are obtained. This approach does not take into account the processes of stress redistribution inherent in nonlinear problems, which constantly occur in the baffle: additional nodal forces in the finite element approach are varying over time [3, 4] due to changes in the rate of irradiation creep and swelling strains, and in recent stages - also due to hidden damage growth. This, as is known [8], leads to a change in stresses, especially in the first part of the operating time, which refers to the unstable creep.

Calculations were done by O.V. Makhnenko and I.V. Mirzov [9–11] were performed in a two-dimensional statement. The materials of the report [9] provide comparative tables, which analyze the data on radiation fluxes used in the calculations of WWER reactor baffles in different organizations and countries. The authors point out that the calculations were performed in an elastic-plastic formulation, but there is no description of mathematical models. Information on “radiation swelling” is given without specifying what measures were used: linear strains, mean strains, the second invariants of the tensor or another.

The second approach is more reasonable for modeling processes in which there is a significant redistribution of stresses over time [5, 8]. Creep problems, including taking into account the accumulated damage and volumetric, time-varying strains, belong to this class. The solution of such problems is performed by integration the systems of differential equations with respect to the nodal displacements of the FE model, which determine the values of stress and strain tensors in the elements. To model the deformation and strength of structural elements of nuclear reactors, this approach was used in [12–17].

The goal of this work is to present the method for determining the temporal changes of the RVI of the WWER type nuclear reactor with long-term operation, taking into account the inhomogeneous cross-sectional temperature distribution, irradiation damage, material creep by use of free and stress-dependent models of irradiation swelling. A baffle of the WWER type reactor is considered as an example of method's use.

METHOD OF SOLUTION AND CONSTITUTIVE EQUATIONS

Mathematical problem statement for the boundary-initial value problem is formulated for the case of the action of thermal, stress and irradiation fields and can be found in [16, 17]. By its use the finite deflections can be considered at arbitrary time step. Due to the obtained in [16] conclusion about the possibility of transition in calculations to a two-dimensional problem statement, the problem is formulated as plane strain one. Following the conclusions in previous section about the necessity of FEM usage for problems of these types, the FEM problem statement is presented below:

$$[K]\{\dot{u}\}=\{\dot{F}\}+\{\dot{F}^{Temp}\}+\{\dot{F}^{c}\}+\{\dot{F}^{sw}\};$$

$$\{\dot{F}\}=\sum_{N_\beta}\int_{V_\beta}\left[N^p\right]^T\cdot\{\dot{P}\}dV+\sum_{N_\beta}\int_{S_2^\beta}\left[N^p\right]^T\{\dot{h}\}dV+$$
$$+\sum_{N_\beta}\int_{V_\beta}\left[\bar{B}\right]^T\cdot[C]\cdot\{\dot{\varepsilon}^T\}dV;$$

$$\{\varepsilon\}=\{\varepsilon^e\}+\{\varepsilon^{Temp}\}+\{c\}+\{e^{sw}\};$$

$$\{\dot{F}^{Temp}\}=\sum_{N_\beta}\int_{V_\beta}\left[\bar{B}\right]^T\cdot[C]\cdot\{\dot{\varepsilon}^{Temp}\}dV;$$

$$\{\dot{F}^{sw}\}=\sum_{N_\beta}\int_{V_\beta}\left[\bar{B}\right]^T\cdot[C]\cdot\{\dot{e}^{sw}\}dV;$$

$$\{\dot{F}^{c}\}=\sum_{N_\beta}\int_{V_\beta}\left[\bar{B}\right]^T\cdot[C]\cdot\{\dot{c}\}dV;$$

$$\{\dot{c}\}=\frac{3}{2}B\frac{\sigma_i^{n-1}}{\left(1-\omega^r\right)^k}\exp\left(-\frac{Q_c}{T}\right)[\hat{C}]\{\sigma\},Q_c=\frac{U_c}{R}; \tag{1}$$

$$\dot{\omega}=H\frac{\sigma_e^m}{\left(1-\omega^r\right)^p}\exp\left(-\frac{Q_d}{T}\right),Q_d=\frac{U_d}{R},$$

$$\omega(0)=\omega_0,\quad \omega(t_*)=\omega_*.$$

Here $\{\sigma\}$, $\{\varepsilon\}$ are stress and strain vectors, $\{P\}$and $\{h\}$ are vectors of volume forces and traction; $[K]$ is the stiffness matrix of system; $\{u\}$ is global vector of nodal displacements; $\{F^{Temp}\}$ is the vector of nodal forces caused by temperature strains as well as $\{F^{sw}\}$ are nodal forces caused by irradiation swelling strains and $\{F^c\}$ are nodal forces caused by irradiation creep strains; $[\bar{B}]$ is the is the matrix differentiation operator; $[C]$ is the matrix of elastic constants; $[N]$ is a matrix of shape functions; β is finite element number; V_β is the volume of the finite element; $\sum_{N_\beta}$ is summation over all finite elements; S_2^β is the surface area of a finite element that is under a traction [3].

Let us consider the vector-matrix formulation of the basic equations used to describe the deformation of the baffle's material under irradiation conditions. Irradiation swelling strains are volumetric. In the general case, it is described by the function S_Φ, which depends on the neutron fluence Φ, time t and temperature T.

The following dependences are used to formulate the constitutive equation for the components of the irradiation swelling strain tensor (i, j = 1, 2):

$$e_{ij}^{sw}=\frac{1}{3}S_\Phi(D,T,...)\delta_{ij}, \tag{2}$$

$$\dot{e}_{ij}^{sw}=\frac{1}{3}\dot{S}_\Phi(\dot{\Phi},t,T,...)\delta_{ij}. \tag{3}$$

Vector components: $\{e^{sw}\}=\{e_{11}^{sw},e_{22}^{sw},0\}^T$. Equations (2) and (3) use function S_Φ or its rate. Them are depended upon the accumulated dose D or neutron fluence Φ, time t, temperature T and material constants.

To date, the functional expression for the function of radiation swelling S_Φ is obtained experimentally, using the processing of the obtained data by mathematical methods, such as the least squares method.

To construct the constitutive equations describing the process of free radiation swelling, experimentally obtained dependences for the strain components or their rates on the temperature and neutron fluence are used [18, 19].

The regularity of 18Cr10NiTi steel swelling – the basic material of pressure vessel internals of a WWER-1000 reactor – in conditions of simulation irradiation by heavy ions was studied. The experimental dependences of the swelling on dose and irradiation temperatures at dose rate 10^{-2} and 10^{-3} dpa/s were obtained. It is shown that on decrease of the rate dose the temperature range of porosity production expands and shifts to a lower temperature exposure, the absolute value of swelling increases. At temperatures corresponding to the maximum swelling of steel, with the dose rate increase the steady state of swelling decreases, and the incubation period increases. The increase of irradiation temperature reduces the incubation period. It is shown in accordance with the reactor and accelerator data that values of temperature maximum, of the incubation period, of swelling rate and the width of swelling temperature dependence have a logarithmic correlation with the dose rate. Obtained in the simulation experiments, systematic data on swelling of austenitic steel, along with the known reactor 18Cr10NiTi data were used in constructing of empirical function to predict swelling of 18Cr10NiTi steel in a wide range of doses, irradiation temperature and dose rate [18],

$$S(k,D,T)=R(k)\cdot\phi\left(D-D_0(k,T)\right)\cdot$$
$$\cdot\exp\left\{-\frac{\left(T-T_{\max}(k)\right)^2}{2\cdot\sigma_T^2(k)}\right\}, \tag{4}$$

where $S(k,D,T)$ is the swelling (%); D is the damage dose (dpa); T is the irradiation temperature (ºC); k is the dose rate (dpa/s); D_0 is the incubation period (dpa); $\phi(x)=x\cdot\theta(x)$, $\theta(x)=\begin{cases}1, & x>0\\ 0, & x\le 0\end{cases}$ is Heaviside unit step function; R is the swelling rate at steady state (%/dpa); $T_{\max}$ is the peak swelling temperature (ºC); σ_T is the temperature dispersion (ºC).

The validity of the extrapolation of the obtained function at lower dose rate characteristic for thermal reactors was analyzed. For this, the comparison of obtained results for swelling and the existing empirical literature functions was carried out [19].

The experimental dependences (4) are further used to perform the adjustment of the constitutive equation in the form (3) for the strain rate in the temperature range of the reactor baffle T=573…710 K at the value of the irradiation dose rate k=5.4·10^{-8} dpa/s.

Fig. 2 shows the time dependence of the free irradiation swelling uniaxial strain, presented for two limiting temperatures of 710 K (curve 1) and 573 K (curve 2). The plots for all other temperatures are similar and located between these two ones. As can be seen from the Fig. 2, the curves differ only in the angle of inclination, i.e. the value of the strain rate as well as by the moment of onset of significant development of swelling.

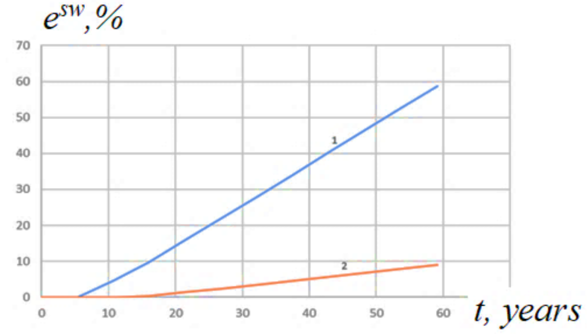


Fig. 2. Irradiation swelling strain versus time

Due to this fact, it is possible to use the classical exponential dependence [5] on the temperature T for the value of the strain rate of radiation swelling:

$$\left\{\dot{e}^{sw}\right\}=\left\{\frac{1}{3}A\exp\left(-\frac{Q}{T}\right),\frac{1}{3}A\exp\left(-\frac{Q}{T}\right),0\right\}, \tag{5}$$

$$Q=\frac{U^{sw}}{R}.$$

Here U^{sw} is irradiation swelling energy of activation; R is universal constant; A is a constant.

Also, according to the expression (4), the moment of the beginning of a stable strain increase is calculated. After processing the experimental data, it was obtained: A=1.54·10^{-3} h^{-m}, Q=5262.12 K.

Let us note that in [16] an approach to take into account the inhomogeneous distribution of the irradiation dose on radius in order to determine the values of irradiation swelling strains was proposed. It was formulated by introducing a function that depends on the radius of the baffle. The same function is used in calculations in this work.

Another formulation for irradiation swelling stain rate function $\dot{S}_{\Phi}$, which depends upon current stress level, was presented in [20, 21]:

$$\dot{S}_{\phi}=C_D nD^{n-1}(t)f_1(T)f_2(\sigma_m)f_3(\kappa)\dot{D}(t), \tag{6}$$

where $f_1=e^{-r(T-T_{\max})^2}$;

$f_2=1+8\cdot10^{-3}\left(0.85\cdot\sigma_m+0.15\sigma_{eq}\right)$; $f_3=e^{-\eta\kappa}$;

$C_D=1.035\cdot10^{-4}$; $n=1.88$; $r=1.825\cdot10^{-4}$; $\eta=8.75$;

$T_{\max}=470^\circ\mathrm{C}$; $\kappa=\int d\varepsilon_{eq}^{p}$ – Odquist's parameter; σ_m – mean stresses.

The method of taking into account thermal strains $\left\{\varepsilon^{Temp}\right\}=\left\{\varepsilon_{11}^{Temp},\varepsilon_{22}^{Temp},0\right\}$; which are volumetric and caused by thermal expansion, is generally accepted [3]:

$$\left\{\varepsilon^{Temp}\right\}=\left\{\alpha\Delta T,\alpha\Delta T,0\right\}. \tag{7}$$

Here α is a coefficient of linear expansion of isotropic material.

To formulate the equation for the irradiation creep strain rate, we use Norton's classical power law [5, 8]. Often, when processing experimental data, it turns out that the obtained dependence is linear [12–14], and the exponent n in (1) should be equal to 2. The matrix $\left[\hat{C}\right]$ has the following form [17]:

$$\left[\hat{C}\right]=\begin{bmatrix}1 & -1/2 & 0\\ -1/2 & 1 & 0\\ 0 & 0 & 3\end{bmatrix}.$$

The formulated FE problem is solved using the finite difference method for time integration [22].

RESULTS AND DISCUSSION

For numerical simulation we use the software package *FEM CREEP* [22], to which the program unit for the calculation of nodal forces *{F^{sw}}* considering the action of irradiation swelling strains is implemented. Plane strain statement is used. Due to the symmetry of the cross section, we consider one quarter of it. FE model is used, with the use of which the initial thermoelastic deformation results are obtained, quantitatively and qualitatively consistent with the data of 3D calculations and data of other authors [16].

First, we consider the results of numerical simulation of the baffle deformation using the equations (6). For the test calculation, a moderate value of the irradiation dose is equal to 42 dpa accumulated over 60 years was set.

Fig. 3 shows a map of the distribution of von Mises equivalent strains along the baffle's section, obtained using equations (6).

Let us note that when using in equations (6) even a moderate amount of the dose accumulated over 60 years, the calculation data due to the finite strain values are questionable. Maximum strains reach 81%, which significantly exceeds the value of the ultimate elongation of this material at fracture, which at temperatures of 300…400 °C is 25…30%. An increase in the dose value leads to even more significant strains and stops the calculations.

This result may be obtained due to the incomplete compliance of this model with the range of stresses and temperatures analyzed for the case of the operational data of the baffle. It is also possible that equations (6) [20, 21] are not suitable for use in the complete solution of the boundary - initial value problem, despite the fact that they are built in incremental form: as can be assumed from publications, calculations are performed for several time values without taking into account stress varying over time. A discussion of the possibility of using equations (6) in solving boundary value problems can be found in [23].

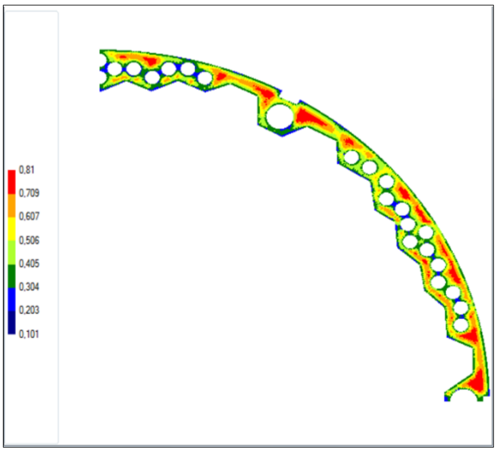


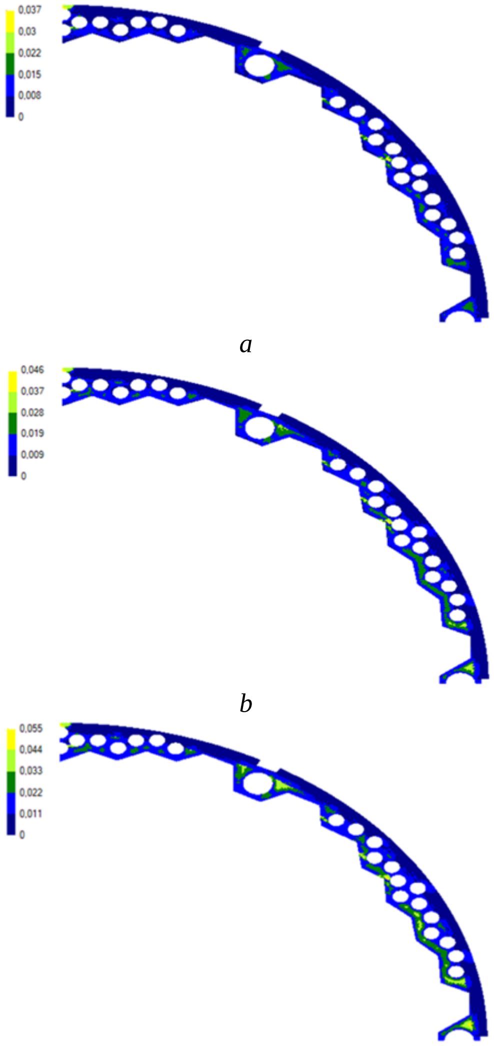
Fig. 3. Distribution of von Mises equivalent strains by baffle cross section, t = 60 years. Using equations (6) [20, 21]

Next, we present the results of calculations of the strains in the baffle using the equations (4)–(5). Inhomogeneous distribution of a dose on radius is accepted. Its maximum value on the inner radius for 60 years of operation was 100 dpa. The distribution of von Mises equivalent strains along the cross section of the baffle for 40–60 years of operation is presented in Fig. 4.

As can be seen from Fig. 4, the maximum deformation occurs in the areas of the channels: 9th, 11th, 14th (counting from the bottom of the images), and at the channel of large diameter located at the top of the image. These facts can be explained by effect of stress concentration.

The application of the refined equation for the swelling strain rate (5) gives much lower values for the maximum strains (4.4…5.5% for 60 years of operation) than those given in [16]. The distribution of strains over the vast majority of cross-section points is very moderate and has values of 1…2%.

It is known that with long-term loading there is an accumulation of hidden damage in the material, the action of which eventually leads to a macroscopic defect (crack). The description of the processes of damage accumulation was carried out using the concepts of Continuous Damage Mechanics (CDM) [5]. The following values of constants for the damage evolution equation were used in the calculations: [16]: $p=m=15.52$; $H=9.55\cdot10^{-48}$ MPa^{-m}/h, $Q_d=1023$ K.



a

b

c

Fig. 4. Distribution of von Mises equivalent strains by baffle cross section, t = 40 (a), 50 (b), and 60 years (c). Using equations (4), (5)

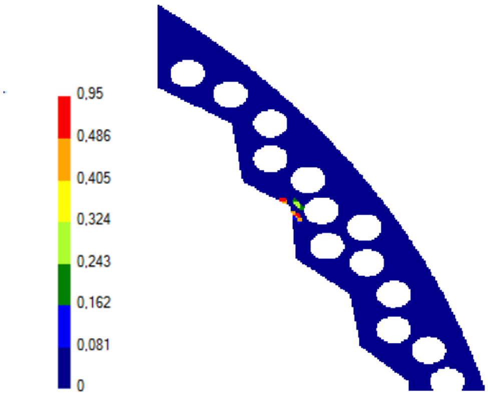


Fig. 5. Distribution of the damage parameter in the fragment of the baffle cross section, t = 47 years

The results of calculations in the form of distribution the damage parameter ω along the baffle cross section (Fig. 5) show that the accumulation of hidden damage is uneven and ends with an arising of macrodefect in the area of 9th hole, where ω has its critical value ($\omega = 0.95$). The obtained value of fracture time is equal to about 47 years. The arisen macrodefect (its size does not exceed 1 mm), as is known [5], may begin to develop further.

CONCLUSIONS

The method of calculation and results of computer modeling of processes of stress-strain state varying and accumulation of hidden damage in the baffle of a WWER-type nuclear reactor, in the material of which of irradiation creep and swelling strains develop, are presented.

The following main conclusions are obtained:

It is established that the model of irradiation swelling, which depends on the current stress level, gives inflated results in the analysis of the strain level, which may be due to its unsuitability for use in the complete solution of the boundary – initial value problem. Probably, the authors of this model used it when calculating only boundary value problems, which did not take into account the stress varying over time, which occurs due to the combined action of irradiation creep and swelling. It is also possible that the model does not fully correspond to the temperature range of the considered baffle.

According to the calculations using the free swelling model, it was found that the maximum strains, which is approximately 4.4…5.5% over 60 years of operation, are occurred in the inner parts of baffle section.

Calculations performed using the approaches of CDM (Continuous Damage Mechanics) have established the possibility of initiation of a small macroscopic defect after approximately 47 years of operation. The zone of its occurrence corresponds to the stress concentrator in the area of the cooling channel. The time and place of origin correlate with the data of the ‘Prometheus’ Research Institute, obtained using the IASCC model.

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ВПЛИВ РАДІАЦІЙНО- ТА ТЕРМОІНДУКОВАНИХ ПРОЦЕСІВ НА ВНУТРІШНЬОКОРПУСНІ ПРИСТРОЇ РЕАКТОРІВ ПРИ ЇХНЬОМУ ДОВГОТРИВАЛОМУ ФУНКЦІОНУВАННІ

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Розроблено метод визначення впливу неоднорідного розподілу температури, радіаційного пошкодження, об'ємного радіаційного розпухання, радіаційної повзучості матеріалу на довготривалу міцність внутрішньокорпусних елементів та їх формозмінення. Визначено деформований стан вигородки ядерного реактору типу ВВЕР. Запропоновано рівняння стану, що враховують приховану пошкоджуваність матеріалу. За отриманими результатами комп’ютерного моделювання проаналізовано поля деформацій перерізу вигородки при її експлуатації протягом 60 років, встановлене місце можливого виникнення макроскопічного дефекту.

ВЛИЯНИЕ РАДИАЦИОННО- И ТЕРМОИНДУЦИРОВАННЫХ ПРОЦЕССОВ НА ВНУТРИКОРПУСНЫЕ УСТРОЙСТВА РЕАКТОРОВ ПРИ ИХ ДЛИТЕЛЬНОМ ФУНКЦИОНИРОВАНИИ

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Разработан метод определения влияния неоднородного распределения температуры, радиационного повреждения, объемного радиационного распухания и радиационной ползучести материала на длительную прочность внутрикорпусных элементов и их формоизменение. Определено деформированное состояние выгородки ядерного реактора типа ВВЭР. Предложено уравнение состояния, учитывающее скрытую повреждаемость материала. По полученным результатам компьютерного моделирования проанализированы поля деформаций сечения выгородки при ее эксплуатации в течение 60 лет, установлено место возможного возникновения макроскопического дефекта.