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Stresses and Strains of Equipment Inside a WWER-1000 Nuclear Reactor

Abstract: The article concerns the modelling of stresses and strains of the enclosure of the active zone and chamber housing inside a Wwer-1000 reactor, taking into consideration welding, heat treatment and the operation of the structure in the conditions of intense radiation. The work presents the input of welding internal stresses and contact stresses into the total stress of the chamber housing inside the reactor vessel. The article-related research involved testing the relaxation of welding internal stresses in the active zone enclosure caused by radiation creep.

Keywords: stress, strain, Wwer-1000, equipment inside the reactor vessel, radiation swelling, welding internal stresses, modelling

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Introduction

Ukrainian nuclear plants operate 13 Wwer-1000 power units, where the design service life of 30 years either has finished recently or will have finished by 2020. Therefore, a current task is to extend the operation time of power units, including elements inside the reactor vessels, two of which are welded structures, i.e. the enclosure of the active zone (a belt with polygonal internal surface, located on the perimeter of the active zone, used for reducing the non-uniform emission of energy from external fuel rods by absorbing excessively emitted energy) and the housing of the chamber inside the reactor vessel used for splitting the entering and leaving of stream of the heat carrier, protecting the reactor vessel against neutron and gamma radiation as well as placing the active zone elements inside the reactor (Fig. 1).

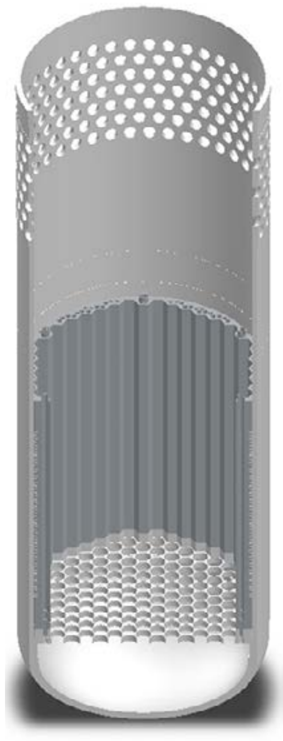

Fig. 1. Enclosure of the active zone and the chamber housing inside the WWER-1000 reactor vessel

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Elements inside the reactor vessel are made of austenitic steel 08H18N10T (X6CrNiTi18-10) and operated in conditions of intense radiation, leading to the radiation volumetric swelling of structural materials. There are several mathematical models describing an increase in material volume during radiation swelling; the simplest of them include temperature-dose dependences of volume increase [1, 2, 3]. However, the process also depends on stresses; an appropriate model was proposed by the Central Research Institute of Structural Materials "Prometey" [4]. The model described an increase in the volume of material during radiation in relation to a dose of radiation, temperature, stress and the intensity of plastic strains:

$$S= C_D \cdot D^n \cdot f_1(T) \cdot f_2(\sigma_m, \sigma_{eq}) \cdot f_3(æ) \geq 0 \qquad (1),$$

where D — accumulated damaging dose (displacements per atom, sna),
C_D=1.035 · 10^{-4}s · sna^{-n}, n=1,88,
$f_1(T) = \exp(-r \cdot T\text{-}470)^2$, r = 1.825·$10^{-4}$ °C^{-2}
σ_m – average stresses, σ_{eq} – intensity of stresses,
$f_2(\sigma_m, \sigma_{eq}) = 1+8\cdot 10^{-3}(0.85\cdot \sigma_m + 0.15\cdot \sigma_{eq})$,
$f_3(æ) = \exp(-8.75\cdot æ)$, $æ = \int_t d\varepsilon_{eq}^{pl}$ – accumulated plastic strain.

In order to apply this model to the design of elements inside the reactor vessel, it is necessary to write this model in the differential-tensor form as well as include welding internal stresses and the heat treatment of the structure.

Objective – improvement of the mathematical model of the radiation swelling of the material of elements inside the reactor vessel as well as the computational test, analysis of stresses and strains and of changes in the shape of elements inside the reactor vessel during operation lasting up to 60 years.

Methodology of Calculating Stresses and Strains of Elements Inside the Reactor Vessel During Radiation Swelling

Improvement of Radiation Swelling Model

The problem of determining the stresses and strains of elements inside the reactor vessel is solved as an elastic-viscous-plastic problem:

$$\varepsilon =, \varepsilon^{el} + \varepsilon^{pl} + \varepsilon^{sw} + \varepsilon^{er}$$

where index *el* corresponds to a plastic strain, *pl* – momentary plasticity strain, *sw* – radiation swelling strain, *cr* – diffusive plasticity strain (creep).

The elastic problem is solved on the basis of the Hooke law, which in the tensor form can be presented as the sum of components, i.e. an isotropic component of a tensor and a deviator:

$$\varepsilon^{el} = \sigma^{dev} \cdot \frac{1}{2G} + I\,\sigma_m \cdot K \qquad (2)$$

where $\sigma^{dev}=\sigma\text{-}I\sigma_m$ – stress deviator,

$\sigma_m = \frac{1}{3} I : \sigma$ – stress averages, $G = \frac{E}{2(1+\nu)}$ – modulus of transverse elasticity, ν - Poisson ratio,

$K = \frac{(1-2\nu)}{E}$ – compression modulus.

Thermal strains in the material of elements inside the reactor vessel result from γ-heating and are described by the second component in equation (2). The first component describes a change in the shape of material related to elastic load.

The work hardening of material was omitted. Plastic strains are described by the equation of plastic flow associated with the Mises plasticity condition [5]:

$$d\varepsilon^{pl} = d\lambda \cdot \sigma^{dev} = d\varepsilon_{eq}^{pl} \cdot \frac{3}{2}\frac{\sigma^{dev}}{\sigma_{eq}}, \qquad \varepsilon^{pl}\Big|_{t=0} = \varepsilon^{residual}$$

where

$$d\lambda \begin{cases} =0, & f<0 \\ =0, & f=0, \ \ df<0 \\ >0, & f=0, \ \ df>0 \end{cases}$$

$$f=\sigma_{eq}^2-\sigma_T^2(T,D)\le 0$$

$\sigma_{eq}=\sqrt{3/2\sigma^{dev}:\sigma^{dev}}$ – intensity of stresses,
$\sigma_T(T, D)$ – material yield point depending on temperature and radiation dose,

$d\varepsilon_{eq}^{pl}=\sqrt{2/3d\varepsilon^{pl}:d\varepsilon^{pl}}\ge 0$ – intensity of plastic strain increase.

The problem concerning the determination of swelling strains is non-linear, therefore dependence (1) should be written in the following differential form:

$$d\varepsilon_{eq}^{sw}=C_D\, n\, D^{n-1}\frac{dD}{dt}f_1(T)\cdot f_2(\sigma_m,\sigma_{eq})\cdot \cdot f_3(æ)\,dt\ge 0 \quad (3)$$

In the mathematical formulation, radiation effects of swelling and creep are tensor quantities and are summed in a tensor manner at every step after time. The swelling strain constitutes an isotropic component of a strain tensor, whereas the creep strain constitutes a deviator component of a strain tensor. The scalar quantity of the increase in swelling strain intensity $d\varepsilon_{eq}^{sw}$ is converted into tensor using the following dependence:

$$d\varepsilon^{sw}=\frac{1}{3}d\varepsilon_{eq}^{sw}I, \qquad \varepsilon^{sw}\Big|_{t=0}=0. \quad (4)$$

The increase in the intensity of radiation creep strain is defined using the dependence proposed by proposed by the Central Research Institute of Structural Materials "Prometey" [4]:

$$d\varepsilon_{eq}^{cr}=\left(B_0\frac{dD}{dt}dt+\omega\cdot d\varepsilon_{eq}^{sw}\right)\sigma_{eq}$$

$$B_0=1\cdot 10^{-6}\,(MPa\cdot sna)^{-1},\ \ \omega=2.95e-3\ MPa^{-1}$$

and is converted into the strain tensor:

$$d\varepsilon^{cr}=d\varepsilon_{eq}^{cr}\cdot\frac{\partial\sigma_{eq}}{\partial\sigma}=d\varepsilon_{eq}^{cr}\cdot\frac{3}{2}\frac{\sigma^{dev}}{\sigma_{eq}}, \qquad \varepsilon^{cr}\Big|_{t=0}=0. \quad (5)$$

The calculation of the increase in radiation swelling (4) and creep (5) takes place at every time step. It is also then that the damaging radiation dose, yield point, stresses and plastic strains are calculated in each finite element. Increases in strain are summed in all time steps. The first invariant of the total tensor of radiation swelling strain, i.e. $I:\varepsilon_{sw}$ is assumed as the volumetric swelling strain.

In the manner presented above, in the existing mathematical model concerning the radiation swelling of the material of elements inside the reactor vessel (and taking into consideration radiation creep [4]) it was possible to move from scalar quantities to the differential-tensor form. This change enables the use of such an improved mathematical model for the computational assessment of stresses and strains of elements inside the reactor vessel.

Welding Internal Stresses in the Housing

The housing inside the reactor vessel is a welded structure containing longitudinal welded joints. The E.O. Paton Electric Welding Institute modelled the field of welding internal stresses in the wall of the housing inside the reactor vessel in relation to multi-run arc welding [6]. The welds of the housing inside the reactor vessel can be situated in the area of the big channel of the active zone enclosure (Fig. 2).

The fields of welding internal stresses in the housing and appropriate strains are transferred for calculations of stresses and strains during the heating of the reactor. Afterwards, stresses

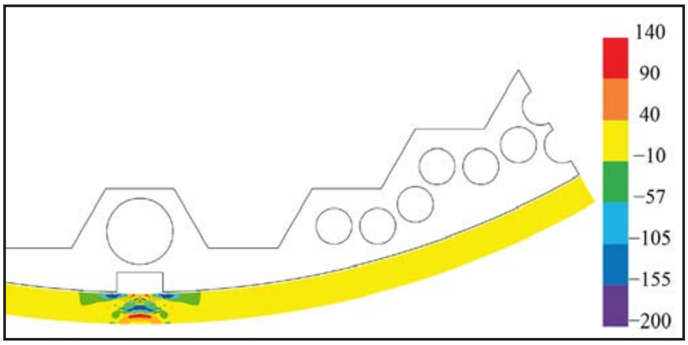


Fig. 2. Distribution of circumferential stresses in the weld zone of the housing of WWER-1000 reactor during production, MPa

and strains in the housing (taking into consideration its non-uniform heating and welding internal stresses) are transferred for calculations of radiation swelling as initial conditions.

Welding Internal Stresses in the Enclosure of the Reactor Active Zone

The enclosure of the active zone of a WWER-1000 reactor is a welded structure. The product information sheet says that the enclosure has been made using electroslag welding. The specialist at the E.O. Paton Electric Welding Institute selected optimum technological conditions for the welding of the enclosure using the electroslag welding guide [7]. They also developed a computational algorithm related to welding internal stresses present when electroslag welding the enclosure of a WWER-1000 reactor taking into consideration the heat treatment of welded joints.

The enclosure of the active zone of a WWER-1000 reactor is subjected to post-weld heat treatment, i.e. tempering at a temperature of 650°C for 6 hours. The heating is accompanied by the relaxation of welding internal stresses caused by thermal creep; maximum axial internal stresses decrease from 305 MPa to 65 MPa, circumferential stresses decrease from 105 MPa to 37 MPa, whereas radial stresses decrease from 90 MPa to 31 MPa (Table 1, Fig. 3). The fields of welding internal stresses in the active zone enclosure and appropriate strains are transferred for calculations of stresses and strains during the heating of the reactor. Afterwards, stresses and strains in the enclosure (taking into consideration its non-uniform heating and welding internal stresses) are transferred for calculations of radiation swelling as initial conditions.

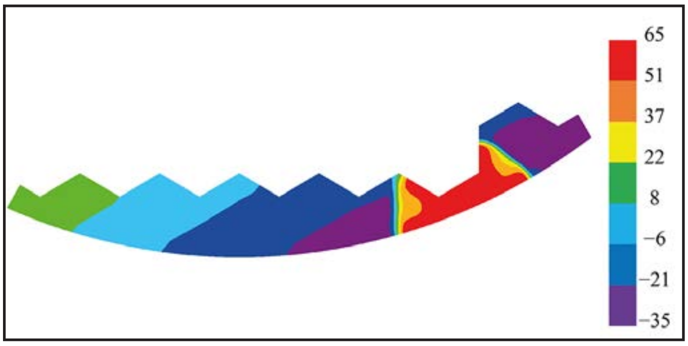


Fig. 3. Distribution of axial welding internal stresses in the enclosure of the active zone of a WWER-1000 reactor after heat treatment, MPa

Results and Discussion

Change in the Shape of the Active Zone Enclosure Caused by Radiation Swelling

The image presenting the swelling of the active zone enclosure was obtained in the research related to publication [6]. The non-uniformity of swelling leads to the deformation of the enclosure. During the reactor operation, distances between the enclosure and heat-emitting fuel assemblies and the housing inside the reactor vessel decrease. The obtained computational results of the radial displacements of the enclosure were validated experimentally in the second power unit of the South-Ukrainian Nuclear Power Plant (JuUAES-2) after 30 years of operation. The calculation results (the full line in Figure 4) correspond well to the experiment (points in Figure 4) both qualitatively and quantitatively.

Table 1. Maximum compressive/tensile welding internal stresses in the enclosure of the reactor active zone, MPa

Stage	Radial	Circumferential	Axial (longitudinal)
1. After welding	−64/90	−52/105	−109/304
2. Heating start at a heat treatment temperature of 650°C	−41/57	−41/75	−67/170
3. Heating end (after 6 h) at a heat treatment temperature of 650°C	−23/24	−21/29	−27/50
4. Cold state after heat treatment	−30/31	−27/37	−34/65

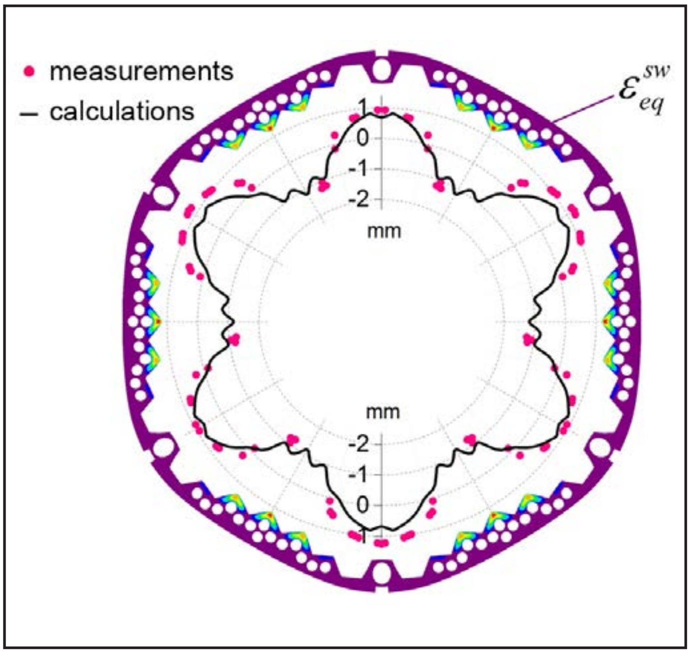


Fig. 4. Qualitative field of swelling, computational and experimental displacements of the internal surface of the enclosure of the active zone of the reactor in nuclear power plant JuUAES-2 during scheduled preventive maintenance after 30 years of operation, mm

On the cross-section of the large channel, the enclosure undergoes an outward deformation of 1 mm. On the cross-section of small channels, the enclosure deforms inside the active zone by 1 mm. It was ascertained that the gap between the enclosure and the housing could close after a time longer than the design life. In the case of normal operation, i.e. in the hot state, the enclosure and the housing will come into contact after 35 years of operation, whereas in the cold state – after 45 years.

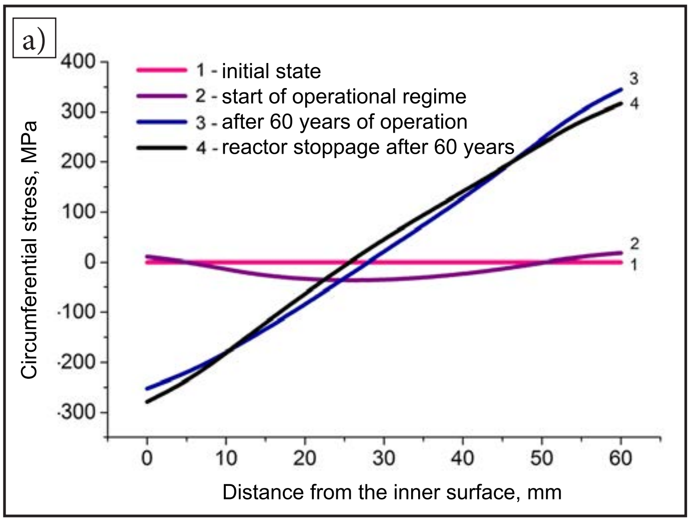
Stresses in the Chamber Housing Inside the Reactor Vessel

Also the housing does not heat up uniformly and swells during operation. Thermal strains lead to the generation of stresses of ±30 MPa. After 60 years of operation, volumetric radiation swelling is responsible for changes in stresses within the range of ±10 MPa. The contact interaction with the enclosure leading to stresses of the housing inside the reactor vessel (across the wall thickness) is significantly higher and could reach 340 MPa after 60 years of operation (Fig. 5a).

Welds in the housing inside the reactor vessel can be located in the area being in contact with the enclosure. In such a case, maximum tensile stresses in the zone of the welds in the housing inside the reactor vessel can reach 440 MPa at the end of an extended operation time (Fig. 5b).

Relaxation of Welding Internal Stresses in the Active Zone Enclosure

The mathematical model of radiation swelling takes into consideration the effect of stresses. Therefore, when modelling the swelling of elements inside the reactor vessel it is important to take into consideration welding internal stresses, entering them into the computational model as the initial condition. The tests described in publication [7] revealed that the effect of welding internal stresses over 60 years of operation



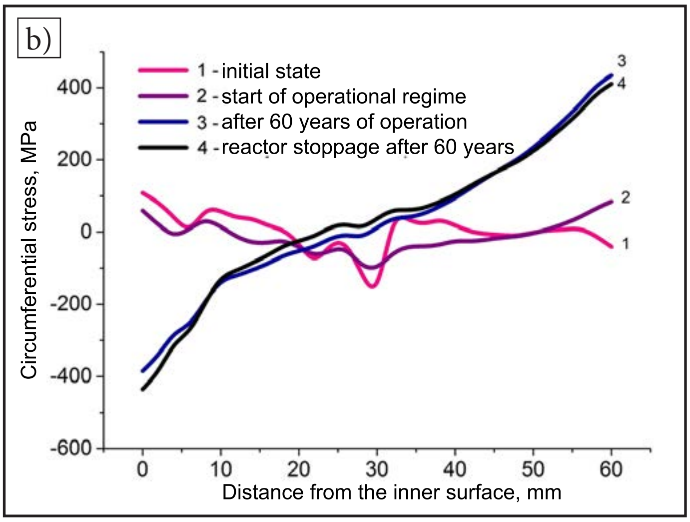


Fig. 5. Circumferential stresses across the thickness of the housing inside the reactor vessel taking into consideration the contact with the enclosure of the active zone: a) without welding internal stresses; b) including welding internal stresses

does not significantly change the swelling of the active zone enclosure in the area of welded joints (Fig. 6). Such a situation can be ascribed to a relatively large distance between the zone of maximum swelling and the area of maximum welding internal stresses. Cross-section 1 passing through the area of maximum welding internal stresses is characterised by a small radiation dose. Cross-section 2 passing through the area of maximum swelling is characterised by the low level of welding internal stresses.

It was revealed that after 60 years, stresses in the zone of welds in problems taking and not taking welding into consideration differ very insignificantly (Fig. 7). This fact can be ascribed to the effect of radiation creep [8, 9].

In order to investigate the relaxation of welding internal stresses in the active zone enclosure in conditions of radiation swelling and creep, it was necessary to solve two problems at the same time, i.e. taking and not taking into consideration welding internal stresses. In addition, at each time step, it was necessary to determine the difference in intensity fields in the above named problems. Figure 8 presents the reduction of the input of welding internal stresses into the total value of stresses in the enclosure (using a time step of 20 years). The relaxation of welding internal stresses becomes more intense along with a decreasing distance to the material internal surface (where radiation is greater).

The obtained dependence specifying the level of welding internal stresses in the active zone enclosure after the process of radiation-induced relaxation (Fig. 9) explains the results presented in Figure 7. The fields of stresses in the enclosure after 60 years of operation in problems concerning swelling, taking and not taking welding into consideration, hardly differ.

It is important that the relaxation of welding internal stresses in the active zone of the reactor

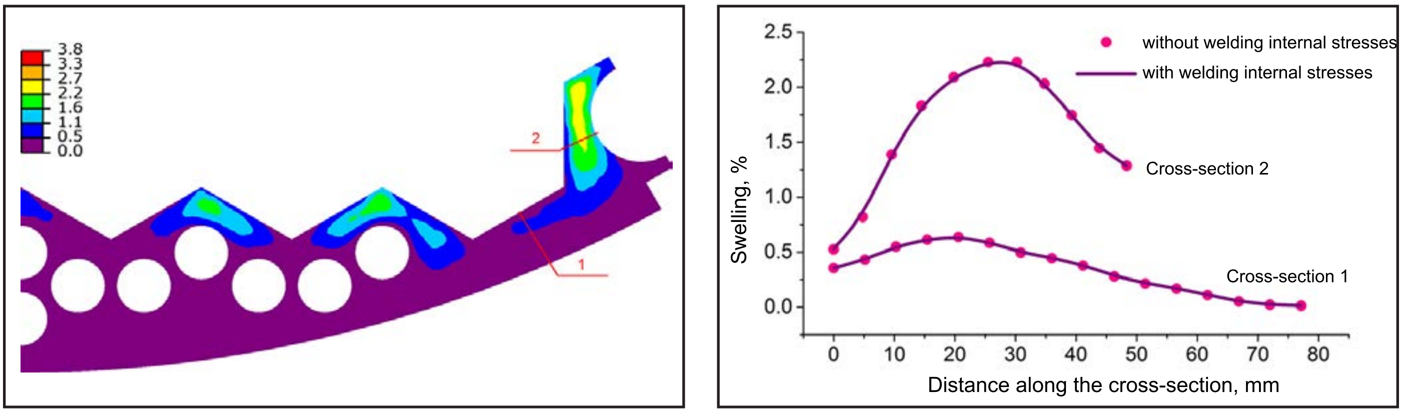


Fig. 6. Field of volumetric swelling strains in the active zone enclosure after 60 years of operation and the distribution of swelling in cross-sections 1 and 2, in problems taking and not taking into consideration welding internal stresses

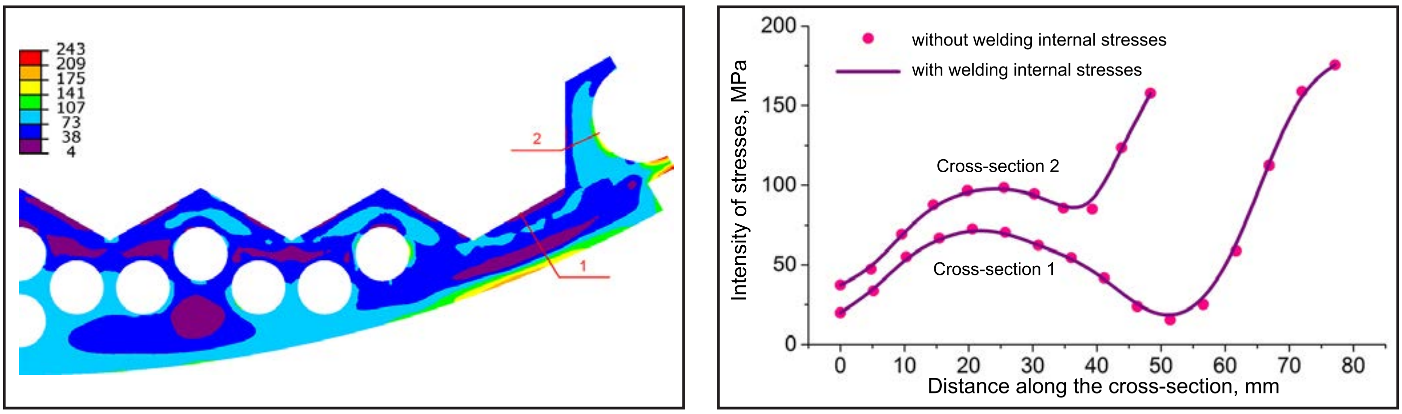


Fig. 7. Field of the intensity of stresses in the active zone enclosure after 60 years of operation and the distribution of stresses in cross-sections 1 and 2, in problems taking and not taking into consideration welding internal stresses

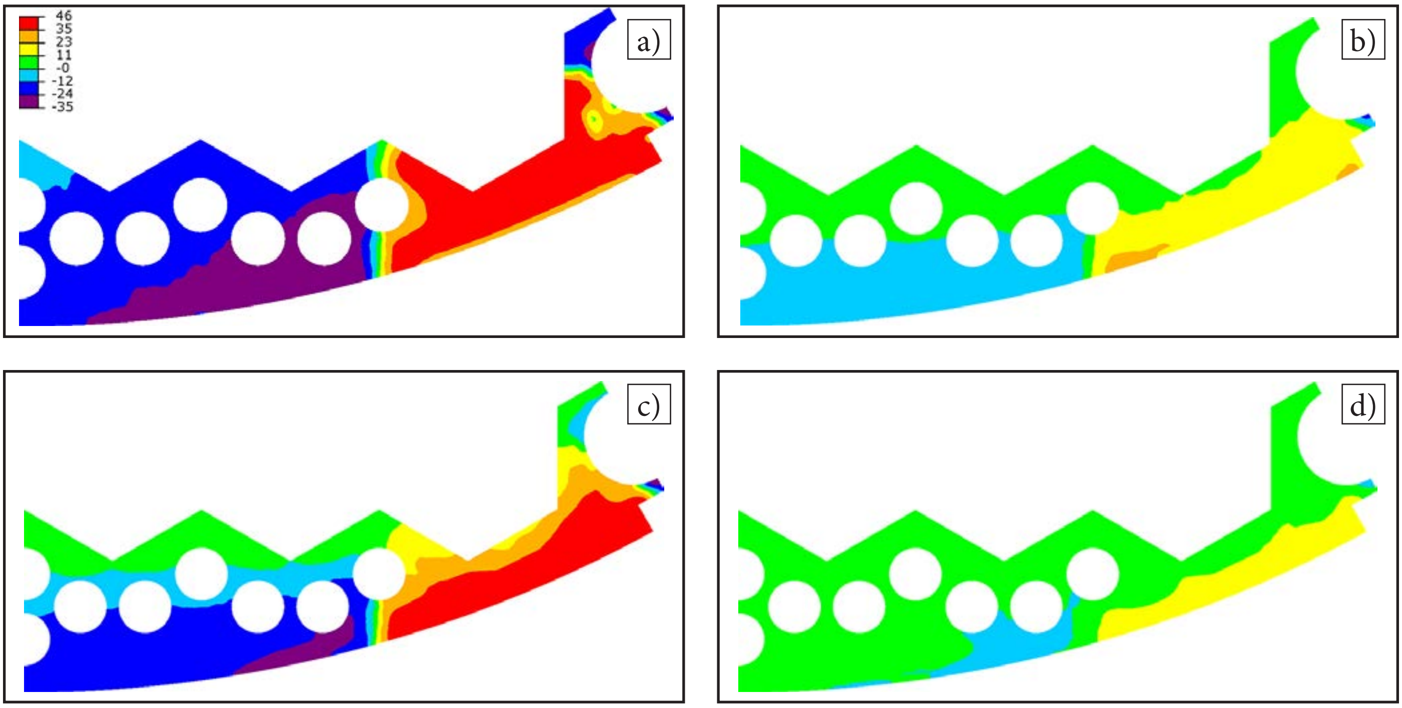


Fig. 8. Relaxation of welding internal stresses in the enclosure of the active zone of a WWER-1000 reactor: a) at the beginning of operation, b) after 20 years, c) after 40 years, d) after 60 years of operation

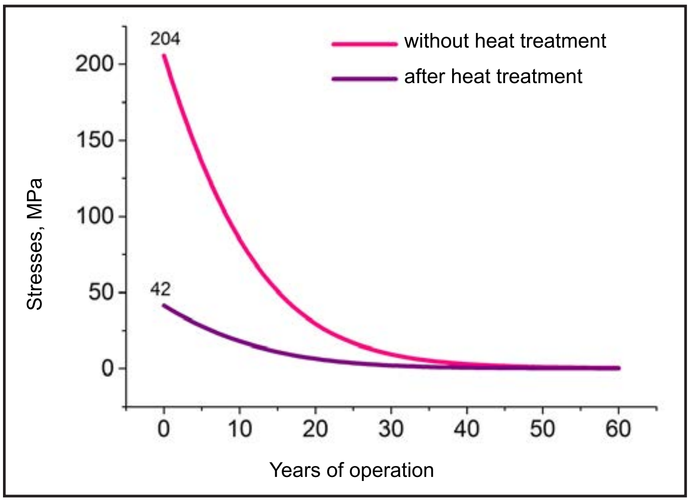


Fig. 9. Quantitative characteristics of the relaxation of welding internal stresses in the enclosure of the active zone of a WWER-1000 reactor during operation

does not take place rapidly, but within 60 years of reactor operation. The quantitative curves presented in Figure 9 can be approximated using the following dependence (6):

$$\sigma=\sigma_0 \cdot 0.92^t \qquad (6),$$

where σ_0 – initial level of welding internal stresses in the active zone enclosure at the beginning of reactor normal operation regime, t – years of operation.

Summary

The justification of extending the service life of welded structures of elements inside a WWER-1000 nuclear reactor, guaranteeing safe and efficient operation, requires information concerning stresses and strains taking into consideration welding internal stresses during the production as well as changes in the distribution of the above named stresses in strains during operation under intense radiation.

In this work, the existing mathematical model (1) of the radiation swelling of steel 08H18N10T was improved and presented in the differential-tensor form (3)÷(5). The results obtained using the improved model revealed that welding internal stresses do not significantly influence the radiation swelling of the material in the zone of welds and decrease during operation as a result of radiation creep. The work also resulted in the obtainment of the quantitative dependence (6) of the relaxation of welding internal stresses in the enclosure of the reactor active zone during operation.

The radiation swelling–induced deformation of the reactor active zone enclosure can lead to its contact with the housing inside the reactor vessel after 35 years of operation.

The greatest input into stresses generated in the housing inside the reactor vessel (up to 340 MPa) after 60 years of normal operation can be caused by the contact interaction of the housing and the enclosure of the reactor active zone. If the welds in the housing are located in the area of contact with the enclosure, maximum tensile stresses in the zone of the welds located in the housing can reach 440 MPa (including welding internal stresses).

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