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EVALUATION OF BRITTLE FRACTURE RESISTANCE OF WWER-1000 REACTOR BAFFLE DURING LONG-TERM SERVICE, TAKING INTO ACCOUNT THE RESIDUAL TECHNOLOGICAL STRESSES

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ABSTRACT

The need to take into account the residual technological stresses (RTS) in the material of the baffle of reactor internals (RI) of NPP power units of WWER-1000 type, resulting from technological processes of welding and postweld heat treatment at extension of safe service period beyond the design life is substantiated. The influence of RTS on the stress-strain state of the baffle, as well as brittle fracture resistance (BFR) of the material in service was determined. It is shown that an essential redistribution of axial and circumferential stresses in the baffle is observed due to allowing for RTS, namely of the zone of high tensile stresses, which under normal operation conditions (NOC) move into the internal volume of the baffle from its outer surface, while the area of these zone becomes larger. Such a redistribution of stresses has an essential influence on the level of stress intensity coefficient on the contour of the cracklike defects. The most critical areas, in terms of brittle strength, form in the inner volume of the baffle, whereas the dimensions of subsurface elliptical crack, which is postulated, can be increased due to widening of the tensile stress zone, thus promoting greater conservatism of BFR assessment. Moreover, taking RTS into account allows a significant lowering of conservatism at assessment of baffle BFR under NOC for surface semielliptic cracks, located on the baffle outer surface, where residual compressive stresses arise during manufacture. Obtained results allow more precise determination of baffle zones, prone to brittle fracture of the material under NOC that is important for improvement of the approaches to determination of RI of WWER-1000 type reactor.

KEYWORDS: WWER-1000, reactor internals, baffle, residual technological stresses, brittle fracture resistance, postulated cracks, stress intensity coefficient, normal operating conditions

INTRODUCTION

WWER-1000 reactor internals (RI) are very important structural elements which influence the life of all power plant. One of the key approaches in the papers on extension of life of NPP safe operation is a predictive evaluation of the structural integrity of structures with the help of mathematical modeling of the physical processes typical for conditions of operation of power units in radiation exposure of structural material. The results of existing investigations [1, 2] justify the insurance of conditions of brittle fracture resistance of RI baffle under normal operating conditions (NOC) and emergencies. However, these papers do not consider the effect of residual technological stresses on structural integrity of RI elements in course of long-term operation.

Mathematical modeling methods allowed determining appearance of high residual technological stresses (RTS) in manufacture of RI of WWER-1000 power unit. It happens in a process of fast air cooling during postweld heat treatment by austenitization mode (T = 1100 °C). A calculation analysis of a level of effect of determined RTS on stress-strain state and brittle fracture resistance (BFR) of the RI baffle in a process of long-term operation up to 60 years with different level of accumulated damaging dose was carried out in this paper.

Inner surface of a thick-walled cylinder shell of the baffle has faceted shape which limits a reactor core (Figure 1, *a*). The structure has a mirror-cyclic symmetry that allows dividing it on the twelve similar 30-deg sectors in modeling (Figure 1, *b*). A baffle section is inhomogeneous and being characterized with the presence of 84 cooling channels and its thickness varies in the limits from 67 to 242 mm. Material is austenitic steel 08Kh18N10T.

INPUT DATA

In order to determine the level of effect of RTS on SSS and BFR of the baffle structure in the process of long-term operation the following input data were used (Figure 2), namely RTS distribution [3]; two distributions of accumulated damaging dose different by level; distribution of heat emission due to γ-heating. Used distributions of the damaging dose and heat emission are taken as typical data from a practice of performance of corresponding calculations.

MODELS OF RADIATION SWELLING AND CREEP

A process of long-term operation of RI baffle under conditions of neutron radiation is accompanied by ra-

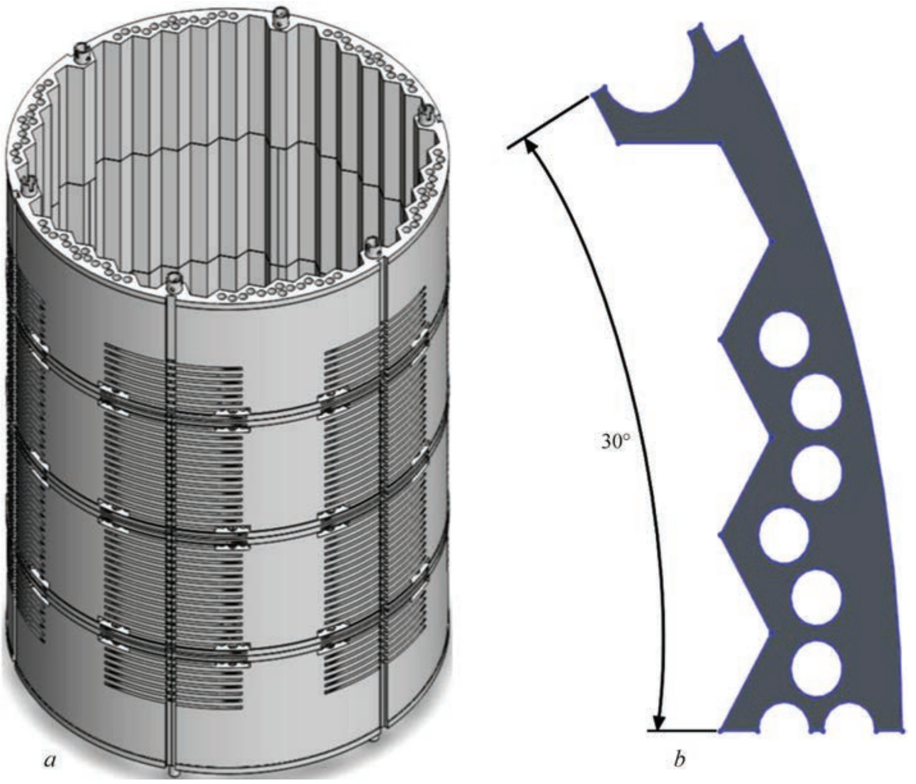

Figure 1. Appearance of baffle (*a*) and its cross-section (30-deg sector) (*b*)

diation swelling which can be described by a model tested in SE NNEGC "Energoatom" [4–6]:

$$S = C_D \cdot D^n \cdot f_1(T) \cdot f_2(\sigma_m, \sigma_{eq}) \cdot f_3(æ),\ S > 0,$$
$$f_1(T) = \exp(-r \cdot (T - T_{\max})^2),$$
$$f_2(\sigma_m, \sigma_{eq}) = 1 + P \cdot (0.85 \cdot \sigma_m + 0.15 \cdot \sigma_{eq}),$$
$$f_3(æ) = \exp(-\eta \cdot æ),$$
$$C_D = 1.035 \cdot 10^{-4}\ \text{dpa}^{-n},\ n = 1.88,$$
$$r = 1.825 \cdot 10^{-4},\ °\text{C}^{-2},\ T_{\max} = 470\ °\text{C}, \quad (1)$$
$$P = 8 \cdot 10^{-3}\ \text{MPa}^{-1},\ \eta = 8.75,$$

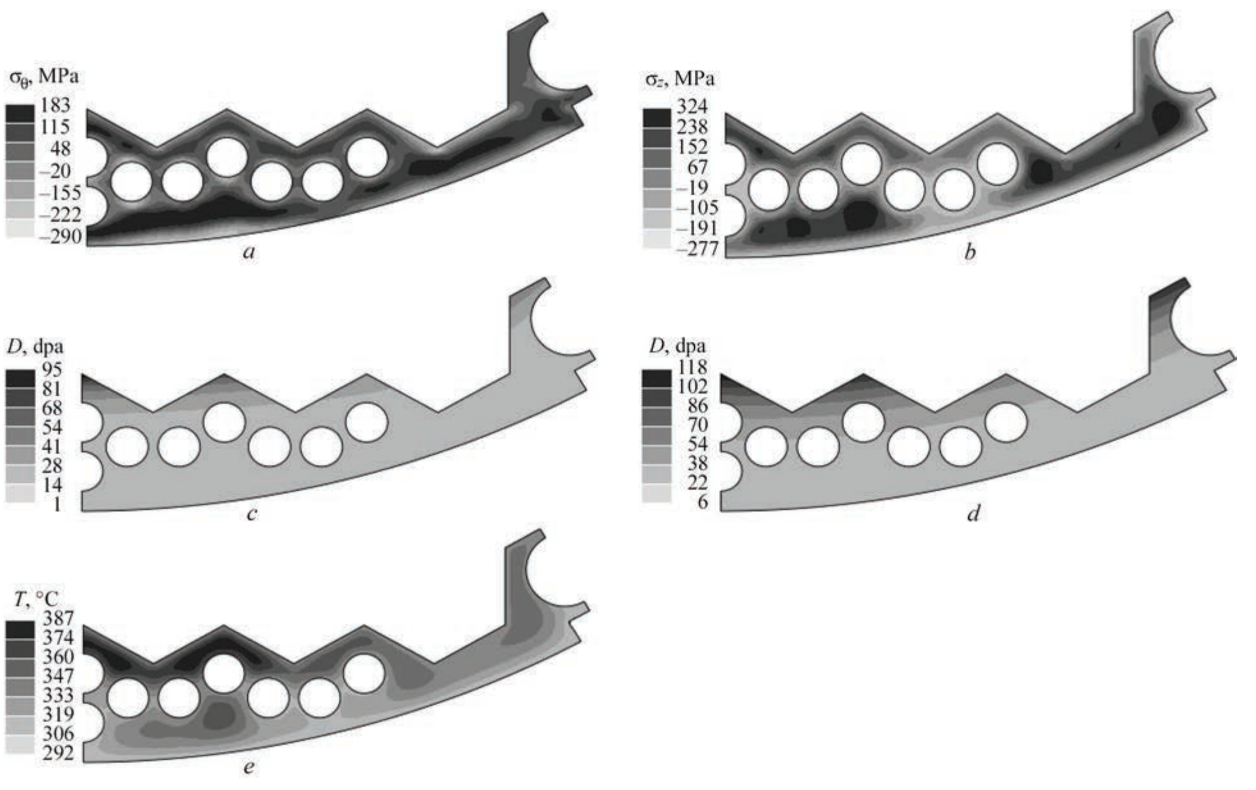

Figure 2. Input data for calculation: distributions of circumferential (*a*) and axial (*b*) RTS; distributions of accumulated damaging dose — variant 1 up to 95 dpa (*c*) and variant 2 up to 118 dpa (*d*); temperature field as a result of γ-heating (heat emission) (*e*)

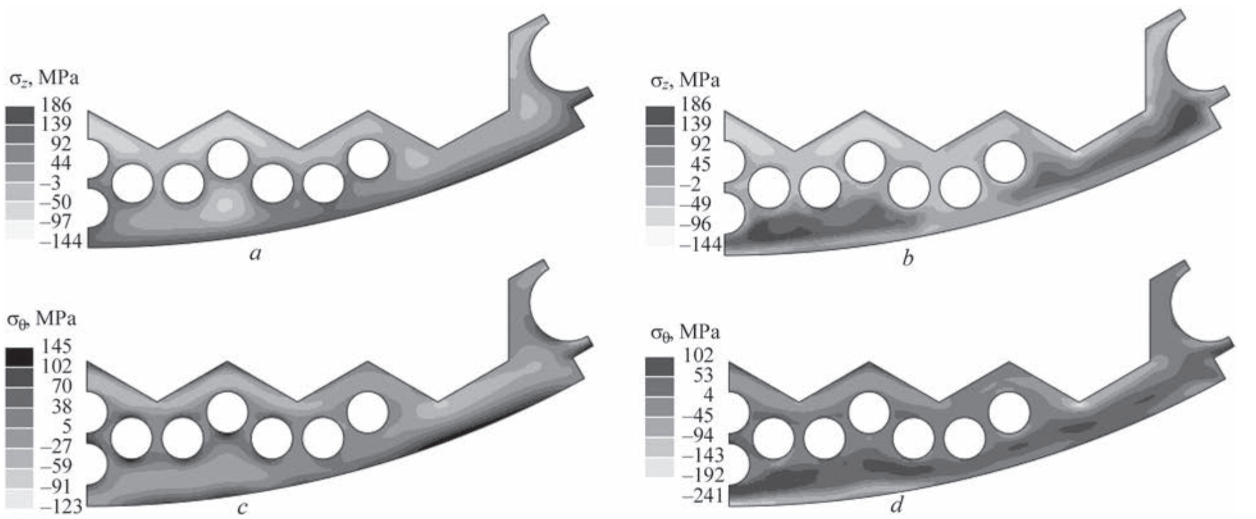

Figure 3. Distributions of stresses in the baffle in its sixtieth year of operation with maximum accumulated dose 95 dpa: *a* — axial component without consideration of RTS; *b* — axial component with RTS consideration; *c* — circumferential component without RTS consideration; *d* — circumferential component with RTS consideration

where *S* is the swelling , %; *D* is the damaging dose, dpa; *T* is the radiation temperature, °C; σ_m are the medium stresses, MPa; σ_{eq} are the equivalent stresses, MPa; æ is the Odqvist parameter.

Also the model takes into account deformations of radiation creep which for 08Kh18N10T steel is described by the law [6]:

$$\frac{d\varepsilon^{cr}}{dt} = \left(B_0 \frac{dD}{dt} + \omega \frac{dS}{dt} \right) \sigma_{eq}, \qquad (2)$$

where ε^{cr} is the radiation creep deformation; $B_0 = 1 \cdot 10^{-6}$ (MPa·dpa)$^{-1}$, $\omega = 2.95 \cdot 10^{-3}$ (MPa^{-1}).

DETERMINATION OF STRESS DISTRIBUTIONS DURING OPERATION

SSS of the baffle taking into account the processes of radiation swelling and creep of material can be determined as a result of solution of a boundary value problem of mechanics of continuous media using finite element method in the elastic-viscous-plastic statement [5, 7]:

$$\varepsilon = \varepsilon^e + \varepsilon^p + \varepsilon^{cr},$$

where ε are the total deformations; ε^e, ε^p, ε^{cr} are elastic, plastic and creep deformations, respectively.

Solution of the corresponding 2D problem with initial and boundary conditions in form of RTS distributions, damaging dose and heat emission due to γ-heating (Figure 2) as well as conditions of heat exchange with coolant of the baffle surfaces [5, 7] by means of continuous monitoring of time with $\Delta t = 0.2$ year step resulted in getting the distributions of stresses in a baffle cross-section in the processes of long-term operation taking and not taking into account RTS. Figures 3, 4 show axial and circumfer-

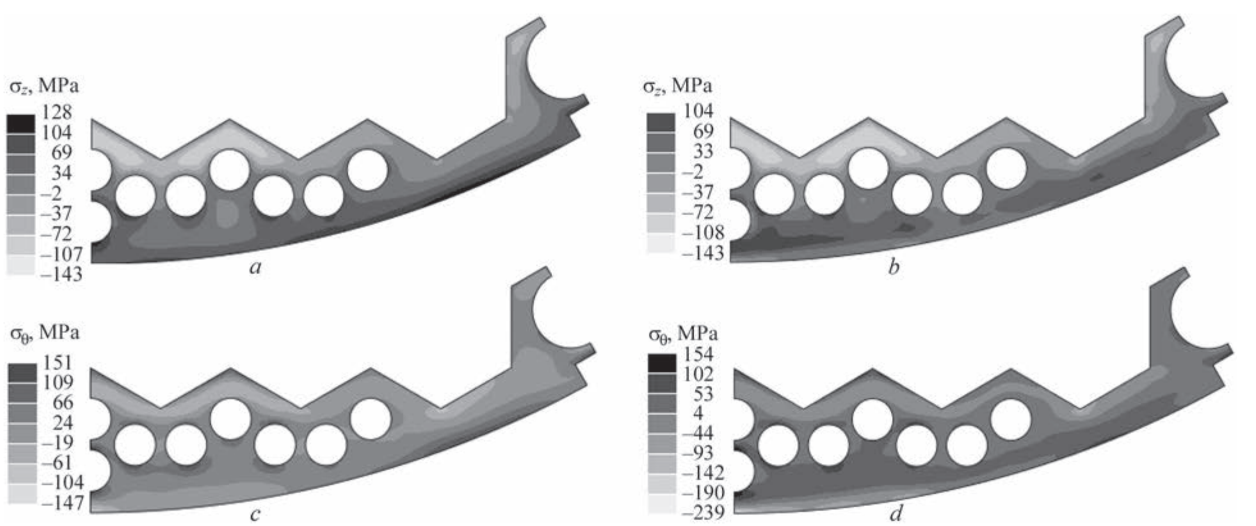

Figure 4. Distributions of stresses in the baffle in its sixtieth year of operation with maximum accumulated dose 118 dpa: *a* — axial component without consideration of RTS; *b* — axial component with RTS consideration; *c* — circumferential component without RTS consideration; *d* — circumferential component with RTS consideration

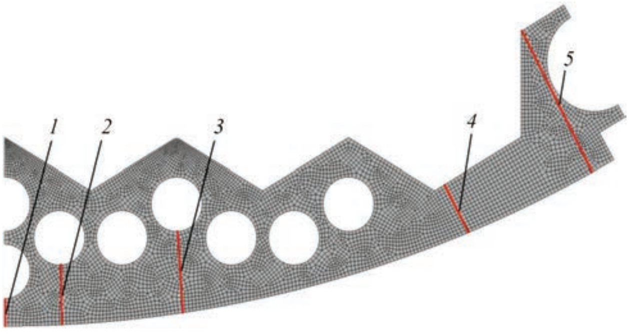

Figure 5. Scheme of location of typical sections for evaluation of RTS effect on SSS of the baffle in process of long-term operation

ential stresses in operating mode of the baffle in its sixtieth year of operation for two considered variants of the level of accumulated damaging dose — 95 dpa and 118 dpa, respectively.

Figures 3, 4 demonstrate noticeable difference of stress distributions in axial and circumferential directions depending on RTS consideration. Taking into account RTS the zones of high tensile stresses from outer wall of the baffle transfer into external volume and their area increases. Also it is necessary to note the effect of the level of damaging accumulated dose on the level of stresses in process of baffle operation.

As can be seen from data on Figures 3, 4 RTS have small effect on distribution of stresses on inner surface of the baffle in area of cooling channels. Therefore, for the analysis there were taken 5 typical sections closer to outer surface, where effect of RTS on SSS of the baffle is the most significant. Figure 5 shows a scheme of their location.

Figures 6, 7 represent the calculation distributions of axial and circumferential stresses in sections No. 1 and No. 5, respectively, in the sixtieth year of operation depending on accumulated damaging dose and considering RTS.

Consideration of RTS can promote decrease of the level of stresses in axial direction in the process of operation (Figure 6, *a*) and closer to the baffle outer surface in section No.1 the stresses even transfer into compressive ones.

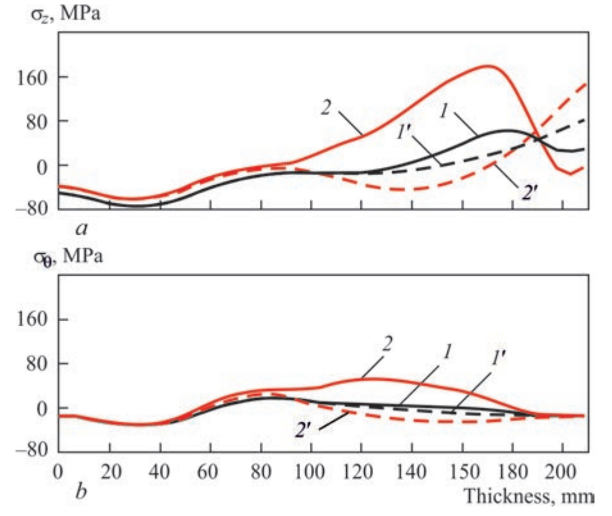

Figure 7. Distribution of axial σ_z (*a*) and circumferential σ_θ stresses in section No. 5 depending on accumulated damaging dose and RTS consideration: *1′* — at D_{max} = 118 dpa; *2′* — at D_{max} = 95 dpa without RTS consideration; *1* — at D_{max} = 118 dpa; *2* — at D_{max} = 95 dpa with RTS consideration

Data from Figure 7, which refer to section No. 5, show that consideration of RTS independent on level of accumulated damaging dose has significant effect on stress distribution, namely takes place formation of the zones of high tensile stresses (up to 180 MPa) in axial direction (Figure 7, *a*).

It should be noted that the circumferential stresses (Figure 6, *b* and Figure 7, *b*) in comparison with axial ones are relatively low in examined sections (up to 50 MPa) and in most of the cases consideration of RTS does not promote significant effect on their distribution.

Also, it was determined that in sections Nos 2–4 the axial stresses in case of taking into account RTS are greatly higher in the baffle inner volume, whereas on the inner and outer surfaces they become lower in comparisons with the calculation case, where RTS have not been considered.

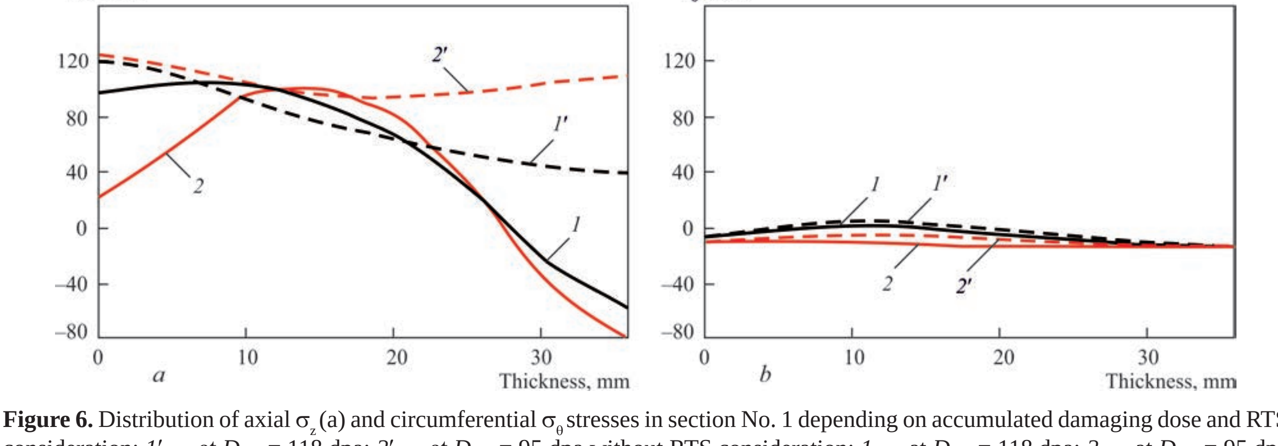

Figure 6. Distribution of axial σ_z (a) and circumferential σ_θ stresses in section No. 1 depending on accumulated damaging dose and RTS consideration: *1′* — at D_{max} = 118 dpa; *2′* — at D_{max} = 95 dpa without RTS consideration; *1* — at D_{max} = 118 dpa; *2* — at D_{max} = 95 dpa with RTS consideration

BFR CALCULATION PROCEDURE

In accordance with the existing requirements [4] BFR calculation is one of the necessary strength calculations during calculation substantiation of RI safe operation. It is performed corresponding to the requirements of acting in Ukraine reference documents [8] as well as it is necessary to take into account the recommendations of foreign documents [6, 9].

Brittle fracture resistance of RI is provided if the following condition is fulfilled under all operation conditions:

$$K_1 \le [K_1]_i, \tag{3}$$

where K_1 is the calculation value of stress intensity coefficient (SIC) on a contour of postulated crack; $[K_1]_i$ is the allowable SIC value, which is determined for normal operation conditions (NOC) (i = 1) with a safety factor $n_k = K_{1c}/[K_1]_1 = 2$, K_{1c} is the critical value of material SIC.

Elliptical subsurface crack with large semi-axis c and smaller semi-axis a (Figure 8, a) as well as semi-elliptical surface crack (Figure 8, b) are considered as a postulated crack. According to PNAE [8] the relationship of semi-axes a/c = 2/3 and according to [4] a/c = 1/3, the maximum postulated defect depth $2a$ can not exceed quarter of base metal thickness.

It should be noted that the RI elements operate under conditions of intensive neutron irradiation.

This in process of operation results in degradation of mechanical properties of the base metal. Therefore, the critical values of SIC in the different points (volumes) of the base metal will depend on the level of accumulated damaging dose as well as radiation temperature and can be described by the next law [4]:

$$J_c(D,T,T_{irr}) = 2.5\cdot 10^{-4}\sigma_Y(D,T,T_{irr})\times \times\left[1 - A_{J(e)}\sqrt{1-\exp(-0.2D)}\right], \tag{4}$$

where σ_y is the material yield strength, MPa; D is the accumulated damaging dose, dpa; $A_{J(e)}$ = 0.93.

In order to determine the SIC critical values using J-integral values there was used a transition formula [1]:

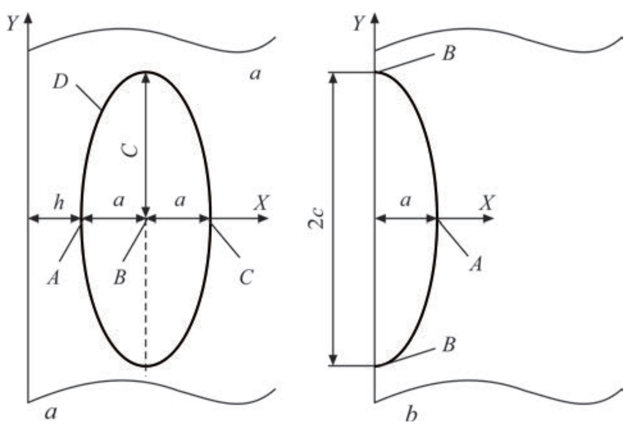

Figure 8. Postulated elliptical (a) and semi-elliptical (b) cracks

$$J = \frac{K_I^2(1-\nu^2)}{E}. \tag{5}$$

Calculation of SIC values for the postulated cracks was carried out by three different procedures according to PNAE [8], VERLIFE [6] and RD EO [9].

METHOD ACCORDING TO PNAE

According to the requirements of PNAE [8] the SIC for cylinder elements being loaded by internal pressure and temperature effect is allowed to be determined by formula:

$$K_I = \eta\left(\sigma_p M_p + \sigma_q M_q\right)\sqrt{\left(\pi\frac{a}{10^3}\right)}\Big/Q, \tag{6}$$

where η is the coefficient that considers the effect of stress concentration; σ_p is the component of tensile stresses, MPa; σ_4 is the component of bending stresses, MPa; $M_p = 1 + 0.12\,(1 - a/c)$, $M_q = 1 - 0.64a/h$; a — crack depth, mm; c is the semi-length of crack, mm; h is the length of zone, in the limit of which a component of bending stresses saves the positive value, mm,

$$Q = \left[1 + 4.6\left(a/2c\right)^{1.65}\right]^{1/2}. \tag{7}$$

A component of tensile stresses (circumferential or axial) are determined by formula:

$$\sigma_{jp} = \frac{1}{s}\int_s \sigma_j dx, \tag{8}$$

where j is the θ or Z coordinate; σ_j is the function of change of stresses on wall thickness; s is the wall thickness in calculation section.

A value of component of bending stresses are determined by formula:

$$\sigma_{jq} = \sigma_{jn} - \sigma_{jp}, \qquad (9$$

where σ_{jn} are the values of function of stress change by wall thickness in point n.

It should be noted that PNAE [8] has no information for which type of the crack-like defects (subsurface, elliptical or surface semi-elliptical) the SIC determination procedure is used.

METHOD ACCORDING TO VERLIFE

Following the VERLIFE recommendations [6] a coefficient of stress intensity K_I is determined from the relationship:

$$K_I = \sigma_K Y\sqrt{a}, \tag{10}$$

where σ_K are the stresses brought to uniform, MPa; Y is the coefficient of crack shape; a is the small semi-axis of crack.

The coefficient of crack shape Y is determined depending on crack type and location of point on its contour. For a subsurface elliptical crack the following expressions are typical:

$$Y_A = \frac{1.79 - 0.66 \cdot a/c}{[1 - \beta^{1.8}(1 - 0.4(a/c) - \gamma^2)]^{0.54}},$$
$$Y_C = \frac{1.79 - 0.66 \cdot a/c}{[1 - \beta^{1.8}(1 - 0.4(a/c) - 0.8\gamma^{0.4})]^{0.54}}, \quad (11)$$

where $\beta = \frac{a}{b+a}$; $\gamma = 0.5 - \frac{b+a}{s}$ s is the base metal thickness, mm.

For surface semi-elliptical crack the shape coefficients are determined in accordance to the following expressions:

$$Y_A = \frac{2 - 0.82 \cdot a/c}{\left\{1 - \left[0.89 - 0.57\left(a/c\right)^{1/2}\right]^3 \left(a/s\right)^{1.5}\right\}^{3.25}},$$
$$Y_B = \left[1.1 + 0.35\left(a/s\right)^2\right]\left(a/c\right)^{1/2} \cdot Y_A. \quad (12)$$

For subsurface elliptical crack the stresses, being brought to uniform, were determined from the following relationships, which describe their distribution by parabolic law:

$$\sigma_{KB} = \frac{\sigma_B + \sigma_C}{2} + \frac{a}{c} \cdot \frac{4\sigma_B - 3\sigma_C - \sigma_A}{30},$$
$$\sigma_{KB} = \frac{\sigma_B + \sigma_C}{2} + \frac{a}{c} \cdot \frac{4\sigma_B - 3\sigma_C - \sigma_A}{30}. \quad (13)$$

When postulating a surface semi-elliptical crack in section 4 the stresses on wall thickness are distributed by linear dependence:

$$\sigma_{KB} = 0.18\,\sigma_A + 0.82\,\sigma_B. \quad (14)$$

It is necessary to note that the VERLIFE procedure of determination of the stress intensity coefficients for a subsurface elliptical crack includes no methods to set a complex law of distribution of stresses and as a result of description of a random distribution of stresses by parabolic law the K_I values can be determined with the significant errors.

METHOD ACCORDING TO RD EO

The method for SIC determination according to RD EO 1.1.2.05.0330–2012 [9] is similar to procedure VERLIFE [6], however, proposes the expressions for SIC calculation at more complex law of stress distribution. Such crack shape coefficients are determined by the following dependencies:

$$Y = \left[1 - \left(\frac{a}{h+a}\right)^{1.8}\left(1 - 0.4\frac{a}{c} - \gamma\right)\right]^{-0.54} \times$$
$$\times \left[\frac{\pi}{1 + 1.464(a/c)^{1.65}}\right]^{0.5}, \quad (15)$$

at $a \le c$; $a \le 9h$; $h + a \le s/2$:

$$\gamma_A = \left(0.5 - \frac{h+a}{s}\right)^2 \quad \gamma_C = 0.8\left(0.5 - \frac{h+a}{s}\right)^{0.4}. \quad (16)$$

$x_j = h + a_j/10$, where $j = 0, 1, 2, \ldots, 20$ coordinate is calculated for the stress distribution set in the arbitrary form (in form of approximation function). Stresses $\sigma_j = \sigma_K(x_j)$ are determined in each x_j point. The values of $\sigma_K(A)$ and $\sigma_K(C)$ brought to uniform are calculated by formulas:

$$\sigma_{eq}(A) = \sum_{j=0}^{20}\left(A_j + \frac{a}{c}B_j\right)\sigma_j,$$
$$\sigma_{eq}(C) = \sum_{j=0}^{20}\left(A_{20-j} + \frac{a}{c}B_{20-j}\right)\sigma_j, \quad (17)$$

where A_J and B_J are the table values.

Among the three methods for SIC determination considered above the latter one, described in RD EO 1.1.2.05.0330–2019 [9], is the most accurate. It takes into account the depth of crack occurrence and the stresses can be described by an arbitrary shape law (in form of approximation function). The procedure, described in VERLIFE [6], is good to use for express-evaluations to brittle fracture resistance as well as for the cracks which are postulated in the zones with linear and parabolic stress distribution.

RESULTS OF CALCULATED EVALUATION OF BFR

As it was mentioned above, there were considered two variants of accumulated damaging dose. Therefore, mechanical properties of baffle material and corresponding SIC critical values will be different for each of the variants. Figure 9 shows the distributions between material yield limit of the baffle in its sixtieth year of operation as well as SIC critical values for different input data.

As can be seen from Figure 9, the level of material yield limit is changed depending on the accumulated damaging dose. Thus, the yield limit is in 438–873 MPa range at the maximum value of accumulated damaging dose 95 dpa and at 118 dpa it becomes 673–838 MPa (Figure 9, *a*, *b*) that, respectively, effect the SIC critical value (Figure 9, *c*, *d*).

It was determined as a result of mathematical modeling of the processes of welding, heat treatment and further operation of RI elements in course of 60 years that the maximum tensile stresses are formed in the axial direction. Therefore, from point of view of conservatism

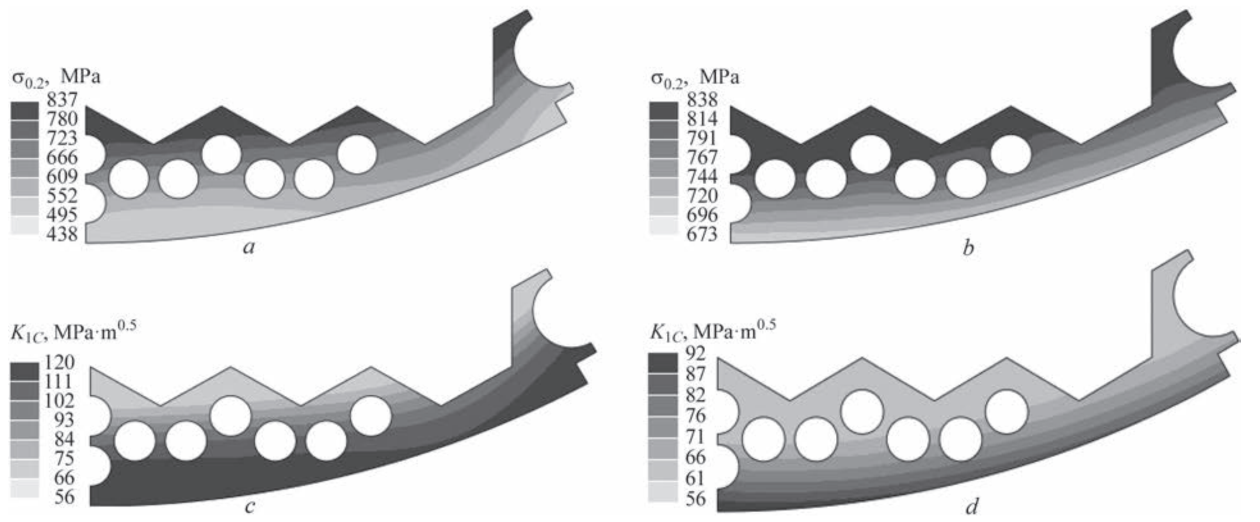

Figure 9. Distributions of yield limit $\sigma_{0.2}$ of baffle material at accumulation of damaging dose of 95 dpa (*a*) and 118 dpa (*b*) and critical value K_{1c} at 95 dpa (*c*) and 118 dpa (*d*)

the subsurface elliptical cracks located in circumferential direction were considered in SIC determination. A scheme of location of the baffle sections, in which the defects were postulated, is shown in Figure 5.

Table 1 presents the results of comparison of SIC values without RTS consideration and Table 2 with RTS consideration for section No. 5 (Figure 5), which is located in a zone of the biggest effect of RTS on SSS of baffle structure. They were obtained according to three procedures described above [8, 9] after 30 and 60 years of operation for two variants of a level of accumulated damaging dose and cracks with various *a*/*c*.

The most conservative are the SIC values obtained using RD EO procedure [9] which is reasonable for application for BFR analysis with arbitrary distribution of stresses in the crack location zone. The methods, described in PNAE [8] and VERLIFE [6], should be used for evaluation of SIC in the less loaded areas with linear or parabolic law of stress distribution. The maximum SIC values in most of the cases are located in point A of

Table 1. SIC for cracks with different *a*/*c* in section No.5 without RTS consideration

a/*c*	Max. accum. dose, dpa	K_A, MPa·m$^{0.5}$		K_C, MPa·m$^{0.5}$		K_D, MPa·m$^{0.5}$		K, MPa·m$^{0.5}$
		RD EO	VERLIFE	RD EO	VERLIFE	RD EO	VERLIFE	PNAE
30 years of operation								
1/3	47.5	25	24.7	6.5	7.7	16.5	16.2	25.7
	59	15.3	15.1	4.4	5.5	10.5	10.3	14.9
2/3	47.5	20.6	20.8	4.6	5.9	14.9	13.3	21.7
	59	19.8	19.6	4.6	6.1	15.4	12.9	16.0
60 years of operation								
1/3	95	24.1	23.8	6.6	8.0	16.1	15.5	24.5
	118	15.5	15.3	5.6	7.4	11.3	11.4	13.8
2/3	95	19.8	20.0	4.7	6.1	14.5	12.4	20.7
	118	19.9	19.7	5.9	8.5	16.5	14.1	14.7

Table 2. SIC for cracks with different *a*/*c* in section No.5 with RTS consideration

a/*c*	Max. accum. dose, dpa	K_A, MPa·m$^{0.5}$		K_C MPa·m$^{0.5}$		K_D, MPa·m$^{0.5}$		K, MPa·m$^{0.5}$
		RD EO	VERLIFE	RD EO	VERLIFE	RD EO	VERLIFE	PNAE
30 years of operation								
1/3	47.5	39.5	38.8	25.1	34.7	30.9	36.7	37.2
	59	19.8	19.3	10.2	15.8	14.2	17.6	16.0
2/3	47.5	44.7	44.0	22.0	28.7	39.3	36.3	40.7
	59	16.7	16.4	7.8	13.2	13.7	14.8	11.7
60 years of operation								
1/3	95	34.6	33.9	21.3	29.7	26.7	31.6	32.4
	118	11.5	11.1	5.0	8.2	7.9	9.6	11.0
2/3	95	39.3	31.5	17.6	25.6	33.4	29.1	35.4
	118	14.7	14.1	5.5	9.8	11.7	11.9	11.7

a contour of postulated crack (Figure 8) and their values are correlated with the results of each procedure.

RTS consideration in one section can have positive as well as negative effect according to the results of SIC determination in section No. 5. For example, consideration of RTS rises conservativeness of SIC calculation in the 30th year of operation by 2.2 times (from 20.6 to 44.7 MPa·m$^{0.5}$).

Baffle sections Nos 1–4 were also examined (Figure 5). SIC calculation was performed in accordance with RD EO [9]. A comparative analysis in the sections was carried out for postulated defects in form of subsurface elliptical cracks depending on operation period, accumulated damaging dose and RTS consideration. Geometry dimensions of the cracks (semi-axes a and c) were chosen depending on dimensions of the zones of tensile stresses and can be changed for one and the same section depending on the level of accumulated damaging dose and RTS consideration. A depth of defect location h was determined depending on its allowable limits.

In section No.1 there were obtained lower values of SIC in RTS consideration than in the model without RTS consideration. For comparison it was considered a calculation variant in the 30th year of operation for higher level of accumulated damaging dose, where relationship between small and large semi-axes of the postulated crack is taken equal a/c = 1/3 and their dimensions due to large zone of tensile stresses correspond to the maximum allowable according to PNAE [8] values a = 9 mm; c = 27 mm at base metal thickness S = 36 mm, crack occurrence depth h = 3mm. It was determined based on all indicated above input parameters that the maximum value without RTS consideration made K_I = 17.2 MPa·m$^{0.5}$ and with RTS consideration K_I = 12.6 MPa·m$^{0.5}$, thus in this case RTS consideration allows reducing conservativeness of BFR evaluation by 27 %. However, the largest decrease of SIC (by 58 %) at RTS consideration was determined in section No.4 with K_I = 41.4 MPa·m$^{0.5}$ up to 17.5 MPa·m$^{0.5}$.

Following the calculation results the SIC increase can also be observed with increase of size of the postulated defect. Calculation case of section No. 2 in the 60th year of operation with the maximum accumulated dose 118 dpa and RTS consideration with different relationships a/c = 1/3 [4] and a/c = 2/3 [8] was considered for comparison. Their dimensions due to large tensile stress area according to PNAE [8] correspond to the maximum allowable values a = 19.5 mm; c = 58.5 mm (at a/c = 1/3) and c = 29.25 mm (at a/c = 2/3) at base metal thickness in section S = 78, depth of crack occurrence h = 2 mm. On the grounds of all input parameters it was determined that in calculation case, where a/c = 1/3 K_I = = 21.4 MPa·m$^{0.5}$ and at a/c = 2/3 K_I = 17.5 MPa·m$^{0.5}$, that is consideration of the existing requirements [4] in this case allows increase conservativeness of SIC evaluation in section No. 2 by 18 % in comparison with PNAE requirements [8]. However, in case when geometry of the baffle section is limited by the size of large semi-axis, increase of area of the postulated defect takes place due to increase of the small semi-axis a. It was determined by the example of section No. 5 that the most conservative SIC evaluation is carried out by the requirements of relationships of semi-axes a/c = 2/3 according to PNAE [8].

The results of calculation showed that the level of SIC value is affected by postulated crack size, selection of which is determined by dimensions of tensile stress zone, which in turn can depend on RTS consideration. Also higher level of radiation (accumulated dose) of the baffle material reduces effect of RTS on stressed state and, respectively, BFR evaluation of structure.

In addition to the subsurface elliptical crack there was also considered a surface semi-elliptical crack. Since in RTS consideration the maximum level of stresses is observed not on the baffle surface, as in the case without RTS consideration, but in its volume, then the SIC values for the surface defect will be lower. Therefore, the crack in only one section with the largest value of axial stresses in the indicated area was examined. Following the data in Figure 3, the highest stresses in axial direction without RTS consideration are in a zone of section No. 4 (Figure 5), and, respectively to the obtained data the highest SIC values are determined in the 30th year of operation for a variant of lower level of damaging dose accumulation. The procedure in accordance with VERLIFE document was used for determination of the maximum SIC for the case without RTS consideration (K_I = 26.6 MPa·m$^{0.5}$) and with RTS consideration the value reduces (K_I = = 7.1 MPa·m$^{0.5}$). Thus, RTS consideration allows significantly reducing conservativeness in determination of SIC for the defect on baffle outer surface.

NOC in addition to steady operation mode includes the modes of heating and cooling during an operation mode setting and reactor stops as well as hydraulic testing. Taking into account low rate of heating and cooling under NOC these processes do not have negative effect on BFR of the baffle. The level of stresses in the baffle significantly decreases in a cold status due to absence of a temperature gradient in relation to a heated status in the operation mode. Increase of pressure of coolant on all baffle surfaces during hydraulic testing promotes additional uniform compression (by 8 MPa), and, respectively, decrease of tensile stresses in the baffle volume in comparison with the conditions of loading in the operation mode, that also promotes fulfillment of BFR condition.

Therefore, the calculation results allowed determining significant effect of RTS on evaluation of BFR of WWER-1000 reactor baffle under NOC. Under emergency conditions the level of J-integral for surface semi-elliptical cracks can reach values close to the critical ones [1]. However, the work does not consider RTS that can significantly affect the results of BFR evaluation. Thus, the next relevant problem is calculation evaluation of BFR of WWER-1000 reactor baffle under conditions of emergency with consideration of determined RTS [1].

CONCLUSIONS

1. Consideration of RTS significantly affect the distribution of stresses in WWER-1000 reactor baffle in operation mode under NOC, namely, there is formation of zones of high axial tensile stresses (up to 180 MPa). At that, thr axial stresses are significantly higher in the baffle inner volume, whereas in the inner and outer surfaces they become lower in comparison with a calculation case, where RTS were not considered. Circumferential stresses are relatively low (up to 50 MPa) and consideration of RTS does not promote significant effect on their distribution.

2. Subsurface elliptical cracks located in a circumferential direction under effect of high axial tensile stresses were considered in performance of calculation BFR evaluation of the baffle under NOC as a postulated defect from point of view of maximum conservatism. The results of calculations in various sections of the baffle showed that conservativeness of BFR evaluation at RTS consideration can rise, but K_1 SIC values for the postulated cracks do not exceed K_{1c} critical value taking into account safety factor $n_k = 2$, i.e. BFR condition is fulfilled and in course of long-term operation the values of BFR safety factor $\eta = K_1/[K_1]_1$ increases at the expense of stress relaxation in a process of radiation creep.

3. The most dangerous from point of view of BFR under NOC is the section No. 5 of the baffle (in zone of large cooling channel), where the SIC maximum values for circumferential elliptical crack reach in the 30th year of operation $K_1 = 45$ MPa·m$^{0.5}$ and in the 60th year it is $K_1 = 39$ MPa·m$^{0.5}$ at allowable SIC values $[K_1]_1 = 58$ MPa·m$^{0.5}$ and $[K_1]_1 = 53$ MPa, respectively. In other words, the minimum value of BFR safety factor during operation rises to $\eta = 1.36$.

4. The higher level of accumulated damaging zone of the baffle material in process of operation promotes decrease of a level of the maximum stresses in the baffle due to effect of radiation creep. Effect of RTS on stressed state decreases, respectively, and BFR evaluation of the structure becomes less conservative.

5. Consideration of RTS allows dramatically decrease the conservativeness in evaluation of baffle BFR under NOC for the surface semi-elliptical cracks, located on outer surface of the baffle, where residual compression stresses are formed in the process of manufacture.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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