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INFLUENCE OF RESIDUAL PROCESS STRESSES ON BRITTLE FRACTURE RESISTANCE OF WWER-1000 REACTOR BAFFLE IN CASE OF AN EMERGENCY

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ABSTRACT

At present, the majority of WWER-1000 reactors in Ukrainian NPPs are going through the procedure of extension of their service life. Reactor internals (RI) are one of the key elements of the structure, which limit the NPP beyond design life. Physical control of RI condition is rather difficult, and even impossible for some areas, so that mathematical modeling is the main method of prediction and analysis of the technical condition. Note that most of the studies in this area are limited to modeling the normal operation mode, but the project also envisages emergency situations (ES), characterized by a rather abrupt change of boundary conditions and loads that promotes formation of quite high stresses. The work analyzes how the residual process stresses generated during RI baffle manufacture, can affect the values of stress intensity factor on the contour of postulated cracks during ES. A significant influence of RPS on the baffle brittle fracture resistance during ES was revealed that should be taken into account at calculation-based substantiation of extension of service life of WWER-1000 type power units.

KEYWORDS: WWER-1000, reactor internals, baffle, residual process stresses, emergency situation, crack-like defect, stress intensity factor

INTRODUCTION

Improvement of the methods of extension of the life of currently operating nuclear power plants in Ukraine is one of the urgent tasks in nuclear power sector. An emergency situation (ES) is the operation mode with stringent loading conditions [1]. In some cases the project envisages not more than one such scenario during the entire term of operation (including operation beyond the design life). Reactor internals (RI), such as the reactor baffle and internal shaft, are some of the key structural elements of WWER-1000 power unit, limiting the NPP term of operation beyond the design life. Similar problems of calculation-based prediction of brittle fracture resistance (BFR) of RI elements in ES [1] and under normal operation conditions were considered earlier [2], but the residual process stresses RDS arising during baffle manufacture were not taken into account. Proceeding from published results of similar calculations [1], *J*-integral values, close to the critical ones, were derived for crack-like defects postulated in the baffle. Considering the results of recent studies in this field, namely a significant influence of RPS on the stress-strain state (SSS) of RI baffle under the normal operation conditions [3], analysis of RPS influence on SSS and BFR of RI baffle under ES conditions will be timely.

EMERGENCY MODE

A big leak at rupture of primary circuit piping of 100–850 mm conditional diameter was considered as an ES. The mathematical model of baffle SSS includes allowing for RPS [4], radiation dose accumulated over 60 years of operation, as well as temperature distributions. An emergency situation, considered in this work, is accompanied by an abrupt drop of coolant pressure and temperature. The initial parameters used were the temperature field, generated as a result of gamma radiation and contact of the coolant with the baffle surface [4], and SSS distribution without allowing for SSS (Figure 1, *a*, *c*) and allowing for SSS (Figure 1, *b*, *d*), which correspond to the normal operating mode of the reactor and are described in [3]. Proceeding from the conditions of conservatism, it was assumed in the computation model that the ES mode occurs after 60 year of reactor operation. Allowing for radiation swelling and creep for the entire term of operation is described by mathematical models [5], the correctness of which was considered in [6].

Development of an emergency situation is accompanied by a change in boundary conditions (heat transfer coefficient and coolant temperature) and loading (pressure) in time. The laws of boundary condition change are shown in Figure 2.

At modeling of the considered ES it was determined that the maximum stress values are observed at moment of time $t = 100$ s from ES start. The temperature field is sown in Figure 3. Stress distributions in the axial direction allowing for RPS and without allowing for them were also derived (Figure 4).

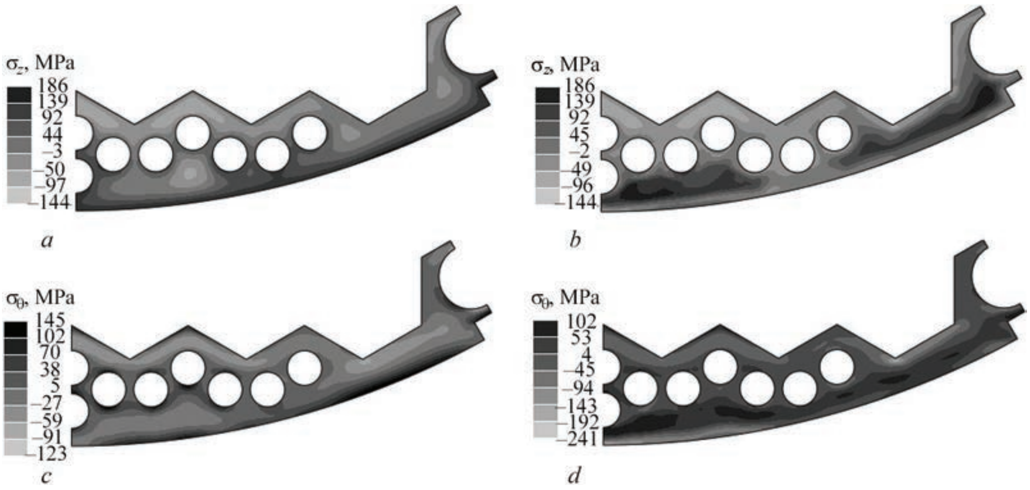

Figure 1. Stress distribution in the baffle in the 60th year of operation: *a* — axial component without allowing for RPS; *b* — axial component allowing for RPS; *c* — circumferential component without allowing for RPS; *d* — circumferential component allowing for RPS

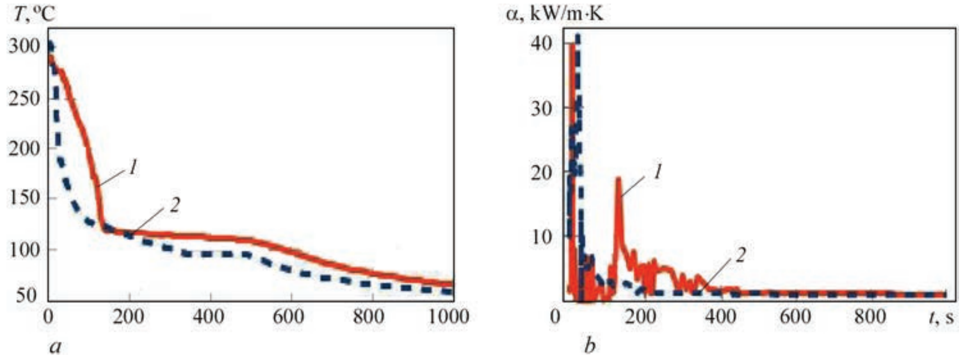

Figure 2. Temperature change (*a*) and heat transfer coefficient (*b*) of baffle walls during ES: *1* — inner surface; *2* — outer surface

Figure 3. Temperature field at moment of time t = 100 s since ES start

As one can see from Figure 4, allowing for RTS essentially influences the stress distribution. So, the maximal level of axial stresses on the baffle inner surface, when allowing for RPS, decreases from 488 to 416 MPa. However, in the baffle volume near the outer surface the compressive stresses (to 200 MPa), when allowing for RPS, turn into tensile stresses (to 50 MPa).

In [1] it was determined that at ES developing in zones 1 and 2 (Figure 4) of the baffle cross-section under consideration the value of *J*-integral for the postulated cracks is in the critical range. It should be noted that the residual process stresses were not taken into account here. In this work, the influence of RPS on the values of stress intensity factor (SIF) on the contour of postulated cracks, which are located in the plane of the baffle cross-section, is considered under the impact of axial stresses in an ES.

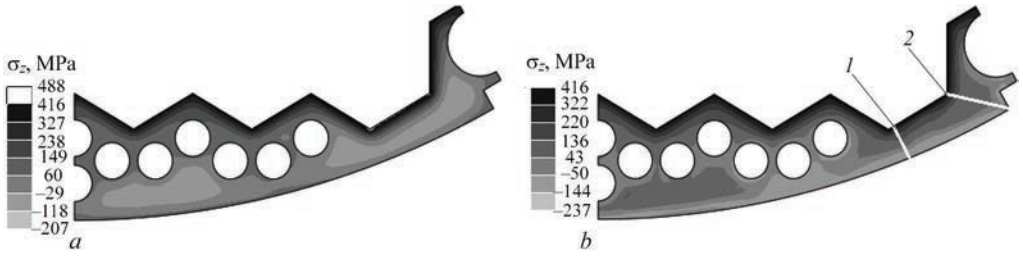

Figure 4. Distributions of axial stresses at t = 100 s since ES start without allowing for (*a*) and allowing for (*b*) RPS

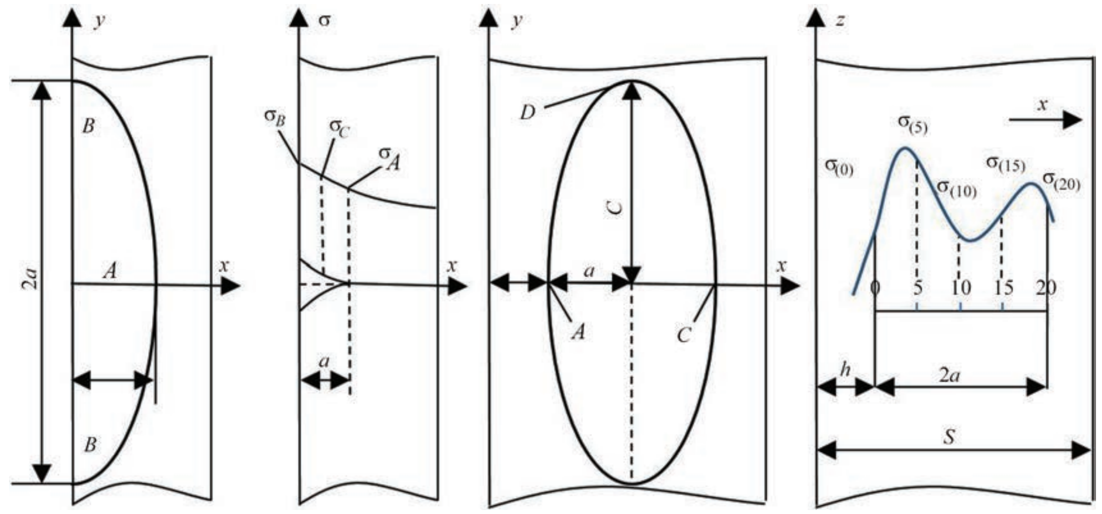

Figure 5. Geometrical parameters of semi-elliptical surface (*a*) and elliptical subsurface crack (*c*) with stress distribution (*b*, *d*)

DETERMINATION OF STRESS INTENSITY FACTOR

SIF determination was performed according to the procedures, described in [7] and [8]:

$$K_I = \sigma_K Y \sqrt{a}, \tag{1}$$

where K_1 is the stress intensity factor, MPa·m$^{0.5}$; σ_K are the stresses reduced to the uniform value, MPa; *Y* is the crack form factor, mm; *a* — minor half-axis of the crack, mm.

As the zone of maximum tensile stresses in the axial direction is located on the baffle inner surface, and when allowing for RPS this zone extends in the direction of the outer surface, the postulated defects were incorporated in the form of a surface semi-elliptical and subsurface elliptical crack (Figure 5), which are located at minimal depth ($h \ge a/9$). The ratio of the minor half-axis to the major one, in keeping with the requirements of [5], is equal to $a/c = 1/3$.

Stress distribution in the case of postulation of an elliptical subsurface crack, given in an arbitrary form, in keeping with [7], is calculated for the following coordinates across the thickness $x_j = h + a/10$, where $j = 0, 1, 2, \ldots, 20$, *h* is the depth of defect location. Stresses $\sigma_j = \sigma_K(x_j)$ are determined in each point x_j. Values reduced to uniform stresses $\sigma_K(A)$ and $\sigma_K(C)$ are calculated by the following dependencies:

$$\sigma_K(A) = \sum_{j=0}^{20}\left(A_j + \frac{a}{c}B_j\right)\sigma_j,$$
$$\sigma_K(C) = \sum_{j=0}^{20}\left(A_{20-j} + \frac{a}{c}B_{20-j}\right)\sigma_j, \tag{2}$$

where A_j and B_j are the tabulated values [7].

Determination of stresses σ reduced to the uniform value, at their parabolic distribution for a surface semi-elliptical crack was performed using the method described in [8]:

$$\sigma_K = 0.61\sigma_A + 0.39\sigma_B +$$
$$+\left\{0.11a/c - 0.28a/s\left[1-(a/c)^{1/2}\right]\right\}(\sigma_A - \sigma_B); \tag{3}$$
$$\sigma_K = 0.18\,\sigma_A + 0.82\,\sigma_B.$$

Form factors for each of the considered cases were also determined by different procedures. So, in keeping with [7], for elliptical subsurface cracks:

$$Y_{A,C} = \left[1-\left(\frac{a}{h+a}\right)^{1.8}\left(1-0.4\frac{a}{c}-\gamma_{A,C}\right)\right]^{-0.54}\times$$
$$\times\left[\frac{\pi}{1+1.464(a/c)^{1.65}}\right]^{0.5} \tag{4}$$

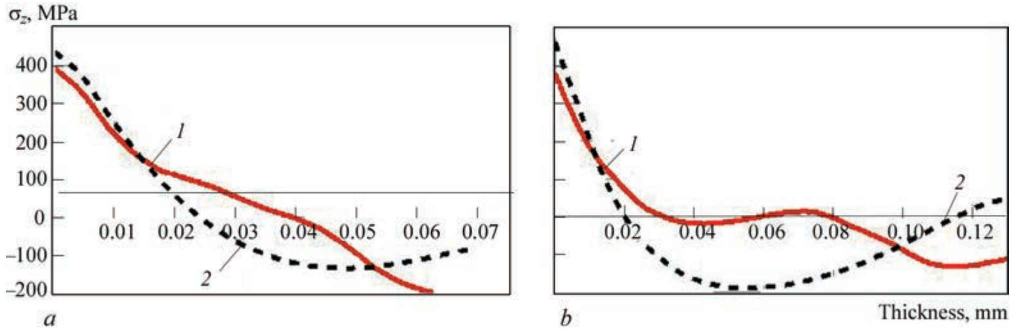

Figure 6. Distribution of axial stresses in baffle sections 1 and 2 at moment of time *t* = 100 s of ES mode: *a* — section 1; *b* — section 2; *1* — allowing for RPS; *2* — without allowing for RPS

Table 1. Geometrical parameters of postulated defects

Section number	a, mm	c, mm	h, mm	s, mm	Y_A	Y_C/Y_B^*	Y_D
Surface semi-elliptical crack							
1 (without RPS)	21.3	63.9	–	71	1.9	1.24	–
1 (from RPS)	35.5	106.5	–	71	2.13	1.46	–
2 (without RPS)	16.375	49.125	–	131	1.77	1.13	–
2 (from RPS)	35.5	106.5	–	131	1.87	1.22	–
Subsurface elliptical crack							
1 (without RPS)	8.875	26.75	1.7	71	2.43	1.86	2.6
1 (from RPS)	17.75	53.25	1.7	71	3.0	2.03	3.52
2 (without RPS)	8.125	24.375	3.3	131	2.06	1.76	2.08
2 (from RPS)	32.75	70.0	3.3	131	2.59	1.82	3.23
Note. $^*Y_B$ – for surface semi-elliptical crack; Y_C for subsurface elliptical crack (Figure 5).							

Table 2. Results of studying maximal SIF

Section number	$\sigma_K(A)$, MPa	$\sigma_K(C)$, $\sigma_K(B)$, MPa	$\sigma_K(D)$, MPa	K_A, MPa·m$^{0.5}$	K_C, K_B, MPa·m$^{0.5}$	K_D, MPa·m$^{0.5}$
Surface semi-elliptical crack						
1 (without RPS)	157.9	364.7	–	43.8	66.1	–
1 (from RPS)	76.4	296.5	–	30.6	81.5	–
2 (without RPS)	238.1	403.2	–	54.0	58.3	–
2 (from RPS)	100.6	294.1	–	35.5	67.5	–
Subsurface elliptical crack						
1 (without RPS)	320.5	83.8	202.2	77.8	24.9	59.1
1 (from RPS)	255.2	55.6	155.4	102.2	17.3	74.8
2 (without RPS)	284.7	68.6	176.6	52.8	12.2	34.0
2 (from RPS)	213.8	45.3	129.6	72.2	3.3	48.0

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

$$\gamma_A = \left(0.5 - \frac{h+a}{s}\right)^2, \gamma_C = 0.8\left(0.5 - \frac{h+a}{s}\right)^{0.4}, \qquad (5)$$

where s is the baffle thickness, mm.

At postulation of the subsurface semi-elliptical cracks in keeping with [8], the form factors were determined by the following dependencies:

$$Y_A = \frac{2 - 0.82a/c}{\left\{1 - \left[0.89 - 0.57(a/c)^{1/2}\right]^3 (a/s)^{1.5}\right\}^{3.25}};$$
$$Y_B = \left[1.1 + 0.35\left(a/s\right)^2\right]\left(a/c\right)^{1/2} Y_A. \qquad (6)$$

CALCULATION RESULTS

In order to determine the influence of RPS on BFR in two sections (Figure 4), two defects were postulated in the form of elliptical subsurface cracks. The geometrical parameters, as well as form factors, derived from expressions (*) for each of the defects, are given in Table 1. Figure 6 shows the distribution of axial stresses at moment of time t = 100 s since the emergency start, from which we can see an essential influence of RPS on the stress level in the considered sections 1 and 2.

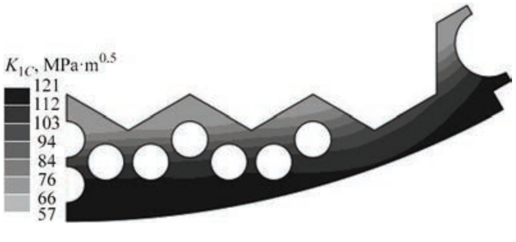

Figure 7. Distribution of critical SIF values in the baffle material at moment of time t = 100 s since ES start

Table 2 shows the results of calculation of maximum equivalent stresses and SIF for three characteristic points of the defects being postulated, at moment of time t = 100 s in ES mode.

As one can see from Table 2, allowing for RPS, on the whole, lowers the values of equivalent stresses, irrespective of the location of characteristic points (*A*, *B*, *C* and *D*) and type of postulated defect, leading to lowering of SIF value. It should be noted, however, that in the case of allowing for RPS, the tensile stress zone becomes greater, due to redistribution of stresses, permitting the postulated crack dimensions to be increased. Increase in the dimensions of the postulated defect can lead to a higher SIF value.

At postulation of a surface semi-elliptical crack, it was determined that in each of the considered sections when allowing for RPS in points *A*, SIF values decrease significantly, by 30 % for section No. 1 and by 34 % for section No. 2. However, an increase by 23 and 16 % is observed in points *B*. Note that the maximal SIF values were determined in points *B*, so that from the viewpoint of BFR evaluation the model allowing for RPS is more conservative.

At consideration of a subsurface elliptical crack it was determined that when allowing for RPS the SIF level for points *A* and *D* becomes higher, and its slight decrease is characteristic for point *C*. An increase in SIF value is observed for points: *A* and *D* by 31 and 27 % in section No. 1, and by 37 % and 41 % in section No. 2, respectively (Table 2).

The elliptical subsurface crack is more hazardous in terms of BFR, and its dimensions may reach critical values in an emergency (in section No. 1 at moment of time $t = 100$ s since ES start, $K_1 = 102.2$ MPa·m$^{0.5}$ allowing for RPS). Distribution of SIF critical values in the baffle material is shown in Figure 7.

An ES with harder boundary conditions is considered in [1]. Here, in one of the sections, which is in an area of significant impact of RPS and corresponds to the considered section No. 2, *J*-integral level reaches 12420 J/m^2 at critical value $J_c = 15400$ J/m^2. In keeping with the data (Table 2), SIF value, when allowing for RPS, can rise by approximately 40 %, i.e. *J*-integral values, derived in [1], can be much higher than the critical value, when allowing for RPS ($J \approx$ ≈ 17000 J/m^2). That is, allowing for RPS can enhance the conservatism of the approach for BFR evaluation and determination of RI baffle life.

CONCLUSIONS

Results of the conducted modeling of SSS and evaluation of BFR in WWER-1000 reactor RI baffle during an emergency in the mode of a big leak at rupture of primary circuit piping with the conditional diameter of 100–850 mm, allowing for and without allowing for RPS in the baffle showed that:

- at the most hazardous moment of time $t = 100$ s from ES start rather high stresses form in the axial direction in the baffle. Allowing for RPS decreases the value of total stresses, but the zone of tensile stresses becomes larger due to their redistribution, which permits increasing the size of the postulated crack and can lead to SIF increase, respectively;
- subsurface elliptical cracks are more hazardous in terms of BFR than the surface semi-elliptical cracks. Allowing for RPS leads to an increase in SIF for subsurface elliptical cracks up to 40 % at moment of time $t = 100$ s since ES start.

Thus, an essential influence of RPS on brittle fracture resistance of the baffle during ES was found, which should be taken into account at calculation-based substantiation of extension of operating life of WWER-1000 type power units.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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