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THE INFLUENCE OF THERMOMECHANICAL LOADING HISTORY ON THE STRESS LEVEL IN WWER NPP REACTOR PRESSURE VESSELS UNDER THERMAL SHOCK

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We present the results of calculations of the kinetics of stress-strain state and stress intensity factors for surface and under-the-cladding circumferential cracks in modeling the emergency core cooldown conditions for the WWER-1000 reactor. The calculation procedure is based on a mixed finite-element method statement which provides stability of numerical solution and a high accuracy of results for both the displacements as well as stresses and strains. The authors analyze the influence of the density of the finite-element discretization of the crack-tip area for the surface and under-the-cladding circumferential cracks on the accuracy and convergence of computation of fracture-mechanics parameters in the modeling of thermal shock conditions. The results of calculation of kinetics of stress intensity factors allowing for the thermomechanical loading history and residual process-induced stress fields are reported. It is demonstrated that if the elastoplastic deformation history and residual process-induced stress fields are disregarded in the calculations of stress intensity factors for under-the-cladding cracks the reactor pressure vessel strength and lifetime may turn out to be overestimated.

Keywords: stress-strain state, residual stresses, stress intensity factors, circumferential crack, reactor pressure vessel, thermal shock, mixed finite-element method representation.

Introduction. To ensure safe operation conditions nuclear power plant (NPP) reactor facilities requires further improvement of the computational models and procedures for calculating the stress-strain states (SSS) in reactor pressure vessels (RPV) allowing for the flaws they may contain and their thermomechanical loading history under various operating conditions.

Mathematical modeling of kinetics of thermomechanical state of reactor pressure vessel requires solving rather complex nonlinear thermomechanical transient boundary-value problems. The calculation of SSS kinetics for a reactor pressure vessel can be reduced to a successive solution of transient thermal conduction problems and a nonlinear thermomechanical boundary-value problem. To provide an adequate description of variations of a stress level in RPV under real operating conditions including emergency core cooldown (thermal shock), one should take into account the combined influence of various factors such as loading history, nonuniformity of heating and cooling, plastic deformation, inhomogeneity of physical-mechanical properties.

The relevant publications [1–14] present numerous data that reflect the accumulated experience and various aspects of computational substantiation of strength of WWER and PWR reactor vessels. They also discuss the standard approaches, the acting service loads and loads occurring during the reactor core emergency core cooldown and design accidents. Given are the data on physical-mechanical properties of the base metal and cladding of RPV; some materials-science aspects of strength assurance are addressed. The above-mentioned publications describe in

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detail the state-of-the-art of strength analysis software products and provide specific examples of their application to various types of calculations and computational models for RPV.

Nowadays, the RPV strength is assessed using an approach that involves calculation of the fracture-mechanics parameters, mostly the stress intensity factors (SIF). However, the currently available software products turn out to be insufficiently accurate and efficient in solving applied fracture-mechanics problems that include inelastic deformation in the vicinity of the crack front, because the large dimension of a discrete problem and the essential nonlinearity of material properties at the crack tip may result in instability or misconvergence of computation processes. The conventional methods of improving accuracy through the increase of the density of finite-element discretization and transition to more complex finite elements does not always prove efficient even in the case of linear problems. For transient and nonlinear three-dimensional thermomechanical problems the said methods are almost unsuitable as the order of the system of nonlinear algebraic equations to be solved and the large number of time steps and iterations would lead to a considerable increase in computational costs. This calls for elaboration of a more consummate apparatus for computational investigations, which would involve new approaches to and algorithms of solving nonlinear thermomechanical problems and fracture-mechanics problems.

In the present work we have obtained new results of calculations of SIF kinetics for NPP WWER-1000 reactor vessel with crack-like defects located in the reactor core region. The calculations were performed for a RPV with a crack "built" into a finite-element (FE) model, which is in line with the international practice and IAEA recommendations [15], taking into account a RPV nonuniform three-dimensional loading due to the occurrence of cold "crests" during a thermal shock.

The calculation procedure is based on a mixed finite-element method (FEM) statement that ensures stability of the numerical solution and high accuracy of results for both the displacements as well as stresses and strains [16]. The procedure has been implemented in the form of software products RELAX [16] and SPACE [17] for solving a wide range of applied problems being addressed in mathematical modeling of the processes of stress formation and redistribution in critical structural members of NPP WWER reactor facilities.

Computational Model of WWER-1000 Reactor Vessel. A finite-element model of WWER-1000 RPV is thick-walled cylindrical vessel with elliptical heads (Fig. 1). In the calculations the anticorrosion cladding on the RPV inner surface was assumed to be 7 mm thick. The physical-mechanical properties of the vessel metal and cladding were taken to be temperature dependent. To model an emergency – a thermal shock – the time- and space-variable boundary conditions of convective heat transfer (the coolant temperatures and heat-transfer coefficients) and pressure in the vessel downcomer were specified for the RPV inner surface using the results of thermohydraulic calculations carried out at OKB "Gidropress." The RPV outer surface was assumed to be heat-insulated. During the SSS calculations the following loads were preset: (i) internal pressure in RPV, (ii) temperature distributions as obtained by solving a transient thermal conduction problem, and (iii) residual stresses. The postulated circumferential crack was assumed to be located at an elevation of weld No. 4 below the inlet nozzle along the axis of the cold water "crest." The calculations of RPV stress level were performed for the surface and under-the-cladding circumferential cracks by following the fragmentation procedure (Fig. 1).

Thermal Field Calculation. We addressed a transient thermal conduction problem including the temperature dependence of the material's thermophysical properties. Figure 2 shows a temperature distribution on the RPV inner surface in the case of modeling a thermal-shock emergency with at a time instant 500 s. A characteristic feature of the temperature distribution is that it is essentially nonuniform in the angular coordinate, which is due to the occurrence of cold water "crests". A comparison between these temperature fields and the calculated results obtained at OKB "Gidropress" demonstrate a good agreement, the difference being no more than 1%.

Calculation of Residual Fabrication-Induced Stresses. A numerical procedure for the assessment of residual stress (RS) fields in RPV with simulation of the cladding–tempering–hydrotesting cycle has been elaborated and implemented. Using it we performed a numerical analysis of the processes of formation and redistribution of RS fields during the following fabrication cycle: anticorrosion cladding, preheating for heat treatment, holding at a temperature of high tempering, cooling down to normal temperature and hydrotesting at the factory.

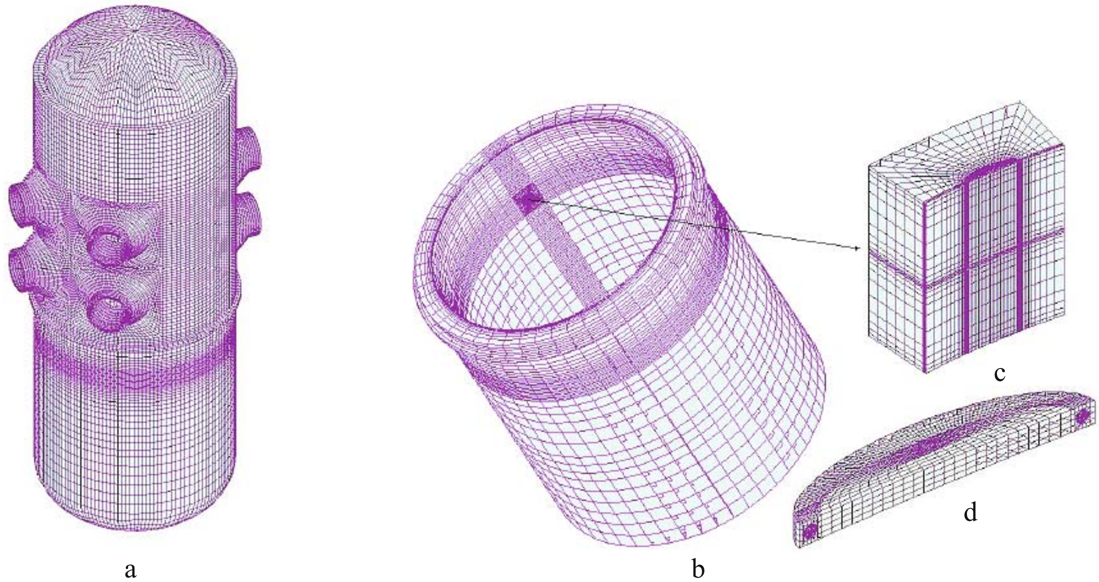

Fig. 1. Discrete computational models of WWER-1000 reactor vessel: (a) complete model; (b) model of RPV cylindrical part; (c) RPV fragment with a “built-in” crack; (d) mesh that extends along the crack front.

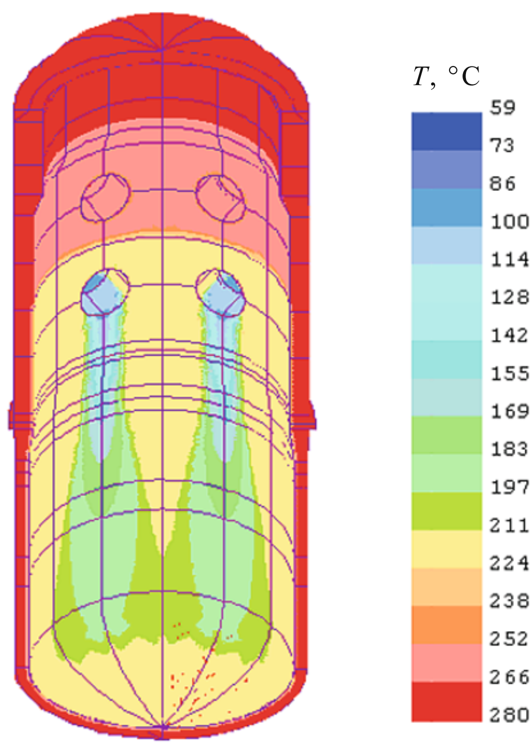

Fig. 2. Temperature distribution on the RPV inner surface at a time instant of 500 s.

The procedure was checked for applicability to the RS calculations with the preset parameters of the above-mentioned fabrication cycle. The calculations showed the tensile residual axial and hoop stresses in the cladding material to be 250 and 200 MPa, respectively. In the base metal region adjacent to the cladding material, as deep as 12 mm, there exist tensile residual stresses too; they do not exceed 40 MPa. Deeper into the base metal, there act compressive stresses (14 MPa). Note that the tensile stress zone is localized not only in the cladding metal but

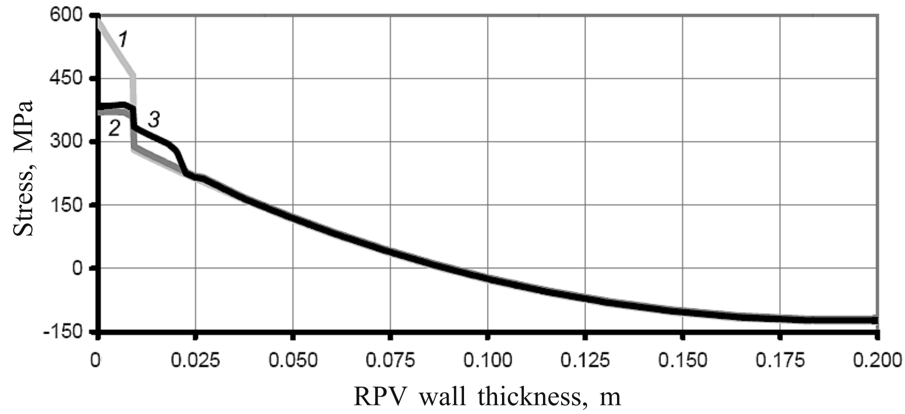

Fig. 3. Distribution of axial stresses in the RPV wall thickness during emergency core cooldown, at a time instant of 2000 s: (*1*), (*2*) elastic and elastoplastic calculations, respectively; (*3*) elastoplastic calculation allowing for residual stresses.

also in the adjacent base metal of RPV. This feature is of great importance as the presence of any defects in this region would lead to the highest risk of RPV fracture during the emergency cooldown. The calculated RS distribution is consistent with the well-known results presented in [2, 6]. A comparison between the RS calculated by the above procedure and the data given in the Code MRKR-SKhR-2004 (Brittle Strength Calculation Procedure for Reactor Pressure Vessels) demonstrates that the difference does not exceed 1.5% for the cladding material, 17% for the adjacent zone of the base metal, and 9% for the remaining part of the reactor vessel.

Calculation of SSS Kinetics for RPV during Emergency Cooldown. In modeling the emergency core cooling conditions, we tackled the nonisothermic thermoplasticity problem including stepwise tracing of the loading history [18].

The calculated data on SSS are shown in Fig. 3 in the form of distribution of axial stresses in the RPV wall thickness at an elevation of weld No. 4 as the one corresponding to the greatest stresses under the thermal shock conditions under study, for the time instant of 2000 s.

Calculation of SIF Kinetics for the Under-the-Cladding and Surface Cracks. Figure 4 gives the results of elastic SSS calculation for the deepest point of the under-the-cladding circumferential semielliptical 15-mm-deep crack located at the level of Weld No. 4 of WWER-1000 RPV, which were obtained in modeling the emergency core cooldown conditions. A method of equivalent volume integration was used for the SIF determination [19]. The mesh spacing in the vicinity of the crack tip was taken equal to 100 μm. A comparison between the calculated SIF values and those obtained at OKB "Gidropress" shows a good agreement, the difference in maximum values being no more than 1%.

When solving the problem in elastoplastic statement, for the SIF determination we employed the technique based on the crack-closure G-integration concept [20]. We analyzed the effect of the density of FE discretization of the crack-tip area for the surface and under-the-cladding circumferential cracks on the accuracy, convergence, and stability of SIF computation in the modeling of thermal shock conditions. A uniform FE disretization of the crack-tip zone was used. The calculations were performed in the axisymmetric problem statement, on the sequence of meshes being densified. The mesh spacing h in the vicinity of a crack tip was taken to be 1000, 100, 10, 1, 0.1, and 0.01 μm. The largest divergence of results was observed on the descending branches associated with the crack-tip stress relieving. For the meshes of spacing 0.1 and 0.01 μm the error of determination of design SIF values was found to be within 1%. Therefore, all further calculations in the axisymmetric problem statement were performed for the meshes of spacing 0.1 μm in the vicinity of the crack tip.

By way of illustration, Fig. 5 gives the results of elastoplastic calculations in terms of convergence of SIF over the sequence of densifying meshes for a 22-mm-deep surface circumferential crack in modeling the thermal shock conditions.

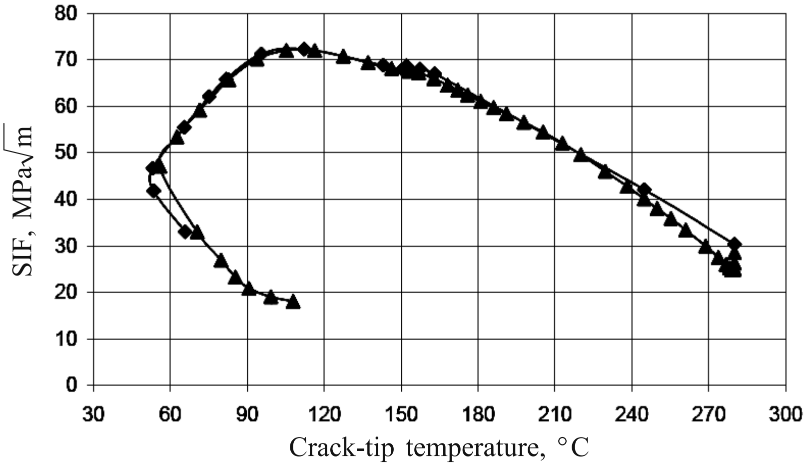

Fig. 4. Variation of SIF vs. temperature at the tip of the 15-mm-deep under-the-cladding circumferential crack: (◆) and (▲) data obtained by Pisarenko Institute of Problems of Strength of the National Academy of Sciences of Ukraine and OKB "Gidrpress," respectively.

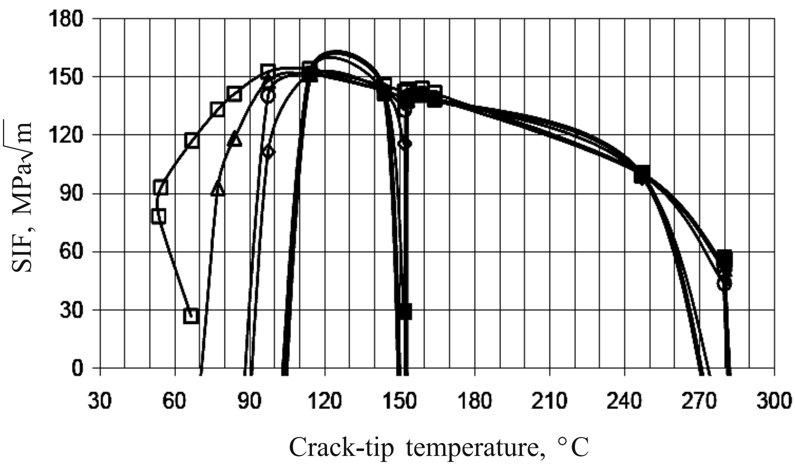

Fig. 5. SIF as a function of the mesh spacing in the elastoplastic calculation for a 22-mm-deep surface circumferential crack: (□) $h = 1000\ \mu m$; (◇) $h = 1\ \mu m$; (△) $h = 100\ \mu m$; (■) $h = 0.1\ \mu m$; (○) $h = 10\ \mu m$; (▲) $h = 0.01\ \mu m$.

According to the present findings, the mesh spacing in the vicinity of the crack tip has a significant effect on the determination of design SIF values. A characteristic feature of the elastoplastic solution obtained by using a mesh of fairly fine discretization is the presence of descending branches at the beginning, in the middle, and at the end of the temperature dependence of SIF, which is due to the material unloading and the formation of a compressive stress zone in the vicinity of the crack tip. The descending segments observed (Fig. 5) are associated with the corresponding (in time) segments of slowing down of the coolant temperature drop under boundary conditions of thermal shock. It has been found out that the compressive stress region for the under-the-cladding and the surface circumferential cracks extends into the base metal to a depth of 140 and 480 μm, respectively. For the under-the- cladding crack the compressive stress region at the base metal–cladding interface propagates as deep as 900 μm into the cladding.

Thus, the use of insufficiently fine discretization of the crack-tip zone in elastoplastic calculations gives no way of revealing the unloading zones; this distorts the true temperature dependence of SIF as obtained by means of sufficiently dense meshes which provide convergence of numerical results.

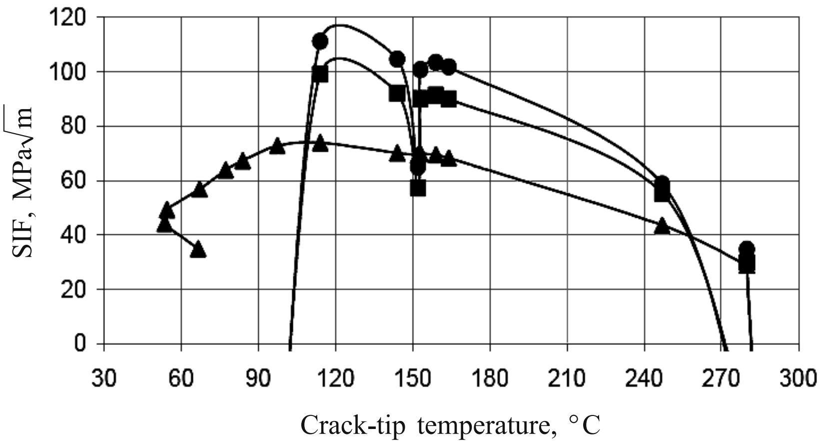

Fig. 6. SIF kinetics for the deepest point of the under-the-cladding circumferential crack of depth 15 mm. Here and in Figs. 7, 8: (▲), (■) elastic and elastoplastic calculations, respectively; (●) elastoplastic calculation allowing for residual stresses.)

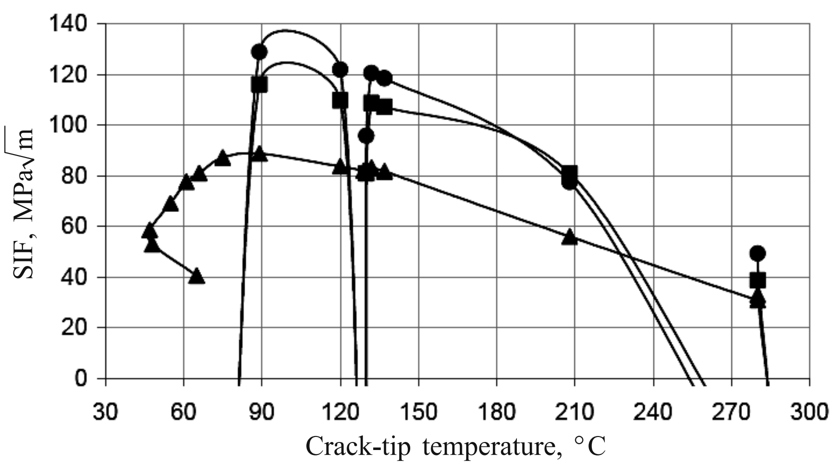

Fig. 7. SIF kinetics at the base metal–cladding interface for a 15-mm-deep under-the-cladding circumferential crack.

Figures 6, 7, and 8 give the calculated results on the SIF kinetics for the under-the-cladding and surface circumferential cracks of depth 15 and 22 mm, respectively. We considered three options of solving the problem: (i) elastic calculation, (ii) elastoplastic calculation allowing for the loading history, and (iii) elastoplastic calculation taking into account the RS formation and redistribution during the fabrication cycle.

Analysis of the calculated results for the under-the-cladding crack reveals that the maximum SIF values were obtained by the calculation options that allowed for the fabrication-induced RS formation and redistribution as well as the history of elastoplastic deformation in a crack-containing RPV during emergency core cooldown. The elastic calculation yields lower SIF values in comparison to the elastoplastic modeling of the loading history, i.e., the use of linear fracture mechanics may result in overestimation of allowed loads. The SIF values obtained by the elastoplastic calculation disregarding fabrication-induced residual stresses are about 25 to 30% higher in comparison to the elastic calculation. At the same time, when solving the problem in the elastoplastic statement including the residual stresses induced by cladding, tempering, and hydrotesting we have an additional 10–15% growth of SIF values for the RPV loading conditions considered. In all the above-mentioned calculation options, the SIF values at the base metal–cladding interface turn out to be higher than those for the deepest point of the under-the-cladding circumferential crack.

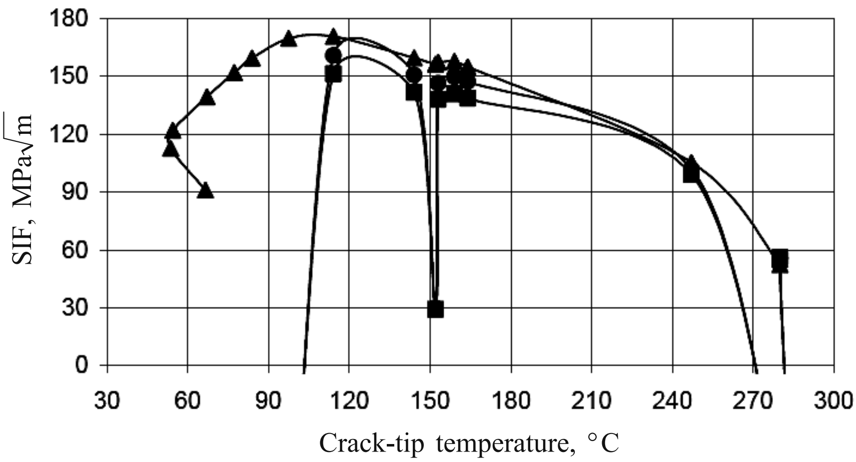

Fig. 8. SIF kinetics for a 22-mm-deep surface circumferential crack.

Thus, disregarding the elastoplastic deformation history and fabrication-induced residual stress fields in the SIF calculations can lead to critical errors during the RPV strength and lifetime assessment. For the surface circumferential cracks, the elastic calculation is more conservative in comparison to the elastoplastic modeling of the loading history. Note that when compared to the elastic calculation the elastoplastic one shows a sharper descent of the temperature dependence of SIF at the end of the emergency cooldown for both the the surface and under-the-cladding cracks. This feature is due to the material unloading and the formation of a compressive stress zone at the crack tip, which can be used for justifying the additional strength reserves for RPV under emergency conditions.

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