

## ELASTOPLASTIC FRACTURE RESISTANCE ANALYSIS OF NPP PRIMARY CIRCUIT EQUIPMENT ELEMENTS

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*Current calculation analysis approaches to the fracture resistance assessment for main equipment elements of the WWER NPP primary circuit are considered. It is noted that the solution of the problems of justifying safe operation, assessment of the integrity and extension of the lifetime of the reactor pressure vessel is essentially dependent on the results of calculations of the kinetics of the stress strain state, a proper consideration of the residual welding stress and strain fields, reliable evaluation of non-linear fracture mechanics parameters. A general methodology is developed for a calculated analysis of the fracture resistance of WWER reactor pressure vessels in the simulation of emergency cooling conditions. The main statements in the elastoplastic calculation of the kinetics of the stress strain state for reactor pressure vessels are formulated with consideration of the residual welding stress and strain fields, and the calculation procedure for determining the fracture parameters of the postulated crack is presented. Using the calculation methods and software product developed, a significant influence of such factors as consideration of the thermomechanical loading history and elastoplastic deformation of the metal in the vicinity of the postulated crack front, different ways of taking into consideration the residual welding stress level, the regularity and density of the finite element mesh in the vicinity of the calculated crack front, the procedure for calculating the elastoplastic fracture parameters in discrete finite element method models on the calculated fracture resistance assessment of WWER-1000 reactor pressure vessels is shown. It is found that the neglect of the loading history and residual stress level after heat treatment results in a non-conservative assessment of the fracture resistance for the collector-to-nozzle welded joint in the PGV-1000 steam generator in the simulation of the operating cycle of loading.*

**Keywords:** stress-strain state, residual stresses, stress intensity factor, postulated crack, reactor pressure vessel, steam generator, pressurized thermal shock, mixed finite element scheme.

**Introduction.** At present, the main areas of investigations on the problems of ensuring the strength and lifetime of NPP equipment elements include: the ultimate state criteria and determination of the in-service degradation of metal properties, calculation of the kinetics of the stress-strain state (SSS), influence of the residual welding stress level and presence of defects, current approaches to the fracture resistance of a material and their implementation into the calculation practice and extension of the operating life. The ensuring of the reactor power vessel (RPV) integrity under all possible conditions of loading, including emergency situations, is one of the main prerequisites for safe operation of NPP power units and extension of the operating life. Under reactor operating conditions caused by emergency situations, the brittle fracture resistance (BFR) ability of the RPV is taken as the basic criterion for its strength and integrity.

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Numerous data reflecting the current state, innovative regulatory approaches, experience and various aspects of calculation justifying the strength of NPP equipment elements (first of all, RPV) are given in [1–10], together with the analysis of the state-of-the-art models, methods and software products for the strength calculation as well as the examples of their application to different types of calculations and computational models for NPP structures.

The solution of problems of justifying safe operation of the RPV, assessment of its integrity and extension of its operating life is strongly dependent on the reliability of results of the SSS calculation analysis, reliable estimation of the fracture mechanics parameters of the RPV material, whereas the most important features of the brittle fracture resistance analysis for a RPV involve adequate and correct simulation of the material behavior nonlinear effects including the account of technological residual stress and strain fields, consideration of the thermomechanical loading history and elastoplastic deformation of the metal in the vicinity of the postulated crack front.

A reliable simulation, which properly describes the available physical processes, requires to ensure the accuracy and convergency of the finite-element solution of the problem, which also depends on the regularity and density of the finite element mesh. In solving the problem in the elastoplastic statement for the purpose of determining the stable calculated values of local fracture parameters, a sufficiently fine discretization is required in the vicinity of the crack front. The experience of solving practical problems testifies that in the simulation of the emergency conditions of RPV loading, the mesh spacing value in the vicinity of the crack front can reach several tens of micrometers or less.

Among the special features of the elastoplastic solution is the presence of the so-called “descending branch” at the end of the temperature dependence of the stress intensity factor (SIF) during RPV thermal shock process. This sharp SIF reduction is caused by the occurrence of the local compressive stress zone during unloading of the metal in the crack front vicinity. For the first time in the calculation practices, the results of the elastoplastic fracture resistance analysis for the RPV that are indicative of the local unloading of the metal at the crack tip were obtained at the Pisarenko Institute of Problems of Strength of the National Academy of Sciences of Ukraine [6, 11]. To determine the calculated SIF values, a procedure was employed based on the crack closure  $G$ -integral concept [11, 12]. It was found that insufficiently fine discretizations in the vicinity of the crack tip used in computational models do not allow the local unloading zones to be detected, thus distorting a true temperature dependence of the SIF obtained with sufficiently fine meshes, for which the convergence of numerical calculation results takes place. It is noteworthy that the presence of a descending branch in the temperature dependence of the SIF at the end of the RPV cooling mode is a sufficiently important factor in assessing the RPV in-service life since it makes it possible to reveal additional margins of safety for brittle strength when extending the RPV operating life.

A critical issue for computation of the SIF variation during the thermal shock process is taking account of the loading history, including the technological heredity. In view of crack detection in collector to PGV-1000 steam generator welded joint No. 111, the problem of modeling the processes of stress generation and redistribution of stresses in the structure using refined computational models of the steam generator has acquired a special urgency.

Simulation of operating loading modes using 3D models of such units with account taken of of the influence of other elements of the reactor unit primary circuit loop and with further consideration of the elastoplastic deformation history and nontrivial effects of manufacturing and rehaul technological operations (in particular, thermal treatment) made it possible to reveal a high level of tensile stresses in the unit in the site of damage occurrence [9, 10]. Nevertheless, the kinetics of the stress generation and redistribution in the collector to the PGV-1000 steam generator shell has not been studied in full, which determines the urgency of investigations in this direction.

Therefore, the material fracture resistance analysis of NPP structural elements should include the solution of boundary problems of nonisothermal thermoplasticity and fracture mechanics problems in the simulation of the non-stationary regimes of thermomechanical loading. In making the calculation analysis, a combined effect of the factors such as the nonuniformity of heating and cooling, thermomechanical loading history, plastic deformation, creep and relaxation processes, residual stresses and strains, inhomogeneity of physico-mechanical properties of the material and their dependence on temperature, variation in the material fracture resistance with consideration of the in-service effects and degradation of the initial properties of the material. Thus, the elastoplastic simulation of the kinetics of the SSS and the fracture resistance analysis of deformable structures of NPP are among the most intricate

problems in the mathematical physics and mechanics of materials and structures. The fracture resistance calculation with consideration of the above-listed factors for a full range of calculation versions of NPP structure loading does not seem possible since the solution of non-stationary and nonlinear boundary-value problems of the thermomechanics and the fracture mechanics problems is a very complex numerical procedure, whose practical implementation results in unacceptable computational costs.

Furthermore, the known commercial software products, the computational analysis of which has in its basis the finite-element method (FEM), are found to be insufficiently accurate and efficient in solving so complex specific applied problems of elastoplastic fracture mechanics, insofar as high dimensionality of the discrete problem and significant non-linearity of the material properties in the vicinity of the calculated crack front can result in the loss of stability or misconvergence of the computational processes.

Traditional approaches to increase the accuracy by increasing the finite-element discretization density or by changing to more sophisticated finite elements are not always efficient even in the case of non-linear problems. These approaches are practically unsuitable for non-stationary and non-linear three-dimensional problems of thermomechanics, since an increase in the order of the system of nonlinear algebraic equations to be solved and a large number of time steps and iterations lead to a significant increase in computational costs.

In view of this, the necessity arises for the development of a more perfect tool required for performing the calculation analysis, including new approaches and algorithms of solving boundary problems of non-isothermal thermoplasticity and fracture mechanics problems, as well as the construction of appropriate computational schemes and models, and the use of modern concepts of fracture mechanics for NPP RPV integrity assessment, in particular, for nuclear reactor and steam generator power vessels.

A general methodology for the fracture resistance analysis of critical elements of WWER NPP Equipment is considered using a RPV as an example.

**Basic Aspects of the Procedure for the Fracture Resistance Analysis of Reactor Pressure Vessels.** The fracture resistance analysis is based on the provisions of the regulatory documents [1, 7, 8] and includes two stages:

1. A simplified procedure for the brittle fracture resistance (BFR) analysis to determine the most critical emergency conditions and locations of the postulated defects.
2. A refined procedure for the fracture resistance analysis in the elastoplastic statement with the direct inclusion of the postulated defects in the computational model for the worst-case loadings.

A simplified BFR analysis consists of the following basic steps:

- (i) calculation of the non-stationary thermal fields for the emergency situation conditions under analysis;
- (ii) elastic analysis of the SSS of the RPV without consideration of the crack and the residual stress fields for the loading conditions under analysis;
- (iii) consideration of the residual welding stresses in the welded joint metal and residual stresses in the base metal due to the deposition of cladding is accomplished by summing the values of residual stresses with the stresses obtained from the performed elastic calculation;
- (iv) brittle fracture resistance analysis is performed using analytical dependences for determining the SIF of the postulated cracks and the calculation data on the stress distribution across the wall thickness of the RPV without a crack;
- (v) based on the results of the performed BFR analysis of the RPV, the emergency conditions, most critical from the standpoint of the BFR, and the locations of the postulated cracks are determined.

When performing the BFR analysis using a simplified procedure, the maximum depth of the calculated postulated cracks is regulated by the normative documents [7, 8]. Considering that for non-stationary loading conditions of the RPV, the worst-case situation in respect of the brittle fracture is not always realized for the maximum depth of the crack, the BFR analysis according to a simplified procedure is also performed for the calculated cracks of a smaller depth.

The fracture resistance analysis using a refined procedure is performed for the most critical emergency conditions and locations of the postulated cracks determined from the performed simplified BFR analysis of the RPV according to a simplified procedure. It includes:

- (i) analysis of the residual stress and plastic strain fields in the welded joint, base metal and anti-corrosion cladding;
- (ii) analysis of non-stationary thermal fields for the most critical emergency situations;
- (iii) elastoplastic analysis of the kinetics of the stress-strain state in the RPV for the most critical conditions with the postulated crack included in the computational model and consideration of the residual stress and strain fields;
- (iv) calculation of the design SIF values for the postulated cracks using the results from the performed elastoplastic analysis and the crack closure  $G$ -integral concept;
- (v) fracture resistance analysis in accordance with the regulatory documents [7, 8] with the determination of the maximum allowable critical brittleness temperature of the RPV metal.

Consider the basic features of the above-stated approach in more detail.

**Analysis of the Kinetics of the SSS.** The procedure for the analysis is based on a sequential solution of the problem of non-stationary thermal conductivity and the boundary problem of non-isothermal thermoplasticity [13].

Here the dependences linking the environment temperature and heat transfer coefficient with time and spatial coordinates, which are required as boundary condition for solving the heat transfer problems, have to be determined using special software packages (such as OKBMIX and KWU-MIX) based on the results of full-scale experiments, and require conduction of general heat-and-hydraulic computations using such software products as RELAP5/MOD3.2 [1].

The analysis of the kinetics of the SSS in the elastoplastic statement is performed based on the FEM using two- and three-dimensional computational models of the RPV with the postulated crack built into a discrete model. The basis of the finite element analysis is the mixed FEM scheme [15] that ensures a continuous approximation for both displacements and stresses, which makes it possible to determine the SSS and fracture mechanics parameters to a high degree of accuracy.

**Calculated Assessment of the Residual Stress and Plastic Strain Fields.** The procedure for the calculated determination of the fields of residual stresses and strains in the RPV involves a simulation of the following processing cycles: producing a welded joint; high-temperature tempering; deposition of anti-corrosion cladding; heat treatment according to a high-temperature tempering regime; hydraulic testing by the manufacturer. In the analysis of the kinetics of stresses and strains due to the processes of welding and cladding followed by the heat treatment and hydrotesting, the hypothesis of the axial symmetry was employed, which makes it possible to consider the problem about the determination of the residual stress and strain fields in the axisymmetric statement. The obtained results showing the nature of the distributions and levels of residual stresses and plastic strains in the simulation of the manufacturing operations of welding, cladding and thermal treatment are in full agreement with the known results [7].

**Calculated Postulated Defects.** In the fracture resistance analysis of the RPV using a simplified and refined procedure, the postulated defect was defined as a flat undercladding semi-elliptical crack of depth  $(0.07-0.125)s$ , where  $s$  is the thickness of the RPV wall with consideration of the cladding thickness [7, 8], and the ratio between crack semi-axes equal to 0.3 [4, 7, 8]. The axially and circumferentially oriented cracks in the metal of circumferential welded joints on the axis of cold water plumes under the inlet nozzle were considered. It is noteworthy that the calculated defect was postulated as an undercladding crack located in the base metal of the RPV, in contrast to a conventional approach according to which in the simplified calculation a surface crack is postulated, whereas in the elastoplastic analysis an undercladding crack is simulated [2].

**Calculation Procedure for Determining the SIF.** The basic aspects of the calculation procedure are based on the application of the crack closure  $G$ -integral concept to discrete FEM models. The computational justification of using the  $G$ -integral concept for the solution of problems of the crack theory on the basis of the mixed FEM scheme is given in [12, 13].

Under the condition of plane strain and with the fulfillment of certain assumptions to calculate the  $G$ -integral, an invariant, i.e., independent of the integration path, Cherepanov–Rice contour  $J$ -integral is used [15]. Here, it should be noted that the invariance of the  $J$ -integral values will occur only in the case that the body is either elastic or obeys the equations of the deformation theory of plasticity [16]. If it is assumed that in the plastic region

the material is deformed according to the flow theory equations [17], then the  $J$ -integral is already not invariant. The above-mentioned plasticity theories coincide if the cracked body is loaded by a monotonically increasing load that varies in proportion to a single parameter, and in this case the equality  $G = J$  is valid. However, at an arbitrary loading history, e.g., under emergency cooling of the RPV, when unloading of the material takes place at the crack tip, or under repeated loading, the equality of two  $G$ - and  $J$ -integrals loses its meaning. In this case, the elastic-plastic fracture resistance analysis using the  $J$ -integral concept becomes unjustified.

Thus, in the elastoplastic simulation of the arbitrary loading history,  $J$ -integral cannot be used as an adequate fracture parameter, whereas the  $G$ -integral retains the reasonable physical meaning as specific work required for the stationary crack growth onset in an elastoplastic body. The use of the  $G$ -integral in discrete FEM models has shown that the results of the elastoplastic calculation are in full agreement with the principle of small scale plastic flow, in particular, with the Irwin plasticity correction and retain this property during mesh refinement [12].

To obtain reliable and stable results for determining the  $G$ -integral and SIF values, the calculations are performed on successively refined FEM meshes. The value of the mesh spacing in the vicinity of the calculated crack front point is chosen from the condition for which the calculated values of the fracture parameters obtained for two successively refined FEM meshes are found to be sufficiently close between themselves. At the stages of active loading, the use of the  $G$ -integral concept in discrete FEM models leads to conservative results of the SIF determination when employing sufficiently moderate size discretization in the vicinity of the crack front. During unloading of the material in the vicinity of the crack front point, the convergence of the results of determining the calculated SIF values is reached for much finer discretization.

**Software Used in the Calculations.** The calculation of non-stationary thermal fields, the kinetics of the SSS and SIF was performed using the software SPACE-RELAX [18]. This computer complex software package was developed at the Pisarenko Institute of Problems of Strength of the National Academy of Sciences of Ukraine to solve a wide range of applied problems, including those involved in mathematical modeling of the processes of stress and strain generation and redistribution in critical structural elements of WWER NPPs, and was authorized for use in the nuclear industry of Ukraine by the appropriate order of the NNEGC (National Nuclear Energy Generating Company) Énergoatom as a nuclear operating organization.

**Selection of Calculation Schemes (Models).** In the SSS calculations of RPV with a postulated crack subjected to thermal shock, one should take into account the influence of numerous factors related to RPV structural parameters, loading conditions, physical-mechanical characteristics of materials, residual welding stresses, crack parameters, calculation techniques and models [1]. Usually the problem simplification is provided by neglecting the effects of several factors and by schematization of the real situation. In order to select the most critical factors, one should analyze the sensitivity of the obtained solutions to variation of this or that factor, as well as to the selected schematization of the real situation. To save time and costs, the available results of earlier studies (e.g., [1]) are used. However, one should bear in mind that the available dependences can exhibit not just a quantitative, but a qualitative change, when the RPV object under study is changed, e.g., from WWER-400 to WWER-1000. Sometimes even small-scale variations of a certain parameter can strongly affect the calculation sensitivity and/or accuracy. Quite important are also qualification and experience of the computation expert, who develops the calculation schemes and includes/tunes out certain factors in the problem solution. The difference between the obtained solutions can be quite large. Thus, due to application of different approaches to simulation of heat-and-hydraulic processes during the thermal shock process (and thus, to estimation of boundary conditions for the heat transfer problem, the difference between calculated values of the maximal allowable temperature of the critical metal brittleness of the similar RPVs amounted, in practice, to few tens of degrees. Another example of different sensitivities in regard to the object under study is the effect on SIF of the difference between the values of elastic modulus and thermal expansion coefficient of the base metal and cladding listed in the normative documents. The difference has no practical effect on the SIF level of a surface crack, but strongly affects the SIF level of a sub-cladding crack in the WWER-1000 metal.

Using the above approaches, a number of factors for the calculated assessment of the fracture resistance are analyzed below, which, in our opinion, have not received due attention in numerous publications on the fracture resistance analysis of reactor pressure vessels and steam generators.

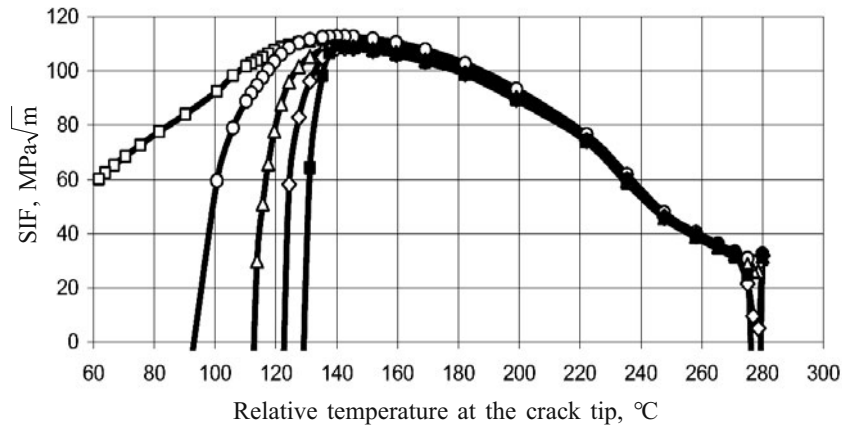


Fig. 1. Variation of the SIF versus temperature at the deepest point of the circumferential undercladding crack for different mesh spacings  $h$ : (□)  $h=1000 \mu\text{m}$ ; (○)  $h=100 \mu\text{m}$ ; (△)  $h=10 \mu\text{m}$ ; (◇)  $h=1 \mu\text{m}$ ; (■)  $h=0.1 \mu\text{m}$ .

**Effect of the Finite Element Discretization Density.** The evaluation of the effect of finite element mesh density in the vicinity of the crack tip was performed in the simulation of typical cooling conditions for the WWER-1000 RPV. The calculations were carried out in the axisymmetric statement taking into account the fields of post-welding stresses and strains. During the problem solution, a uniform triangular mesh was used in the vicinity of the undercladding circumferential 20 mm deep crack tip located on the axis of the plume of cold water at the level of welded joint No. 4.

The accuracy and convergence of the calculation results were verified on successively refined finite element meshes. The value of the mesh spacing at the crack tip was taken to be equal to 1000, 100, 10, 1, 0.1 and 0.01  $\mu\text{m}$ . Figure 1 shows the results of the elastoplastic calculations, whence it follows that the mesh spacing value in the vicinity of the crack tip has a significant influence on the determination of the calculated SIF-values. A specific feature of the elastoplastic solution is the presence of a descending branch at the end of the process of emergency cooling (pressurized thermal shock), which is related to unloading of the material in the vicinity of the crack tip. The use of sufficiently coarse meshes in the elastoplastic calculations does not allow revealing the zones of unloading in the vicinity of the crack tip, which distorts the true temperature dependence of the SIF obtained with sufficiently fine meshes for which convergence of the numerical calculation results takes place. The analysis of the elastoplastic calculation results in the three-dimensional statement leads to a similar conclusion. The above circumstance is a very important design factor since the neglect of unloading at the crack tip results in much more conservative assessment of the allowable critical brittleness temperature of the RPV metal and, hence, its lifetime.

**Consideration of the Residual Welding Stress Level.** The calculation analysis was performed for five alternative considerations of the fields of residual welding stresses used in the world-wide calculation practices: 1) the stress-free-temperature method; 2) heating to high tempering temperature and cooling down to normal temperature; 3) the stress-free-temperature method and additional loading under which additional tensile stresses of 100 MPa occur in welded joints; 4) heating to high tempering temperature, cooling down to normal temperature and additional tensile stresses of 100 MPa; 5) elastoplastic calculation with consideration given to a complete cycle of generation and re-distribution of residual stress and strain fields.

Figure 2 illustrates the results of elastoplastic calculations for a 15 mm deep circumferential undercladding crack located at the level of welding joint No. 4 of the WWER-1000 RPV in the simulation of specific cooling conditions.

From the plots it follows that the consideration of residual stresses with the use of variants 1 and 2 leads to the discrepancy of the SIF calculation results under pressurized thermal shock of less than 1%. However, the SIF values thus obtained are significantly non-conservative as compared to the other alternative variants of consideration of residual stresses, insofar as, in effect, only the residual stresses occurring after the anti-corrosion cladding

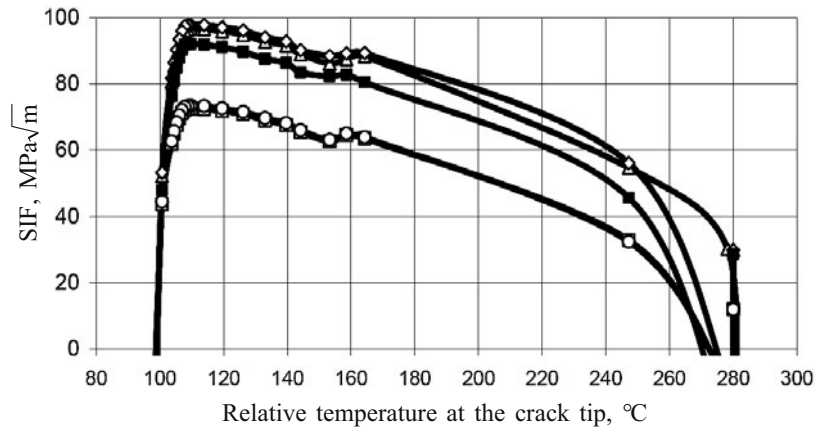


Fig. 2. Variation of the SIF versus temperature at the deepest point of the circumferential undercladding crack for different ways of taking into consideration the residual stress fields: (□) variant 1; (○) variant 2; (△) variant 3; (◇) variant 4; (■) variant 5.

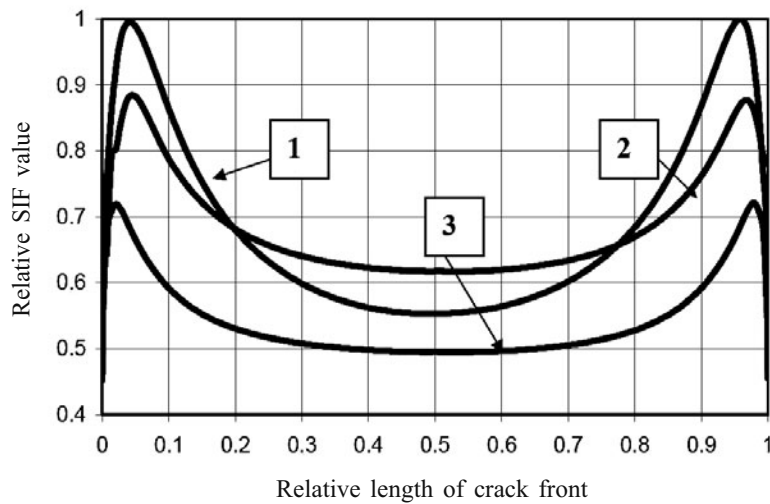


Fig. 3. Distribution of relative SIF values along the surface circumferential crack front in the steam generator assembly: (1) calculation with account of the loading history and residual stress level; (2) calculation with account of the loading history; (3) calculation with no account of the loading history and residual stress level.

deposition on the inner surface of the RPV are taken into account, whereas the residual stresses in welded joints are neglected.

One of the possible ways of taking into consideration the post-welding stresses is the additional loading method with which additional axial tensile stresses of about 100 MPa occur in cylindrical shells of the RPV.

The calculations using the additional loading method result in much higher SIF values under the pressurized thermal shock. However, the results of the SIF calculation for the third and fourth variants significantly differ between themselves only at the initial stage of cooling and practically coincide in the regions with the maximum SIF values.

In the simulation of the manufacturing operations of welding and deposition of the anti-corrosion cladding, the elastoplastic calculation with the consideration of a complete cycle of generation and re-distribution of the residual stress fields results in less conservative evaluations of the critical brittleness temperature as compared to variants 3 and 4, which provide the account of the additional loading. At the same time, these evaluations are more conservative as compared to those of variants 1 and 2, which neglect the residual stresses in the welded joint zone.

**Consideration of the Loading History.** To evaluate the influence of thermomechanical loading history on the fracture resistance of the “hot” collector-to-nozzle welded joint in a PGV-1000 steam generator, the operating cycle of loading was simulated. The calculation of the SSS of the welded joint was performed in the elastoplastic statement with and without consideration of the loading history.

The fracture resistance analysis with consideration of the loading history was performed in the simulation of the operating cycle of loading: hydrotesting (HT) → unloading after the HT → normal operating conditions (NOC). The residual stress and strain fields obtained from the computational modeling of welding and heat treatment processes were assumed as the initial state.

The analysis without consideration of the loading history was carried out for the NOC by a single loading in the stress-free initial state.

The computational three-dimensional finite element model included a steam generator, main coolant pipeline and RPV. A surface 18 mm deep semi-elliptical crack with the ratio of the semi-axes of 2/3 located in the zone of the maximum stress level in the fillet of the welded joint was postulated. The solution to the problem was obtained by the fragmentation procedure.

It follows from the calculation results (Fig. 3) that the neglect of the loading history and residual stress level after the heat treatment leads to the underestimated (by up to 28%) calculated SIF values and hence to a non-conservative assessment of the fracture resistance for the welded joint in modeling the operating cycle of loading.

## CONCLUSIONS

1. The state-of-the-art calculation approaches to the assessment of the fracture resistance of critical equipment components of the WWER NPP primary circuit have been considered. It is noted that the solution of problems of justifying safe operation, assessment of the integrity of the RPV and extension of its lifetime is essentially dependent on the fracture resistance criteria, calculation results for the kinetics of the stress strain state, and reliable evaluation of nonlinear fracture mechanics parameters.

2. The general methodology for the fracture resistance analysis of WWER-1000 reactor pressure vessels in the simulation of emergency cooling conditions has been developed. The main statements in the elastoplastic calculation of the kinetics of the stress strain state for reactor pressure vessels have been formulated with a consideration of the residual welding stress and strain fields. Additionally, the calculation procedure for determining the calculated SIF values along the postulated crack front has been developed.

3. Using the developed calculation methods and software, a significant influence on the calculated assessment of the WWER-1000 RPV fracture resistance of such factors as consideration of the thermomechanical loading history and elastoplastic deformation of the metal in the vicinity of the postulated crack front, consideration of the fields of residual welding stresses and strains, regularity and density of the finite element mesh in the vicinity of the calculated crack, the procedure for calculating the elastoplastic fracture parameters in discrete FEM models, has been revealed.

4. It is shown that the refined elastoplastic calculation at the stage of material unloading in the crack tip vicinity during the RPV thermal shock can substantiate the additional RPV strength and life values, whereas the neglect of the loading history results in a non-conservative assessment of the fracture resistance for the “hot” collector-to-nozzle welded joint in a PGV-1000 steam generator in the simulation of the operating loading cycle.

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