Chapter 15
State-of-the-Art Methods of Material's Current State Assessment and Life-Time Prediction for NPP Primary Circuit Equipment

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15.1 Introduction

The global practice of justifying the structural integrity of critical nuclear power plant (NPP) components shows that the regulatory framework in Ukraine requires improvement for the correct justification of the strength and lifetime of the first-circuit NPP's equipment components.

The most critical element of the first-circuit NPP's equipment components is the reactor pressure vessel (RPV), so special attention is paid to the development of methods for assessing its strength and lifetime prediction. At the same time, world experience shows that the RPV service life is limited by the results of brittle fracture resistance calculations. When evaluating the RPV brittle strength, on the one hand, numerical calculations of the stress intensity factor (SIF) of RPV elements with a postulated crack under thermal shock conditions are required. On the other hand, it is necessary to know the current state of the RPV metal to build a fracture toughness–temperature dependence. Precisely, the use of modern improved calculation methods and methods of predicting the degree of RPV metal degradation level during its operation makes it possible to assess RPV durability and lifetime accurately.

Monitoring the condition of the RPV metal during the entire service life is one of the main conditions for ensuring the reliable and safe operation of the RPV and the entire power plant. The RPV is the main safety barrier of the reactor plant and cannot be replaced due to technical and economic expediency, and in practice, its condition determines the lifetime of the entire power unit.

A necessary condition for the safe operation of the VVER-1000 reactor plant is the preservation of the fracture toughness temperature margin of the RPV materials. Over time, as a result of radiation embrittlement, this margin, that is, the difference between the maximum allowable critical brittleness temperature (T_k^a) and the actual one (T_k),

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decreases, increasing the probability of brittle fracture of the reactor. According to the PNAE G-7-002-86 (1989) standard, the critical brittleness temperature T_K is considered one of the key parameters characterizing the fracture toughness of RPV materials. The critical brittleness temperature is used in determining safety limits for thermohydraulic parameters during RPV routine hydraulic tests. Calculations on the RPV brittle strength for normal operation conditions, violations of normal operation conditions, and emergency situations are also carried out using the results of mechanical tests of surveillance specimens (SS). In addition, comparing the T_K value with the maximum permissible brittleness temperature T_k^a allows us to confirm the RPV design lifetime and assess the possibility of extending its service life. Thus, safe operation of the RPV VVER-1000 is ensured only in the case when the T_K value remains below T_k^a at any operation regime.

The program for controlling the properties of the RPV metal using SS, made from the material of this vessel, is the basis for establishing changes in the RPV metal mechanical characteristics under operating conditions. The SS test results are used to predict the RPV lifetime from the point of view of resistance to brittle failure.

Cylindrical specimens for uniaxial tension tests, Charpy specimens for impact bending tests, and compact CT specimens (or COD) for fracture toughness tests are used as test specimens.

Many studies show that radiation embrittlement makes the most significant contribution to the shift of the critical brittleness temperature of the metal (Kevorkyan et al. 2004; Margolyn et al. 2010; Nikolaev 2007; Wallin 1991; Wallin et al. 1984). When developing methods for predicting the RPV lifetime, great attention is paid to the radiation effect on the change of mechanical characteristics, primarily the critical brittleness temperature. Unfortunately, the limited number of SSs does not allow for developing a unified methodology for predicting metal radiation embrittlement. Therefore, today several such methodologies are used in various regulatory documents (VVER-1000 2009; IAEA-TECDOC-1442 2005; PNAE G-7-002-86 1989; MRKR CHR 2004; VERLIFE 2008). The issue of the use of certain methods is still debatable, and now in Ukraine, there is still no unified state standard for assessing the RPV strength and lifetime.

With the development of computer technology and calculation methods, the task of evaluating the resistance to brittle fracture of the first-circuit NPP's equipment components can be solved with quite a high accuracy. However, the accuracy of the obtained solution is affected by many factors that require their analysis. In modern regulatory documents, the use of various approaches is allowed, which involve the use of both engineering methods (Marie and Chapuliot 2008; MR 108.7-86 1980) and finite element (FE) models (two and three dimensional) with a built-in crack to determine the SIF (Choi et al. 2019; González-Albuixech et al. 2016; Kharchenko et al. 2018; Kharchenko and Kondryakov 2007; Qian and Niffenegger 2013; VERLIFE 2008).

Recently, along with the classical FE method (FEM), other methods of calculation have been actively developing. This is due to the shortcomings of FEM, which are caused by the significant dependence of calculation results on the FE mesh density. In particular, mixed FEM schemes are being developed (Kharchenko et al. 2018). Also, one of the promising methods is the extended finite element method (XFEM), which makes it possible to obtain satisfactory results in calculating the resistance to brittle fracture without modeling a built-in crack (Belytschko and Black 1999; González-Albuixech et al. 2014; Mora et al. 2019). Using XFEM allows us to calculate the resistance to brittle fracture for different shapes, sizes, and locations of cracks in complex units, for example, the nozzle area, where generating a high-quality FE mesh is difficult when modeling a pre-existing crack (Chapuliot 2016; Liu 2018). At the same time, to obtain more accurate results, it is advisable to use the submodeling technique (Kim 2005; Marenic et al. 2010), which has proven itself well in assessing the strength of complex units of equipment elements.

This chapter considers several factors that can significantly influence the determination of RPV structural integrity and lifetime. A detailed analysis of the well-known methods for estimating RE and predicting the fracture toughness–temperature dependences was carried out using the SS test results of weld metal of the representative RPV with a high Ni content. Existing methods are compared, and their advantages and disadvantages are shown. Also, the results of numerical modeling of the RPV cylindrical part and the nozzle zone using classical and extended FE methods are compared.

15.2 Methods of Radiation and Thermal Embrittlement Assessment of NPP Reactor Pressure Vessel Materials

The use of different RE assessment methods can significantly affect the estimation of the first-circuit NPP's equipment components lifetime, particularly the RPV. At the same time, there is currently no universal method. Their development and improvement continue, especially to take into account new experimental data from SS tests. Therefore, using the most conservative approach with enough justification is advisable for such assessments.

The assessment of RPV metal RE involves the construction of trend curves Tk(F) based on the SS tests results. Next, the critical value T_k^{crit} is determined based on the known design fluence value. If the condition $T_k^{\mathrm{crit}} = T_{ka}$ is fulfilled, the RPV lifetime can be extended. Different methods are used to construct trend curves, which differ in processing SS tests experimental data (Charpy specimens).

Different methods of approximation are used to determine ΔT_F according to the SS test results. In this case, ΔT_F is usually written in the following form:

$$\Delta T_F = A_F \cdot \left(\frac{F}{F_0}\right)^n \tag{15.1}$$

To define A_F and n parameters, different methods of analysis are used:

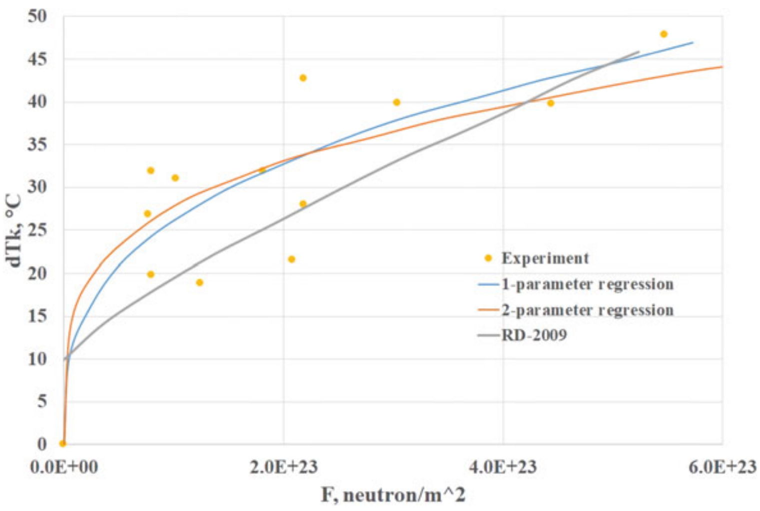

Fig. 15.1 Radiation embrittlement curves constructed by various methods of regression analysis

1. One-parameter regression method (regression parameter is only coefficient A_F, $n = 1/3$). This method is used in the regulatory document PNAE G-7-002-86 (1989).
2. Two-parameter regression method (regression parameters are both A_F and n coefficients). This method is used in the regulatory document Verlife-2008 (VERLIFE 2008).
3. RD-2009 technique. The method for evaluating material properties in the radiation and thermal embrittlement process, which is set out in the regulatory document (VVER-1000 2009), allows estimating the shift of critical brittleness temperature based both on the standard and side-grooved Charpy specimen test results and constructing a theoretical curve based on empirical coefficients using chemical composition data.

Figure 15.1 shows RE curves constructed by different methods for the weld metal of one of the representative RPVs. As can be seen, the choice of the method of processing experimental data and evaluating the metal RE affects the obtained results significantly. Currently, there is no universal technique for a large scatter of experimental data and their insufficient number, especially for high fluence values.

15.3 Methods of Construction of Fracture Toughness–Temperature Dependences and RPV Lifetime Assessment

To estimate the residual RPV lifetime, a comparison is made between the calculated SIF temperature curves, obtained from the results of calculations on the resistance to brittle fracture of the RPV element with a crack, and the fracture toughness–temperature dependences obtained from the results of the SS tests and constructed for a given fluence level.

The limited amount of SSs and experimental data, especially at high fluence values, does not make it possible to accurately predict the state of the metal for overdesign service life. Therefore, today there are several methods of constructing fracture toughness–temperature dependences.

Direct and indirect methods can be used to construct fracture toughness–temperature dependences. With direct methods, fracture toughness tests are carried out, and temperature dependences are determined by the single-temperature or multi-temperature method. In this case, the fracture toughness characteristics can be determined directly for the degraded material without data on its initial properties. Direct methods include the methods of Master Curve (MC) (Wallin 1999), Basic Curve (BC) (MRKR CHR 2004), and Unified Curve (UC) (VVER-1000 2009). Indirect methods use the Charpy impact bending test data and a correlation formula relating the critical brittleness temperature and the fracture toughness–temperature dependences. In this case, it is necessary to know the initial critical brittleness temperature T_{k0}, and SS tests are needed only to determine $\Delta T k_0$.

According to the MC method, the fracture toughness–temperature dependences are described by (15.2) for CT-specimen with a thickness of $B = 150$ mm and a probability of failure $P_f = 5\,\%$, where T_0 is the reference temperature, which is determined according to ASTM E 1921-13a (2015)

$$K_{JC}^{5\%}(T) = 23.32 + 23.385\,\exp\{[0.019\,(T - T_0)\}. \tag{15.2}$$

The BC method is a modification of the MC method and allows the use of test results for both fracture toughness and impact strength to predict $K_{JC}(T)$ curves (MRKR CHR 2004). The dependence of $K_{JC}(T)$ according to the BC method for the reference thickness of the specimen $B = 150$ mm with the probability of failure $P_f = 5\%$ is written as

$$K_{Jc}(0.05) = 23 + 48\,\exp\{0.019\,(T - T_k)\}. \tag{15.3}$$

The UC method was developed at the Prometheus Research and Development Center based on the probabilistic "Prometheus model" for predicting fracture toughness, using a new local brittle fracture criterion (VVER-1000 2009; Margolyn et al.

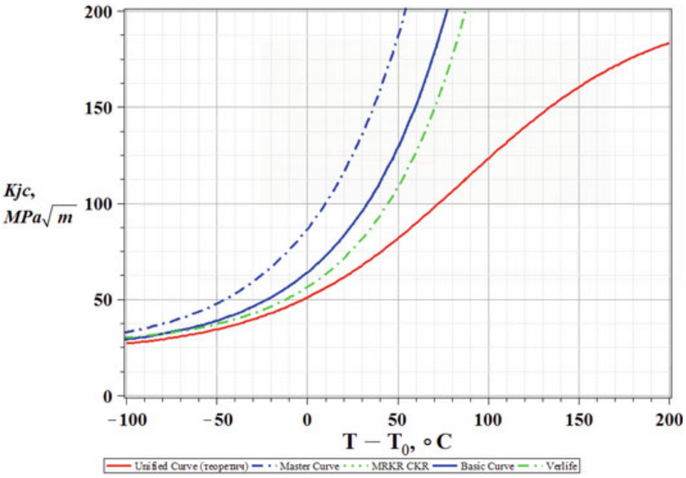

Fig. 15.2 Fracture toughness–temperature dependences for the weld metal of one of the representative RPVs

2010). According to the UC method, the fracture toughness temperature of specimens with a thickness of $B = 25$ mm at $P_f = 50\%$ of RPV steels at any degree of embrittlement can be described by the dependence

$$K_{JC}^{\text{calc}}(T) = k\left[K_{\text{JC}}^{\text{shelf}} - K_{\min}\Omega_{\text{calc}}\left(1 + \tanh\left(\frac{T - \delta T_{\text{type}} - 130}{105}\right)\right)\right] + K_{\min}. \tag{15.4}$$

The parameter Ω can be determined based on the results of tests on fracture toughness or impact strength (VVER-1000 2009).

Within the framework of the international project TAREG 2.01/00 (2008), an analysis of all described methods was carried out. Figure 15.2 shows fracture toughness–temperature dependences obtained by various methods for the weld metal of one of the representative RPVs. As can be seen, the differences between fracture toughness–temperature dependences are quite significant. It is primarily due to insufficient experimental data, especially at high fluence values corresponding to the design ones. Since there is currently no unified regulatory framework in Ukraine for assessing the RPV strength and lifetime, it is necessary to analyze the SS test results using different methods and justify their choice using the principle of conservatism of results.

Further, various methods of determining the SIF are considered, and the results obtained with these methods are compared.

15.4 Engineering Methods of the SIF Assessment

For any load conditions, the SIF for surface cracks can be calculated using engineering methods for determining the stress state of a solid without cracks (VERLIFE 2008). Two such methods are considered in this work.

According to the first method (MR 108.7-86 1980), the SIF is calculated according to the formula

$$K_I = \sigma_k Y a^{1/2}, \tag{15.5}$$

where Y is the shape factor, a is the crack length, and σ_k is the equivalent stresses.

The following equations are used for the surface crack (Fig. 15.3):

- at point A (deep point) $Y = Y_A$ and $\sigma_k = \sigma_{kA}$, where Y_A is defined as follows:

$$Y_A = \frac{2 - 0.82\,a/c}{\left\{1 - \left[0.89 - 0.57(a/c)^{1/2}\right]^3 (a/s)^{1.5}\right\}^{3.25}}; \tag{15.6}$$

- at point B (point on the surface) $Y = Y_B$, $\sigma_k = \sigma_{kB}$ and

$$Y_B = \left[1.1 + 0.35(a/s)^2\right](a/c)^{1/2} Y_A.$$

The equivalent stress σ_K required for calculating the SIF is determined by the components of σ_A, σ_B and σ_C, which are normal to the crack plane at points A, B, and C, respectively.

If the stresses do not change along the thickness of the RPV wall, then $\sigma_{kA} = \sigma_{kB} = \sigma_A = \sigma_B$. If the stresses change linearly across the wall thickness, then

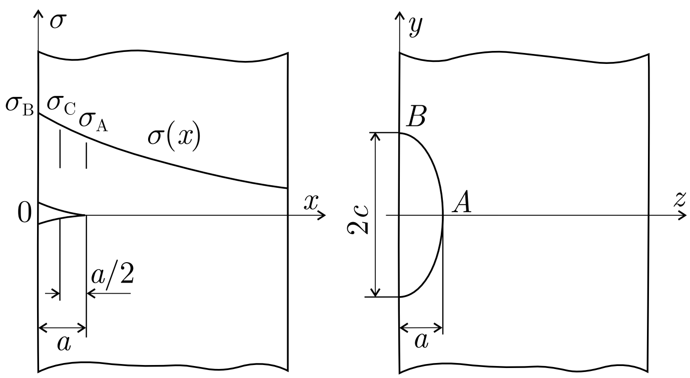

Fig. 15.3 Geometry of a surface crack (VERLIFE 2008)

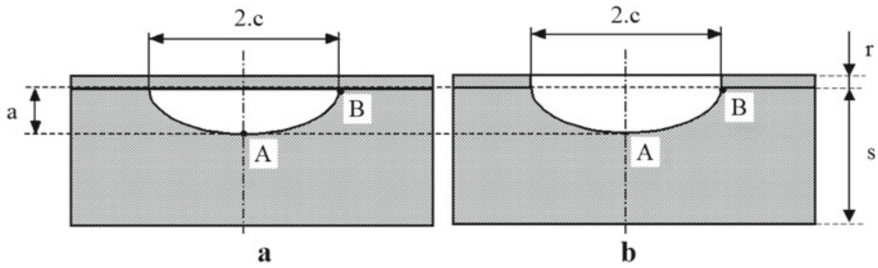

Fig. 15.4 Geometry of the surface (**b**) and undercladding (**a**) crack (VERLIFE 2008)

$$\sigma_{KA} = 0.61\sigma_A + 0.39\sigma_B + \Big\{0.11\, a/c - 0.28\, a/s\left[1 - (a/c)^{1/2}\right]\Big\}(\sigma_A - \sigma_B), \quad (15.7)$$

$$\sigma_{KB} = 0.18\,\sigma_A + 0.82\,\sigma_B. \quad (15.8)$$

If the stresses along the wall thickness change according to the parabolic law, then

$$\sigma_{KA} = 0.111\,(3\;\; \sigma_A + \sigma_B + 5\,\sigma_C) + 0.4a/c\big(0.38\sigma_A - 0.17\sigma_B - 0.21\,\sigma_C\big) - 0.28a/s\left[1 - (a/c)^{1/2}\right](\sigma_A - \sigma_B)\,, \quad (15.9)$$

$$\sigma_{KB} = 0.64\,\sigma_B + 0.36\,\sigma_C. \quad (15.10)$$

The second method (Marie and Chapuliot 2008; VERLIFE 2008) makes it possible to estimate the SIF taking into account the cladding (Fig. 15.4). According to this technique, the stress distribution along the thickness of the RPV wall is described by a polynomial of the third or fourth degree (Fig. 15.5):

$$\sigma = \sigma_0 + \sigma_1 \frac{x}{s+r} + \sigma_2\left(\frac{x}{s+r}\right)^2 + \sigma_3\left(\frac{x}{s+r}\right)^3 + \sigma_4\left(\frac{x}{s+r}\right)^4. \quad (15.11)$$

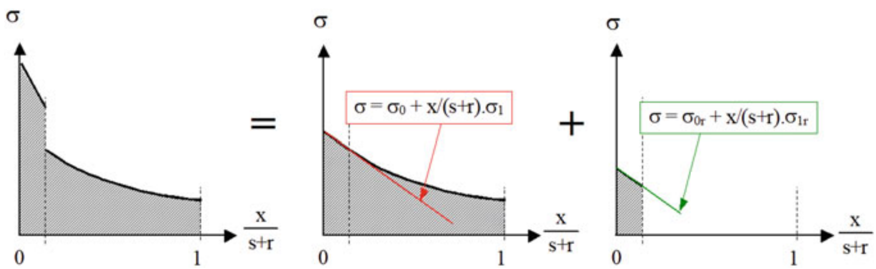

Fig. 15.5 Description of the stress distribution along the RPW wall thickness (VERLIFE 2008)

Then the stresses in the cladding are added. They are approximated by the following linear law:

$$\sigma = \sigma_{0r} + \sigma_{r1} \frac{x}{s + r}. \tag{15.12}$$

Then the stress coefficients $\sigma_0, \ldots, \sigma_4$, σ_{0r}, and σ_{1r} are calculated. After determining such coefficients, the SIF can be calculated using influence functions. The values of such functions are given in tabular form (VERLIFE 2008) for different values of crack sizes, cladding thickness, and the ratio of Young's moduli of the cladding and base metal. With the help of table values, the SIF values for the crack deep point can be calculated:

$$K_I = \left(\sigma_0 i_0 + \sigma_1 i_1 \frac{a + r}{s + r} + \sigma_2 i_2 \left(\frac{a + r}{s + r} \right)^2 + \sigma_3 i_3 \left(\frac{a + r}{s + r} \right)^3 + \sigma_4 i_4 \left(\frac{a + r}{s + r} \right)^4 + \sigma_{0r} i_{0r} + \sigma_{1r} i_{1r} \frac{a + r}{s + r} \right) \sqrt{\pi (a + r)}, \tag{15.13}$$

and for the point on the border of the base metal–cladding:

$$K_I = \left(\sigma_0 i_0 + \sigma_1 i_1 \frac{a + r}{s + r} + \sigma_2 i_2 \left(\frac{a + r}{s + r} \right)^2 + \sigma_3 i_3 \left(\frac{a + r}{s + r} \right)^3 + \sigma_4 i_4 \left(\frac{a + r}{s + r} \right)^4 \right) \sqrt{\pi a}, \tag{15.14}$$

where a is the crack depth in the base metal and r is the cladding thickness.

15.5 Calculation of SIF of a Pre-Existing Crack

Most of the modern regulatory documents (IAEA-TECDOC-1442 2005; VERLIFE 2008) recommend calculating the SIF using FEM and a postulated defect of a given size built into the model. This method requires using a mesh with sufficient density around the crack tip, which leads to an increase in calculation time. However, it makes it possible to obtain more accurate results and take into account elastic–plastic effects.

Regulatory documents recommend calculating semi-elliptical cracks with semi-axis ratios $a/c = 0.3$ and 0.7 in the axial and circumferential directions. An example of an FE mesh of RPV cylindrical part with built-in postulated semi-elliptical axial crack, with a ratio of semi-axes $a/c = 0.3$ and a depth $a = 17$ mm, is shown in Fig. 15.6a.

Numerical modeling of the RPV cylindrical part with cracks of different sizes and orientations was carried out using the above-described SIF calculation methods.

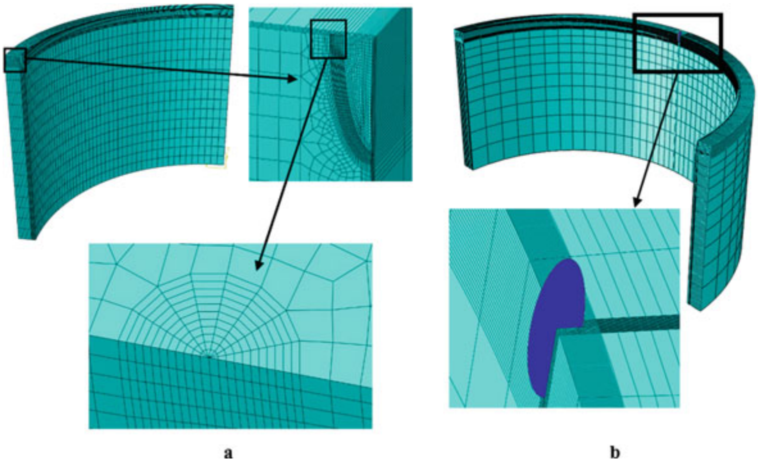

Fig. 15.6 Finite element model (**a**) and model using the XFEM approach (**b**) for the RPV cylindrical part with pre-existing crack

Calculations were performed for simplified 2D models and three-dimensional models with a pre-existing crack in an elastic formulation with the material's mechanical properties according to PNAE G-7-002-86 (1989) for one of the characteristic thermal shock emergency regimes. Figure 15.7a shows the SIF–temperature dependences for an axial semi-elliptical crack with a ratio of semi-axes $a/c = 0.3$. The curves are obtained using two engineering methods and a numerical method for a model with the crack in a two-dimensional formulation. It can be seen that the engineering methods give similar results, while the numerical calculation for the pre-existing crack model in 2D formulation gives overestimated results. Therefore, three-dimensional finite element models are usually used to determine brittle fracture resistance. It can be seen in Fig. 15.7b that using 3D models reduces the conservatism of the results. Furthermore, the crack orientation affects the results. Figure 15.7c shows that an axial crack, in this case, is more dangerous than a circumferential one with the same ratio $a/c = 0.3$.

15.6 Application of the Extended Finite Element Method

The XFEM approach, developed based on FEM by T. Belychko and T. Black (1999), is a numerical method for solving differential equations with discontinuous functions. The XFEM approach was created to overcome difficulties in solving problems with localized singularities. Solving these problems by the classical FEM is relatively inefficient compared with XFEM. The main idea of XFEM is to use a special approximation of the displacement field, which can model any irregular crack surfaces and the asymptotic stress field near the crack tip. At the same time, there is

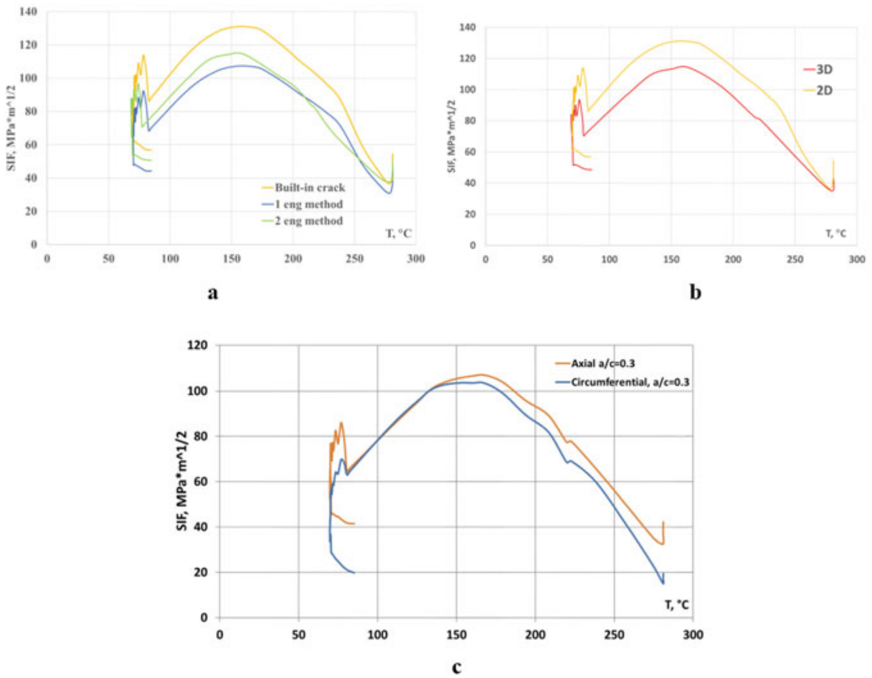

Fig. 15.7 SIF–temperature dependences: for an axial crack in a two-dimensional formulation, calculated according to the first and second engineering methods and built-in crack method (**a**); for built-in axial crack, using 2D and 3D models (**b**); for circumferential and axial cracks, calculated according to the first engineering method in 3D formulation (**c**)

no need to change the finite element mesh and embed the crack in the calculation model. It is desirable to have a sufficiently dense FE mesh around the crack tip to obtain more accurate results.

The need to study brittle fracture resistance for different sizes, orientations, and locations (undercladding, with penetration into the cladding) of cracks makes it necessary to build separate FE meshes when using classical FEM (Choi et al. 2019) or use approximate engineering and analytical methods (Li et al. 2020). Therefore, the XFEM approach is often used to study the brittle fracture resistance of first-circuit NPP's equipment components.

To verify the accuracy of XFEM, the RPV cylindrical part with an axial crack with the ratio of semi-axes $a/c = 0.3$ was analyzed. The FE model for using XFEM is shown in Fig. 15.6b. The obtained SIF–temperature dependences for the characteristic thermal shock regime agree well for both methods (Fig. 15.8).

Many studies have been developed to evaluate the brittle fracture resistance of cylindrical parts of the first-circuit NPP's equipment components. These methods are implemented in some international regulatory documents. At the same time, evaluating brittle fracture resistance for complex units of the first-circuit NPP's equipment

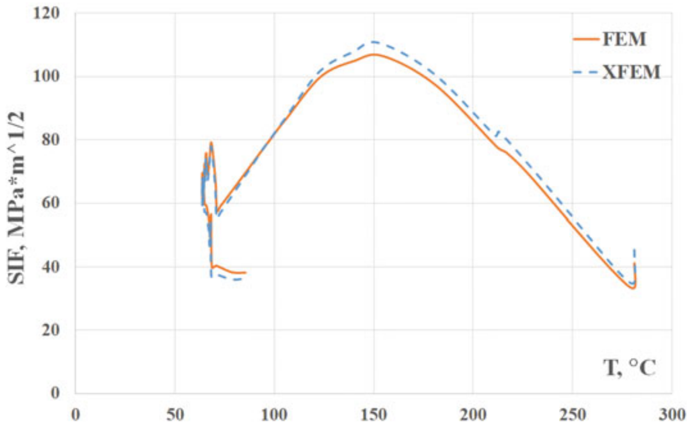

Fig. 15.8 SIF–temperature dependences for an axial crack with $a/c = 0.3$ in the RPV cylindrical part

components is a rather difficult task. First, it applies to the RPV nozzle zone, and there is currently no universal approach for estimating the brittle fracture resistance of such complex units. Developing FE models of the nozzle zone with pre-existing cracks, especially considering the cladding, is highly complicated. Hence, the use of XFEM helps solve such problems.

The "submodeling" technique can also be used to obtain more accurate results and save calculation time. This technique consists in "cutting out" the necessary part (constructive unit) from the global model with the addition to the cut planes of the boundary conditions (displacements) obtained during the calculation of the global model. In this case, the global model can have a sufficiently sparse mesh, significantly reducing the calculation time. At the same time, the cut part (submodel) can have a denser mesh and be supplemented with other geometric elements and conditions. The "submodeling" technique uses the Saint-Venant principle. If the valid boundary conditions at the cut plane are replaced by equivalent boundary conditions for a static formulation, then sufficiently accurate results can be obtained for complex geometric units with stress concentrators. Recently, the "submodeling" technique has been widely used in assessing the strength and durability of first-circuit NPP's equipment components (Kim 2005; Marenic et al. 2010), which significantly reduces the calculation time and increases the accuracy of the obtained results.

In this chapter, calculations of the RPV nozzle zone were carried out using the "submodeling" technique and XFEM. The calculations were performed for four cracks with a depth of 29.4 mm (0.1 of the RPV wall thickness) with the ratio of semi-axes $a/c = 0.3$ and 0.7 in the axial and circumferential directions. At the same time, the axial cracks are located in the inlet nozzles in such a way that the plane of the crack is formed by the axis of the nozzle and the RPV axis, and the main axis of the semi-ellipse forms an angle of 45° with the horizontal axis (the axis of the nozzle). The circumferential cracks are turned 90° relative to the axial ones (Fig. 15.9).

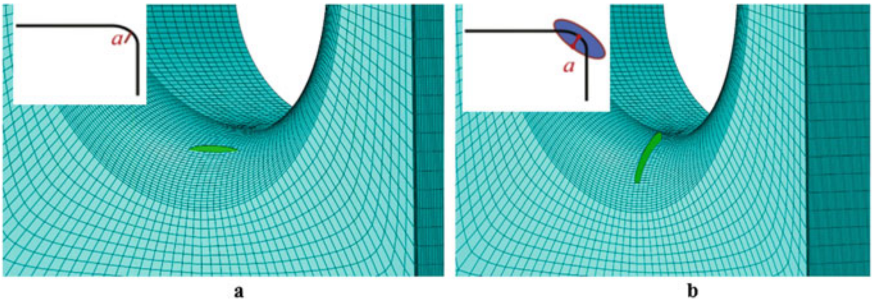

Fig. 15.9 The location of the circumferential (**a**) and axial (**b**) cracks in the RPV nozzle zone

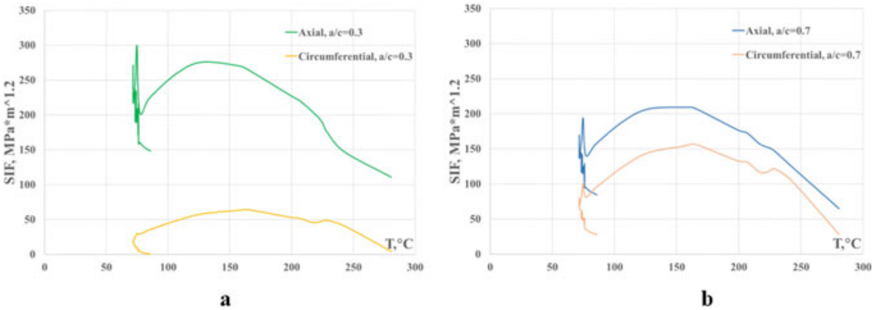

Fig. 15.10 SIF–temperature dependences in the RPV nozzle zone for the characteristic regime of thermal shock for an axial and circumferential crack with $a/c = 0.3$ (**a**) and $a/c = 0.7$ (**b**)

Figure 15.10 compares the SIF–temperature dependences for all cracks. The dimensions being equal, axial cracks are more dangerous than circumferential ones. At the same time, cracks with a ratio of semi-axes $a/c = 0.3$ (Fig. 15.10a) are more sensitive to the location direction than cracks with $a/c = 0.7$ (Fig. 15.10b).

Thus, applying the extended finite element method makes it possible to carry out an express analysis of the influence of the size, shape, and location direction of cracks in the RPV nozzle zone and determine the most dangerous cracks in terms of brittle fracture resistance.

Based on XFEM, an express technique of resistance to brittle fracture assessment with the possibility of varying the shape, size, and location of the crack has been developed. The effectiveness of this technique was illustrated by numerical modeling of the RPV cylindrical and nozzle part for one of the dangerous regimes of thermal shock.

15.7 Conclusions

- Based on a detailed analysis of known methods of radiation embrittlement assessment and prediction of fracture toughness–temperature dependences, as well as their comparison, were carried out using the surveillance specimen's test results of the weld metal of a representative RPV with a high Ni content.
- According to various regression analysis methods, the RE trend curves for the weld metal of one of the representative RPVs were constructed. In addition, it was shown that the methods for experimental data procession and RPV metal radiation embrittlement evaluation significantly affect the results.
- A significant difference was shown in fracture toughness temperature dependences obtained using different methods for the weld metal of one of the characteristic RPVs, primarily due to insufficient experimental data, especially at high fluence values that correspond to the design values.
- With the use of various methods, the evaluation of brittle fracture resistance for the RPV cylindrical part under the characteristic regime of thermal shock was fulfilled.
- Based on the extended finite element method, an express technique of resistance to brittle fracture assessment with the possibility of varying the shape, size, and location of the crack has been developed, which will allow us to effectively determine the crack's critical size and the most dangerous place in the structural element. The effectiveness of using this technique was illustrated by the example of numerical modeling of the RPV cylindrical and nozzle part for one of the dangerous regimes of thermal shock.

The research results presented in this chapter were used within the framework of the international project TAREG 2.01/00, during the performance of the state examination of works on justification of the strength and fracture resistance of the RPV VVER-1000 reactors at the power units of the Zaporizhzhya, Rivne, and South-Ukrainian NPPs, as well as in works on the lifetime extension and safe operation of power units No. 1,2,3 of the VP "RAES".

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