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Some problems VVER Pressure Vessel brittle fracture in the regimes of maximum design emergency

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ABSTRACT

On the base of the analysis of real properties of pressure vessel metal in as-produced condition after irradiation, its defectivity, temperature fields, stress-strain state and stress intensity factors in most dangerous regimes (rupture of Du25, Du50, Du80) it is shown that at the water temperature in the system SECZ vessels not less than +20°C the brittle fracture resistance of pressure vessels is provided and an additional water preheating is not required.

1. INTRODUCTION

At present brittle fracture resistance estimation of reactor pressure vessels (RPV) in the emergency situation is carried out on the fracture initiation criterion by static loading with the use of the relation $[K_I]_3 = f(T - T_k)$ and safety margins $n_k = 1$ and $\Delta T = 0$ [1]. By this, the assessment of safety operation conditions is determined proceeding from the touching of the temperature dependences K_{Ic} and K_I, constructed for various moments of time, which are most characteristic of the process of emergency cooling of RPV. In the Russian Code PNAE G-7-002-86 [2] fracture toughness temperature dependence is constructed with 95% probability on the basis of test results of a sufficient number of specimens. Real $K_{Ic} = f(T - T_k)$ values for the pressure vessel considered are, as a rule, higher and this factor should be taken into account by an individual approach to the estimation of radiation service life, proceeding from a more correct information about chemical composition of materials of the given RPV. By this, for certain elements (base metal or weld) it is necessary first of all to know DBTT and fracture toughness temperature dependence as well as the content of such elements as phosphorus, copper and nickel, which effect the coefficient of radiation embrittlement. To ensure the absence of brittle fracture in emergency situation for a definite RPV it is necessary to carry out the analysis which could take into consideration different models of emergency occurring and in particular, cold water feed on RPV heated up to 290 °C, as well as the possibility of its preheating and mixing, defect sizes.

In this study the calculation is carried out for RPV of Kalinin NPP. For a possible set of emergency regimes the envelope was constructed, which characterizes SIF dependence on temperature $K_I = f(T)$ for circular cracks (depth - 0.05 - 0.25 S, S - RPV wall thikness), the presence of which may be observed in most damaged zones - support shell and circumferential welds. These zones are most greatly loaded and are subjected to maximum embrittlement for a whole period of operation.

In this connection the existing Manual for V-320 and V-338 Kalinin NPP foresees (for temperature attack reduction) the preheating of boric solution of water to 55 °C by water feeding in RPV from the SECZ and tanks of emergency supply of boric solution. The solution of the problem of water preheating temperature reduction from 55 to 20 °C and below can be obtained only on the base of the detailed analysis of the conditions of emergency regime occurring at real NPPs as well as on the base of conservative assessment of RPV ultimate states with regard for real properties of metal of the given power unit.

At Kalinin NPP in order to increase minimum temperatures of water the following measures were carried out:

- temperature in tanks with boric solution (3 tanks, 750 m^3) was increased to 50 °C;
- temperature in the tank (2-nd unit - 3 tanks) of the emergency supply of concentrated boric solution was higher or equal to 50 °C;
- the design of the first errection project and schemes of technological protection foresee the governors of cooling rate in the primary circuit, which also operate in emergency regimes.

In this study two problems have been solved:

- groundation of initial data for calculation $K_I = f(T)$ and $K_{Ic} = f(T)$;
- carrying out of calculation and analysis of allowable conditions of operation (water preheating in SECZ) for units 1 and 2 of Kalinin NPP.

2. INITIAL DATA OF MATERIALS FOR CALCULATION

As the initial data of materials for calculations one takes their chemical composition, mechanical properties (including DBTT and fracture toughness) and irradiation embrittlemet coefficient. The values of these characteristics for units 1 and 2 of Kalinin NPP are partially given in Table 1 for the base metal of support, upper and lower shells as well as for metal of joining circumferential welds.

Table 1. The chemical composition and mechanical properties of RPV materials.

		Content of elements, %										At 20 C				At 350 C				
Unit		C	Si	Mn	Cr	Ni	Mo	V	S	P	Cu	UTS MPa	YS MPa	A %	Z %	UTS MPa	YS MPa	A %	Z %	T
	sup	0.16	0.24	0.48	1.83	1.16	0.55	0.08	0.009	0.007	0.05	706	599	23.3	76.5	580	500	17.2	72.7	-20
1	weld3	0.04	0.28	0.98	1.71	1.76	0.66	-	0.006	0.010	0.04	620	524	20.5	71.5	546	474	16.4	63.0	-10
	top	0.15	0.21	0.40	1.81	1.23	0.52	0.08	0.011	0.005	0.06	634	544	18.4	78.5	563	487	17.4	75.3	-20
	weld4	0.06	0.29	0.96	1.75	1.78	0.67	-	0.012	0.006	0.04	661	564	22.4	69.0	533	462	15.0	67.0	< 0
	bot	0.13	0.27	0.46	1.97	1.12	0.51	0.09	0.012	0.006	0.04	660	565	25.2	77.3	611	540	17.2	72.8	-25
	sup	0.17	0.26	0.39	2.02	1.18	0.52	0.08	0.012	0.009	0.05	736	628	21.6	73.2	613	539	16.5	71.2	-45
2	weld3	0.06	0.36	0.76	1.72	1.64	0.63	-	0.008	0.008	0.03	651	555	23.8	72.0	546	480	15.5	69.0	-40
	top	0.16	0.24	0.47	1.84	1.13	0.52	0.10	0.010	0.007	0.05	705	590	19.6	75.0	584	518	16.3	73.2	-15
	weld4	0.06	0.36	0.79	1.75	1.59	0.62	-	0.007	0.008	0.02	674	557	21.7	68.5	548	548	14.8	65.0	-40
	bot	0.17	0.32	0.43	2.06	1.09	0.55	0.10	0.010	0.007	0.04	732	622	22.3	75.3	612	532	17.0	73.8	-35

Note: sup - support shell;
top - top shell of core zone;
bot - bottom shell of core zone.

The allowable SIF values, specified by Russian Code, depend on reduced temperature and event calculated. For emergency situations it is assumed [2]

$[K_I]_3 = 74 + 11 \exp[3.85 \cdot 10^{-2} (T - T_k)]$ - for base metal

$[K_I]_3 = 35 + 53 \exp[2.17 \cdot 10^{-2}(T - T_k)]$ - for weld metal

where T_k - DBTT of RPV after operating time, T - the RPV wall temperature in the point, determined as the tip of hypothetical crack.

However, nowadays the available in Russian Code relations are insufficient for the following reasons:

- the stated above relations do not permit to assess the permissible $[K_I]_3$ vaues not only by high but also by mean degrees of embrittlement of base metal (at $\Delta T > 80^\circ C$);
- the real low shelf of K_{Ic} curves for 15X2HMFA steel and its weldments is significantly lower, than in Russian Code and it may result in dangerous errors;
- in current Russian Code (in conrast to Code ASME, used in some countries) one does not foresee the situation of crack retarding, which takes place by thermoshock testing of large-scaled specimens and models.

The Russian Code have shortcomings in the assessment of PTS effect on K_{Ic} value, which is of a decisive importance for analysis results of RPV brittle fracture, as in this case failure is realized by K_f value exceeding K_{Ic} value by two times and more.

Therefore, for calculations fracture toughness curves were also used for 15X2HMFA steel and its welded joints, which were constructed with 95% probability. By their plotting the reduction of the lower shelf due to irradiation was taken into account.

The radiation embrittlement coefficient for calculation performance was taken from Russian Code $A_F = 23$ for base metal and $A_F = 20$ for weld metal. Besides, with consideration of lower level of harmful impurities both in base metal and weld metal (see Table 1) the radiation embrittlement coefficients were taken equal to $A_F = 18$ and $A_F = 12$, respectively.

By non-destructive testing (units 1 and 2 of Kalinin NPP) crack-like defects were not detected. However, in calculations the presence of defects was considered. Real defects, the allowance of which is not excluded by using even alternative NDT techniques are schematized according to the recomendation [6], one assumes as a most dangerous defect - a surface crack with the correlation of semi-axes a/c = 2/3 according to Russian Code and a/c = 1/3 according to ASME Code, as it is more conservative. Two crack shapes with depths from 0.05 to 0.25S have been considered according to the requirement of Russian Code. By inspecting RPV with the probability 95% the sizes of real defects [4] do not exceed 10 mm (i.e. 0.05S). This value is confirmed by the inlet inspection results. It should be noted that cracks of the size (0.05-0.1)S appear on the critical way by the analysis of SIF and RPV strength, as they are in the area of the action of maximum tensile stresses and minimum temperatures. The real sizes of defects to 0.1S were taken into account when plotting permissible curves $[K_{cr}] = f(T)$.

The distribution of fluence neutron at E > 0.5Mev on height of cylindrical shell was accepted as conservative estimation:

$5.7 \cdot 10^{23}$ neutr/m^2 - for base metal of core area,

$4.5 \cdot 10^{23}$ neutr/m^2 - for circumferential weld Nr. 4,

$5.7 \cdot 10^{23}$ neutr/m^2 - for circumferential weld Nr. 3.

In calculations the real values of fluence neutron were taken:

$4.4 \cdot 10^{23}$ neutr/m^2 - for central area of core zone,

$1.4 \cdot 10^{23}$ neutr/m^2 - for upper section of core zone,

$3.2 \cdot 10^{23}$ neutr/m^2 - for circumferential weld Nr.4,

$4.4 \cdot 10^{23}$ neutr/m^2 - for circumferential weld Nr.3.

3. LOADING CONDITIONS OF RPV IN EMERGENCY REGIMES

One assumes the loading conditions of V-320 and V-338 type reactors to be idential. By loss of sealing of the primary or secondary circuits cold boric solution is supplied in RPV from SECZ and tanks with boric solution. The solution temperature in tank and SECZ can be from 55 to 5°C according to the Manual. The operation conditions of RPV in regimes of sealing loss of the primary and secondary circuits may be divided into two groups:

- regimes with a large loss of coolant and fast drop of pressure in the primary circuit before the beginning of SECZ reservoir' operation, and by this RPV is practically instantly filled with cold water;
- regimes with water level drop in pressure compensator due to loss of coolant or its cooling (In this group it is inevitable that "cold tongues" will appear by SECZ operation).

The analysis of temperature and stress fields in RPV by filling from SECZ is given in calculations [5], carried out by the designer. The temperature distribution is obtained by the method of elementary thermal balances. By RPV loading in non-axis symmetric temperature field the stress state was determined by superposition of solutions of:

- axis-symmetric problem, considering radial and meridional gradients of temperatures, internal pressure;
- plane problem, considering circular gradient of temperatures; plane problem for a ring for cylindrical part of RPV limitted by two cross-sections and loaded by thermal field with maximum circular gradient of temperatures.

The calculations have been performed for the following regimes:

1) leak of the primary circuit Du50, water temperature T=20°C;
2) leak of the primary circuit Du80 (one high pressure pump is operating, water temperature T=20°C), "cold tongue" from SECZ reservoir;
3) leak of the primary circuit Du80 (one high pressure pump is operating, water temperature T=20°C), "cold tongue" from tanks of boric water store;
4) leak of the primary circuit Du80 (one high pressure pump is operating, water temperature T=55°C);
5) leak od the primary circuit Du80 (two high pressure pumps are operating, water temperature T=20°C);
6) large leak of the primary circuit, water temperature T = 20 ° C.

For support shell regime 7 has been considered - leak of the primary circuit Du25.

The analysis has shown that regime 3 is worst of all, of which it is typical the occurrence of very cold "tongues" and maximum meridional stresses σ_z= 699.4 MPa in base metal and σ_z=759.4 MPa in weld metal Nr 3 and 4. Here, σ_z is equal to the sum of bend and membrane stresses.

Thus, the necessity of measures made at Kalinin NPP has been confirmed. They exclude "cold tongues" of liquid from tanks of boric water store with the temperature 20 ° C tanks to its preheating in tanks to 50 ° C. Therefore in our subsequent analysis of strength and determination of safe operation time this regime was not considered. The rest regimes with their loading levels arrange in sequence succession 2 - 5 - 6 - 1 - 4 - 3.

By this, weld Nr 4 zone became loaded by 1.1 times higher meridional stresses than base metal on the boundary with cladding in a most dangerous section 1 - 2. With regard for boric solution mixing with coolant the regimes in the area of top and bottom shells appeared more sparing in comparison with the calculation.

4. STRENGTH ANALYSIS AND ALLOWABLE OPERATION TIME

The calculation of SIF distribution through thickness as applied to operating loads for a surface crack has been carried out in this study for RPV and nozzle shell as applied to regimes 1 - 6 and 7. The RPV calculation has been performed for a semi-elliptical surface crack ($a/c = 2/3$ and $a/c = 1/3$) by the methods, stated in Refs [6 , 7]. For nozzle zone the calculation of SIF distribution in angle part of joint was performed for surface angle crack.

For support zone the calculation has been carried out with two methods according to the procedure [6] and by using influence function [7] with the calculated nominal stresses.

Brittle fracture resistance assessment was performed by three ways:

1. Determination of margin of brittle fracture on the temperature $[\Delta T]$ by means of comparing ultimate (for the given operation time) $[K_I]_3 = f(T)$ or $[K_{cr}] = f(T)$ curves with the envelope of series of $K_I = f(T)$ for various correlation of defect semi-axes and depth ($0.05 < a/S < 0.1$, $1/3 < a/c < 2/3$). The envelope is plotted on minimum values of temperature for maximum calculated time τ of process proceeding (filling of pressure vessel with water).

2. Determination of margin of brittle fracture on the level K_I as extremum of the relations

$$n_k = \min [K_I]_3/K_I = \min f(a, \sigma_z)$$

$$n_k = \min [K_{cr}]/K_I = \min f(a, \sigma_z)$$

3. Determination of allowable pressure value $[p] = f(K_I, a)$ (for the given regime) from the condition

$$[p] = 0.145/\sqrt{a}\,(\beta\,[K_{cr}] - K_I); \quad \sigma_z = p\,R_{in}/(R_{out} - R_{in}),$$

where σ_z - is the value of meridional stresses from inner pressure;

p - is the proposed design pressure.

Brittle fracture of RPV is provided when one of the following conditions is realized: $n_k > 1$, $\Delta T_k > 0^\circ$ C, $[p] > p$.

The generalization of brittle fracture analysis results for RPV has been performed in the coordinates K_I - T in Fig.1 for core area, in Fig.2 for support shell and Fig.3 for metal of circumferential welds 3 and 4. The curves 4,5 in Fig.1 and curve 3 in Fig.3 are plotted according to the calculation on conservative distributions of temperatures and stresses. The subsequent corrected calculations show, that real values of stresses and SIF are considerably lower, than in the first calculations and correspond to the envelope (curve 6) of the series of curves $K_I = f(T)$ in Fig.1 and the envelope (curve 4) in Fig.3. The comparison of shelf ΔT_k in Table 2 and in Fig.3 shows, that for the assumed model of embrittlement the absence of water preheating in SECZ tanks does not limit the RPV service life (30 years) both for core area and metal of welds Nr.3 and 4 of the units 1 and 2 of Kalinin NPP even if the effects of shallow craks and PTS are not taken into consideration. The use of the effects stated above permits not to restrict RPV operation time (40 years). However for weld metal the ultimate operation time is 30 years. It might be noted, that the elastic-linear approach accepted for RPV brittle fracture assessment is conservative, as it forbids any, even stable crack initiation. With the use of this approach any defect initiation in a dangerous zone, proceeding from the pre-condition $K_I = K_{Ic}$, must cause guillotine rupture of RPV due to instable propagation of brittle crack.

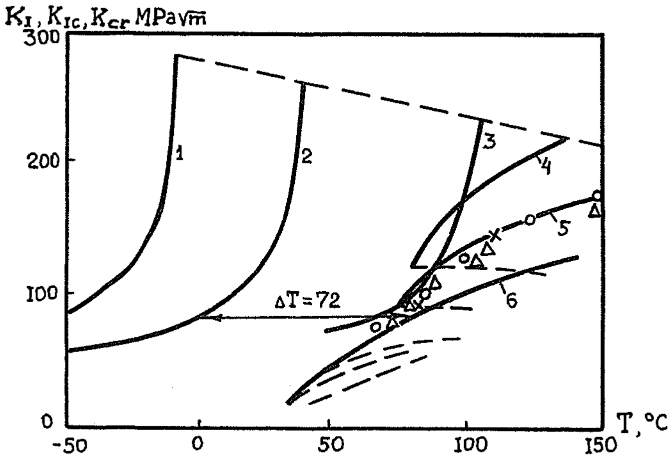

Fig. 1. Analysis of RPV failure for top shell: 1, 2, 3 - ultimate curves for base metal; 4, 5 - SIF level by thermoshock for cracks a/c=1/3 and a/c=2/3; 6 - the same but this consideration of mixing.

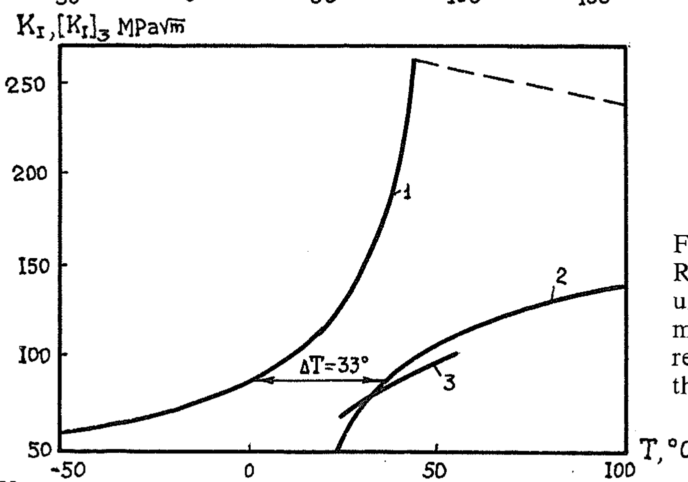

Fig. 2. Failure analysis of RPV support shell: 1 - ultimate curve for base metal; 2 - SIF level in the regime leak (Du 25); 3 - the same (Du 850).

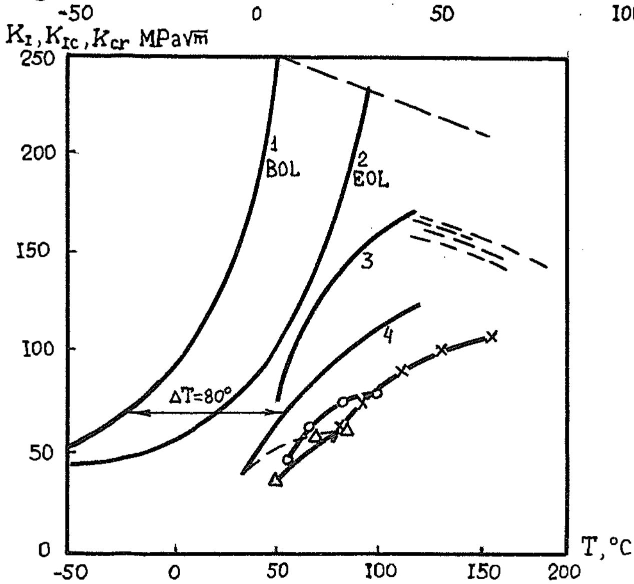

Fig. 3. Analysis of RPV for circumferential weld: 1, 2 - ultimate curves for weld metal; 3 - SIF level by thermoshock; 4 - the same in regime to this consideration of mixing.

Table 2. Calculated parameters of embrittled RPV materials for Kalinin NPP.

Location	Fluence, n/m² 30 years	Fluence, n/m² 40 years	T_{ko} °C	P %	Cu %	A_F	Shift ΔT, °C 30 years	Shift ΔT, °C 40 years	T_k, °C 30 years	T_k, °C 40years
Top shell 15X2HMFAA steel	$5.7 \cdot 10^{23}$	$7.6 \cdot 10^{23}$	-25	0.007	0.06	18	68	76	43	53
Weld 3	$5.7 \cdot 10^{23}$	$7.6 \cdot 10^{23}$	-10	0.010	0.04	12	46	51	36	41
Weld 4	$4.5 \cdot 10^{23}$	$6.0 \cdot 10^{23}$	0	0.006	0.04	12	43	47	43	47
Welds 3&4 calculation	$5.7 \cdot 10^{23}$	$7.6 \cdot 10^{23}$	0	-	-	12	46	51	46	51

The corrected analysis of fracture toughness RPV by emergency situation should be based not only on the consideration of crack initiation conditions, but also on its retarding after jump up. For example, by achieving [at the time moment τ=0.4 hrs (regime 3) at the tip of 18 mm crack (0.1S)] the critical conditions for RPV to the end of operation time (40 years), namely $K_I = K_{Ic}$ = 115 MPa$\sqrt{m}$, $T_{op} = T_k$ =158 °C. The initiation of this crack (Fig. 4) will lead not to RPV rupture, but only to crack

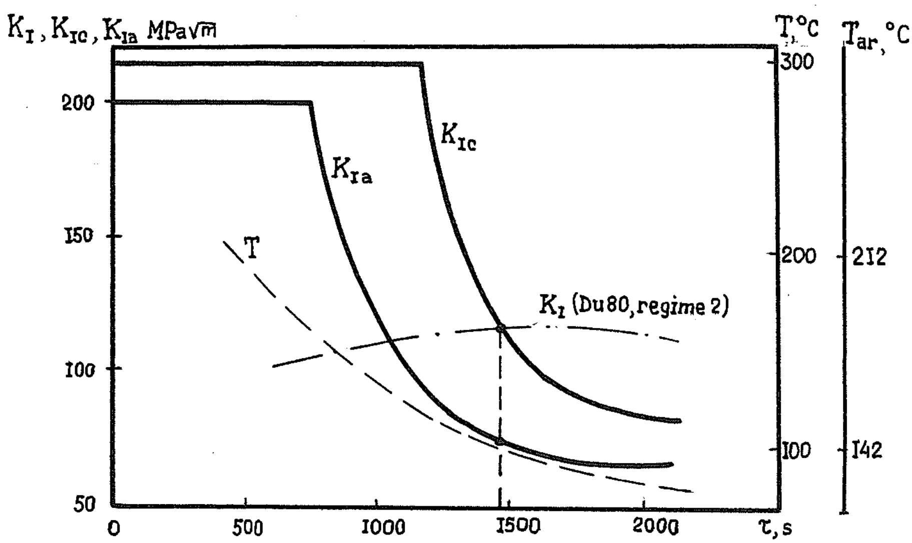

Fig. 4 Analysis of 18 mm deep crack pop-in RPV wall (top shell) depending on cooling time in regime 2: K_{IC}, K_{Ia} - ultimate parameters for base metal (40 years); $T(\tau)$ - temperature at the crack tip a=18 mm.

propagation in depth (jump up) with a subsequent retarding in a warmer layer of metal at $T=T_{ar}=180^oC$ at a depth of 24 mm (0.12S). By the further cooling of RPV and temperature reduction in this area K_{Ic} value will decrease and the second start of crack will occur, the crack tip will be at a depth of 24 mm from inner wall of pressure vessel. It should be noted that the estimation of pop-in value was based on K_{Ia} determination by crack jump up. The further crak growth and the appearance of jump ups are limitted by the curve of autopressing by preliminary thermomechanical loading $K_I = (K_I)_{max}$.

On the dropping branch of the curve K_I (T), i.e. after passing the point $K_I = (K_I)_{max}$ brittle fracture initiation is impossible. This conclusion refers in particular to the analysis of data on fracture of welds Nr 4 of V-320 RPV, shown in Fig.3. For some of these six more dangerous regimes the intersection of curves $K_{cr} = f(T)$ and K_I (T) took place on the dropping branch of SIF.

5. CONCLUSION

The performed calculated and experimental groundation permitted on the base of brittle fracture analysis to establish the safe operation time for units 1 and 2 of Kalinin NPP without water preheating of SECZ pressure tanks. The analysis included conservative and normative assessment and found it possible not to carry out water preheating in SECZ for 20 years operation and for 30 years - by the absence of data contradicting pre-conditions introduced in calculations.

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