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APPROACH TO THE JUSTIFICATION OF THE SAFETY CONCEPT «LEAK BEFORE BREAK» FOR THE FLANGE CONNECTIONS OF REACTOR UNIT VVER

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ABSTRACT

Practicability of "Leak before break"(LBB) concept appliance for construction elements of existing and projected blocks of nuclear power plants was justified many years ago [10]. Technical means and organizational measures should be created to provide timely detection of a stable through crack inside the pipelines of the reactor coolant circuit and the shift of the reactor unit into safety state before the crack acquire critical sizes. In the document [10] it is only considered to apply the LBB concept to the pipelines of the reactor coolant circuit.

Stress-strain state calculations in conditions of exploitation for the elements of pressure vessel flange connectors and the reactor head, pullout part and the shell of reactor coolant pump set, header and the vessel of the steam generator have shown that a gap can appear between two thickening surfaces due to the stud destruction and the leak can occur. [2,8].

Probability calculations of flange connection destruction have shown that due to stress redistribution in fastening elements (for the destruction of one or several studs) the most probable event is the formation of the consecutive row of destroyed studs (domino effect). [6]. That kind of a row can be analyzed as the through crack formation in a ring welded joint. Under certain conditions, the process of increasing the number of damaged studs can take «avalanche» type and that can lead to guillotine rupture of flange connection. Appliance of the LBB safety concept to flange connections can help to account and prevent the possibility of coolant circuit connections rupture.

METHOD DESCRIPTION

The same algorithm conducts calculated justification of LBB concept for flange connection, basically, as for the pipelines. [4]. The only difference is that the critical number of destroyed studs is being defined, which means the destruction of the neighboring studs and all following studs is occurring by "avalanche-type". Two approaches exist for definition of the critical number of the destroyed studs – probabilistic and deterministic. At probabilistic approach the number of destroyed studs is considered to be critical if the probability of rupture of the closest undestroyed stud exceeds $\tau \cdot 10^{-7}$ reactor/year, where τ - period of exploitation between technical survey. It was assumed that in the case of technical surveys, the broken studs are guaranteed to be detected and replaced by undamaged ones. At deterministic approach the number of destroyed studs is considered to be critical if the stress in the closest undestroyed studs exceeds minimal (guaranteed) yield stress.

In both cases, critical size of destroyed studs row is calculated at maximum rated load (MRL) multiplied by stress safety factor. Therefore, critical size is being divided by appropriate safety factor for the crack length and for acquired row of destroyed studs gap area between connectors is calculated with normal operating (NO) conditions. Pressure of the coolant at normal operation and the gap area are used to estimate the coolant consumption per unit of time, which is multiplied by safety factor for sensitivity of leak detection system (LDS). If calculated coolant consumption, taking into account all safety factors, exceeds the sensitivity of LDS, it is considered, that LBB condition for regarded flange connection is fulfilled. For calculations the values of safety factors for MRL, critical sizes and sensitivity of LDS can be taken from guideline documents for LBB safety concept for the pipelines.

Calculation analysis of LBB condition for flange connections of the primary coolant circuit for VVER reactor unit consists of three stages. On the first stage the stress strain state for all elements of the connection in different operating conditions accounting possibility of stud rupture is calculated. Database for amounts of stresses in studs is formed for further stud destruction probability calculations. General provisions of stress strain state modeling methods for three-dimensional construction elements with finite element method using program UZOR 1.0, are given in Ref. [7]. One of the main features of applied algorithm is the realization of superelement algorithm, which is considered to be “superstructure” for traditional finite element method and gives significant advantages in parallel computing organization and stress strain state calculations of partially destroyed objects.

Acquired data about stress strain state of flange connections allows estimating the fact of gap appearance due to destruction of one or several studs and calculating the gap area. To estimate the size of the gap and the area of its expansion the graph is made for the vertical displacements of higher and lower end of the gasket along the cylindrical forming. The calculation results of stud stresses are used for critical size of the row of destroyed studs estimation for both deterministic and probabilistic assessments.

On the second stage the stud destruction probability assessment is performed using program MAVR 5.1, which is intended to perform calculations of leak appearance probability and ruptures of thick-wall pipelines and pressure vessels due to crack growth during exploitation. [1,11].

The initial data for these calculations are:

- stress and temperature fields in the wall of the object under specified operating conditions,
- flaw detection characteristics,
- parameters of material defectiveness (amount and size of defects),
- physico-mechanical and strength properties of the material,
- impurity content in the material,
- loading history for the considered period of work (sequence, frequency and duration of design modes).

Data on flaw detection control are set taking into account the probability of missing defects. The remaining parameters and characteristics indicated above, besides the characteristics of the loading history, are set taking into account the statistical variation of the experimental and operational data. Fatigue crack growth is described by the Paris equation.

The distribution of critical crack sizes is determined based on the criteria for brittle, brittle-viscous and viscous types of fracture, in accordance with the requirements of relevant guidance documents.

The stud destruction probability during the operation period is calculated by the formula:

$$P_d = 1-(1-p_1)(1-p_2)(1-p_3)\left(1-p_4\right), \tag{1}$$

where p_1, p_2 and p_3 — fracture probabilities by brittle, brittle-viscous and viscous mechanisms, p_4 - probability of loss of the bearing capacity of the stud due to the excess of the plasticity limit, which is determined by the probability distribution

At the third stage, the calculation of the coolant consumption is carried out in accordance with the recommendations [3] according to the formula:

$$Q = \varepsilon\sqrt{\frac{2(P_{in}-P_{out})}{\rho_{in}}}\int_0^c \frac{4V(x/c)dx}{\sqrt{1+S_m+S_f}}, \tag{2}$$

where:

$$S_f = \frac{R_a t}{V^2(x/c)}; \tag{3}$$

ε — jet compression ratio, P_{in} — pressure in the vessel, P_{out} — output pressure, ρ_{in} — the density of the fluid in the vessel, $2V(x)$ – gap opening with length 2c, $0 \le x \le 2c$, S_m — coefficient of local resistance to fluid entry, S_f — friction drag coefficient due to fluid viscosity, R_a — roughness of flange sealing surfaces, t — pressure vessel or pipe wall thickness.

Disclosure dependency $V(x)$ is determined by specifying the shape of the gap. If the form is elliptical:

$$V(x) = \frac{xA(2c - x)}{\pi c^3}, \qquad (4)$$

where A – gap area.

When assessing the consumption of the coolant through the gap between the flanges, in contrast to the case with a crack, it is necessary to take into account the flow deceleration during the flow around the rods of damaged studs, which partially cover the gap. In the first approximation, accounting the illustrative nature of the calculations, the "effective" gap opening area was used.: $A_{ef} = A(1 - d_s/\Delta_s)$, where d_s - stud diameter, Δ_s - distance between adjacent studs.

AN EXAMPLE OF THE ANALYSIS OF THE LBB CONCEPT

This approach to the justification of the LBB safety concept for flange connections is illustrated by the example of flange connection of the lid and the reactor vessel - the main joint of VVER-TOI. The sketch of the main joint is shown in Figure 1.

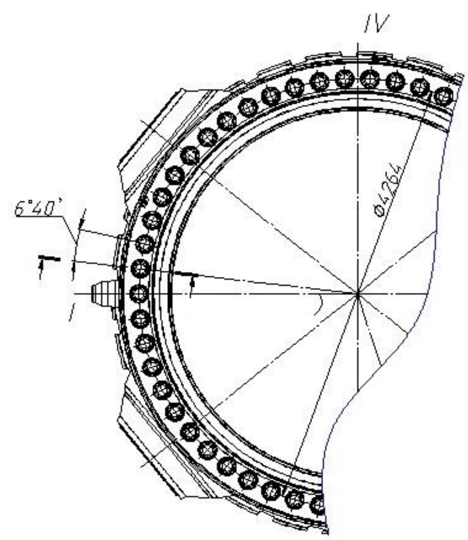

Figure 1. The sketch of the main joint.

The lid of the reactor is a stamp-welded construction consisting of a steel sheet of truncated ellipsoid shape and a flange, which are interconnected by a weld. The reactor vessel is a vertical cylindrical vessel with an elliptical bottom. The ellipsoid of the lid, the flange of the lid, the reactor vessel, and the flange joint are made of steel 15H2NMFA. The inner surface of the lid and reactor vessel is clad with anticorrosive overlay. A sketch of the lid and a fragment of the sealing zone of the lid flange are shown in Figures 1 and 2.

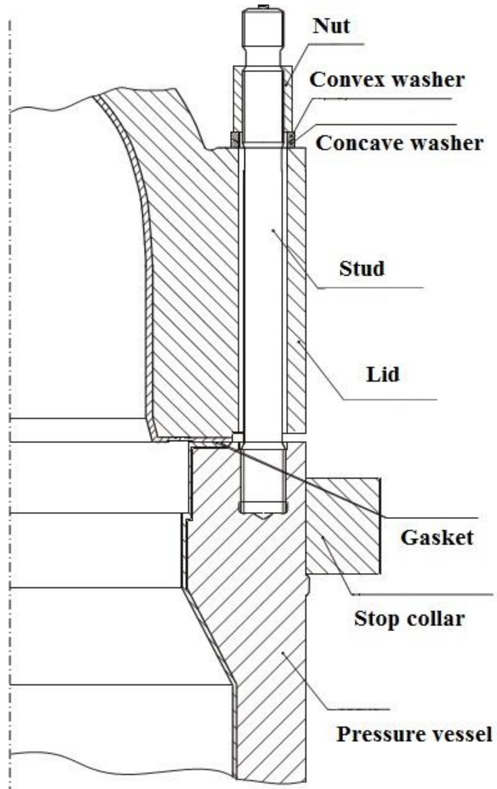

Figure 2. The sketch of the flange connection.

To accommodate the main connector studs in the lid flange, there are 54 holes with a diameter of 180 mm (Fig. 2). On the end surface of the vessel flange, 54 threaded holes M170x6 for the main seal studs and two annular grooves of triangular cross-section, made in the overlaying metal and intended for installation of bar seal gaskets, are evenly circumferentially located.

Details of the main connector include studs, nuts, convex washers, concave washers and two gaskets. The lid is fixed to the body with 54 studs, nuts M170x6 and 54 pairs of washers (Fig.2). The studs are a cylindrical rod with a diameter of the working section of 161 mm and a M170x6 thread at the edges, having an internal hole with a diameter of 35 mm. The listed parts are made of steel grade 38XH3MFA. The toughness of the connection is provided by crimping two nickel-bar gaskets installed in the sealing grooves of the housing flange.

The stress state in the studs is determined by technological and operational loads. Prior to the start of operation, the nuts of the threaded connection are tightened, the contact area of the lid and the flange of the vessel is compressed to obtain a hermetic connection during operation and test modes. When the studs are tightened, significant axial tensile stresses take place in it, which are unevenly distributed along the height of its working part and across the cross section of the stud, which corresponds to the simultaneous action of stretching and bending.

The main loading factors during operation are the pressure of the primary circuit and uneven temperature fields, which emerge due to the temperature difference of the primary coolant and the environment surrounding the reactor vessel. The working part of the stud is in direct contact with the air inside the containment shell piercing through the gaps between the flange and the lid around the perimeter of the flange joint. In this case, the circulation of the environment inside the gaps is very limited and when calculating temperature fields it is considered that there is a thermal contact between the surface of the studs and the loops of the lid flange. The finite element model of the main connector contains 518130 8-node three-dimensional finite elements, 605154 nodes, 1815462 degrees of freedom (Fig.3).

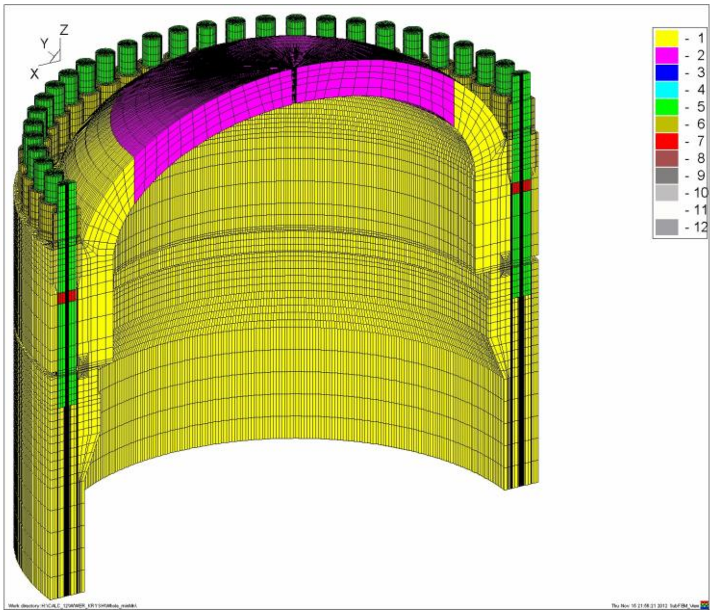

Figure 3. Finite element model of the main connector of the reactor shell.

The results of the stress-strain state calculations of flange connections elements are used to estimate the critical size of a number of destroyed studs in deterministic and probabilistic approaches. When analyzing the conditions for performing the LBB, the safety factors for stresses equals 1.4 and the critical size of a number of damaged studs 2.0 were taken.

On Fig. 4 the dependence of the membrane stresses on the outermost stud for the number of destroyed studs at maximal calculated loads is shown. The guaranteed value of the yield point of the material of the studs at the operating temperature is ~ 670 MPa [9]. Under the deterministic criticality condition, the row consists of 13 broken studs. Taking into account the safety factor for the size of the critical row, the area of the gap opening and the coolant flow rate were calculated for a series of 6 destroyed studs.

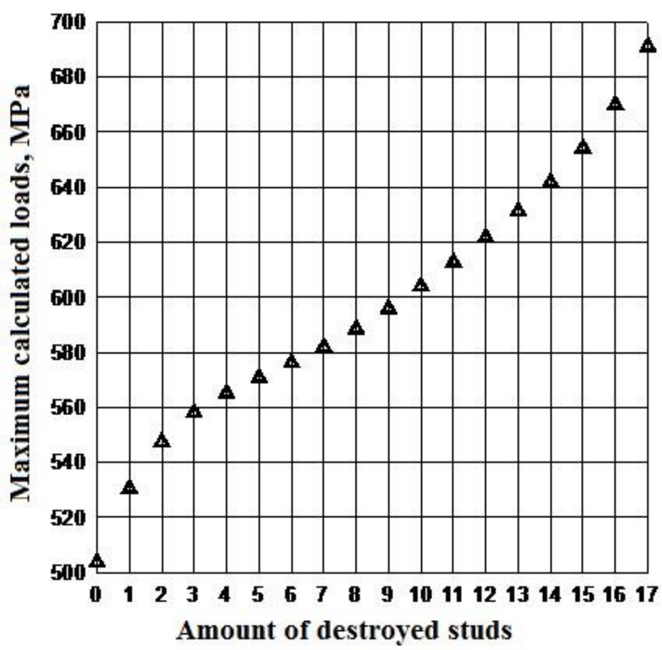

Figure 4. Dependence of the stresses on the neighboring studs from the amount of the destroyed studs

On Fig. 5 the dependence of the probability of destruction of the outmost stud for the amount of damaged studs at maximal calculated loads and the four-year cycle between technical surveys is shown. The critical row consists of 16 destroyed studs, the calculation of the area of the gap opening and the coolant consumption was carried out for amount of 8 destroyed studs.

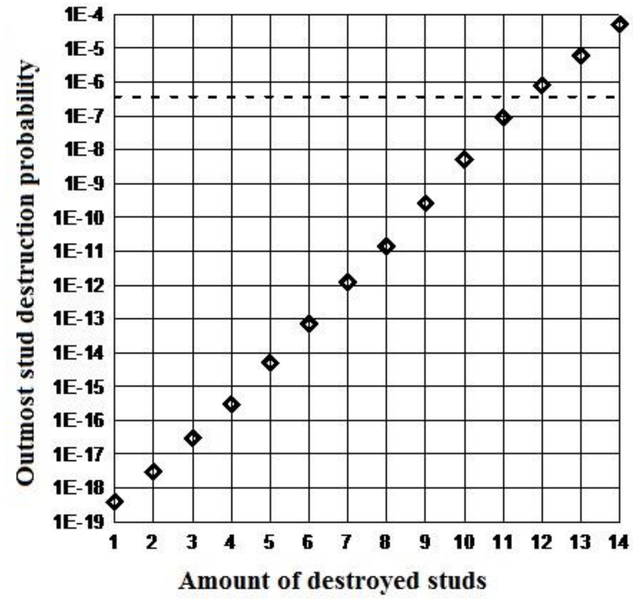

Figure 5. Fracture probability of the neighboring stud depending on the amount of the destroyed studs.

Figure 6 shows the gap area values A and A_{ef} for different numbers of damaged studs under normal operating conditions.

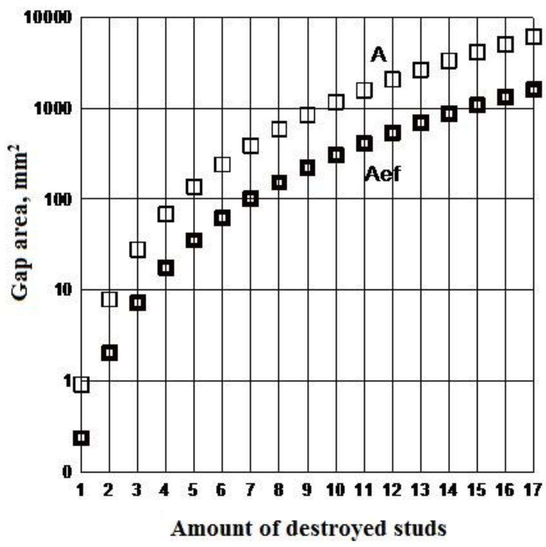

Figure 6. Calculated A and “effective” A_{eff} gap areas for different amount of the destroyed studs under normal operating conditions.

The calculation of the coolant consumption rate was carried out with the following values of the listed parameters: ε = 1, P_{in} = 16.2 MPa, P_{out} = 0.1 MPa, ρin = 998 kg/m^3, Sm =1, t = 0.360 m. In accordance with [5], the permissible roughness of the sealing surfaces of the flanges R_a =12.5 μm.

Figure 7 shows the dependence of the coolant consumption rate from the amount of destroyed studs.

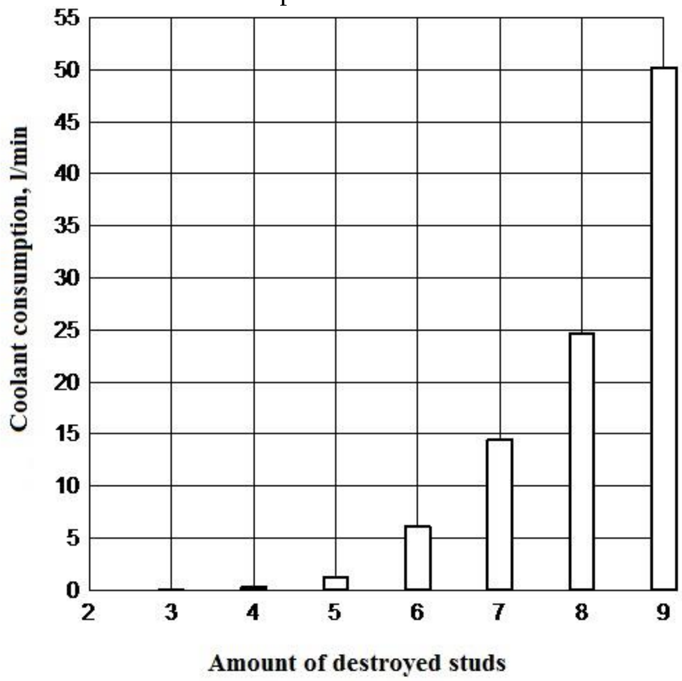

Figure 7. Dependence of the coolant flow rate from the amount of the destroyed studs.

Coolant consumption rate with the deterministic criterion of the gap corresponding to half of the critical series was 24.7 l / min. The coolant flow rate at the probabilistic criterion of such a gap was 6.2 l / min.

The fulfillment of the LBB condition is determined by the sensitivity of the LDS and the safety factor for this parameter. With a LDS sensitivity of 3.8 l / min and a safety factor of sensitivity, which equals 10, the LBB condition is not fulfilled with either deterministic or probabilistic rupture criterion. When the safety factor of sensitivity equals 5, the condition of LBB is performed for deterministic criterion. Thus, with accepted guidance documents and equipment with LDS 3.8 l/ min the LBB safety concept cannot be applied. The solution of this problem can be the equipment with LDS of 1.9 l/min or the changes in guidance documents, especially in the safety factors.

It should be emphasized that the considered example is intended to demonstrate the feasibility of applying the LBB safety concept to flanged connections of the reactor units. In the development plan of the approach, it is supposed to clarify the methodology for calculating the coolant consumption rate and to analyze the justification of the safety factors.

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