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THE ANALYSIS OF A STEAM GENERATOR PGV-1000 FAILURE POSSIBILITY DUE TO DESTRUCTION OF A STUDS OF A COLLECTOR COVER

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ABSTRACT

An assessment of a probability of destruction of reactors design elements are necessary for calculations of reliability parameters, that is one from stages of the safety of nuclear power plants (NPP) substantiation. The operating conditions of steam generator header are characterized by a complicated thermal-mechanics loading and by an aggressive effect of a corrosion medium. The realization of adequate strength calculations for thus kind of design elements is a complicated task. The basic methodology and some results of an estimation of steam generator PGV-1000 failure probability, connected with a leak appearance in a header cover flange joint due to destruction of fastening studs, ensuring dense junction of a cover with a flange and a protection from a penetration of the coolant from the first circuit to the second circuit, are presented in this paper. The calculations include three stages. The stressed-strained state calculations of the design elements of the header cover flange joint with application of a detail three-dimensional finite element model were conducted at the first stage of the analysis. The data base on stresses levels acting in studs in various modes of operation with allowance of number of destroyed studs is created by the results obtained on the first stage. This data base was used at the second stage of calculation of a destruction probabilities of one stud depending on a state (broken / unbroken) of remaining studs. The probabilities of realization of various combinations of a mutual disposition of the broken and unbroken studs are calculated on the third stage of investigation. These probabilities were used for an estimation of probability of a cover break-away and of leak appearance in the header cover flange joint due to destruction of studs.

Keywords: steam generator, header cover, stud, destruction, probability.

1. INTRODUCTION

To estimate the probability of leaks in the zone PGV-1000 steam generator header cover, it is necessary to analyze the possibility of failure of main fastening parts (studs). These studs are intended to ensure tight seal between the cover and the flange through two nickel gaskets and to prevent leak of primary circuit coolant into the secondary circuit. The fragment of the finite element model of the cover fastening joint, including one stud and main dimensions is given in Fig.1. Twenty studs are uniformly arranged around the cover periphery.

A stud is a cylindrical bar with the diameter of working part of 50 mm, with the internal hole of 10 mm in diameter, and metric thread (M60) at the both ends. The length of the working part of the spud is 195 mm. The studs are made of high-strength 38HN3MFA steel. The cover and flange are made of 10GN2MFA steel. The nickel gaskets have initial diameter of 6 mm.

The stressed state of a stud may vary during its service. In the initial moment (so-called tightened state) the nuts are tightened up and the gaskets are compressed to obtain joint that will be hermetically sealed under any operating and testing conditions. The tightening force is determined according to the "Norms …", 1989, on the basis of safe stress levels for the stud material. It should be noted that large axial tensile stresses in the stud result from its tightening. These stresses are non-uniformly distributed over the cross section and along the height of the working part of the stud, and this situation corresponds to simultaneous actions of tension and bending. As a result of stress diagram analysis, the membrane (uniform tension) and bending components can be distinguished. According to the standard, the membrane component of the stress in tightened stud shall be less than 260 MPa.

The main loading factors are the pressure of the primary and secondary circuits and non-uniform temperature fields caused by the difference of coolant temperatures in the primary (T1) and secondary (T2) circuits. The working part of the stud contacts directly with the secondary circuit steam through gaps between the flange and the cover around the edges of the flange joint. In normal operating mode of the "hot" header, temperature T1 is 320 ^{o}C (temperature of the primary circuit coolant) and T2 (temperature of steam) is 278.5 ^{o}C. For the "cold" header these temperatures are 290 and 278.5 ^{o}C, respectively. The change in the stresses in the stud with changing temperature can be also caused by the difference in coefficients of linear expansion of structural steels.

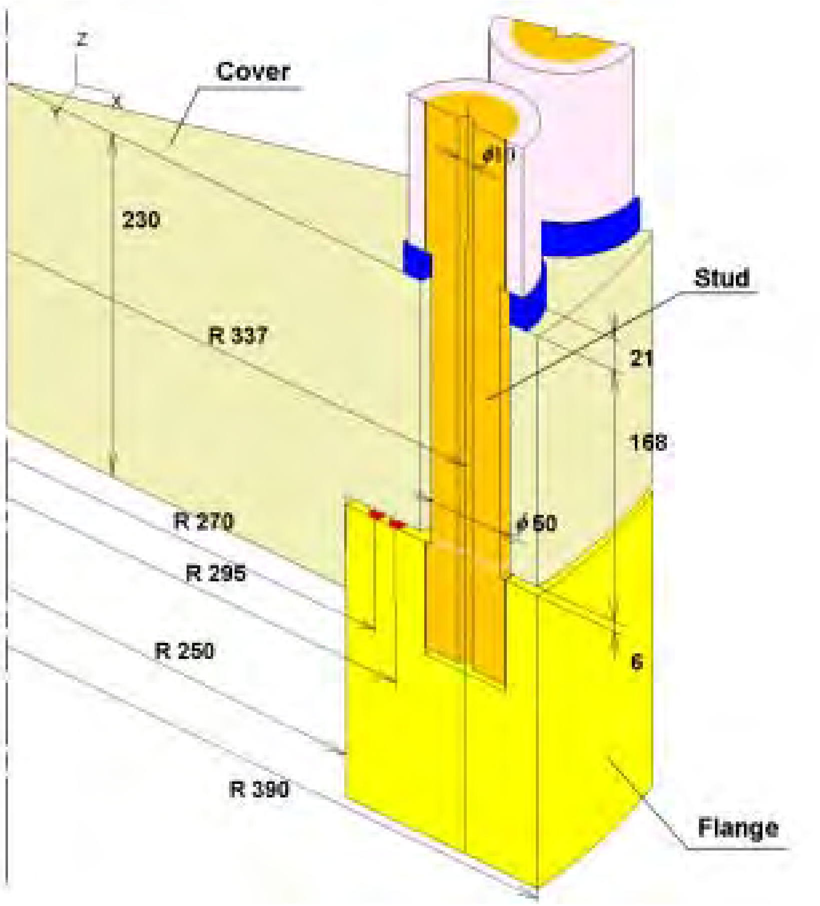


Fig.1 Geometry and main dimensions of the stud and cover/flange joint.

2. CALCULATIONS METHOD PECULIARITIES AND INITIAL DATA FOR ANALYSIS OF STRESSED STAINED STATE (SSS) OF HEADER COVER FLANGE JOINT.

Main peculiarities of the numerical simulation of SSS of three-dimensional structures with the UZOR 1.0 computer code realizing the finite element method and super element approach has been described by Kiselev A.S., KiselevA.S. and Danichev V.V., 1999. The finite element model of the cover joint including one symmetry plane and 10 studs was developed to analyze SSS of the stud bolting the cover to the flange in the upper part of the header of the PGV-1000 steam generator (Fig. 2). This model is also used to create a database of stud stresses for subsequent estimation of the stud failure probability, leaks, and cover breaking-away. The model includes 105101 nodes and 87240 linear volume eight-node finite elements.

Different colors and numbers in Fig. 2 mark design elements of the considered unit being included in the model. Although the materials have numbers from 1 to 8, it does not mean that all these materials have different mechanical properties. This method of indexing is used to set different design elements apart, though they work jointly. So, material 1 is the flange (steel 10GN2MFA), material 2 is the cover (steel 10GN2MFA), materials 3 and

4 are the washer and nut respectively (steel 38HN3MFA), materials 2 and 8 are the studs (steel 38HN3MFA), materials 5 and 7 are the nickel gasket.

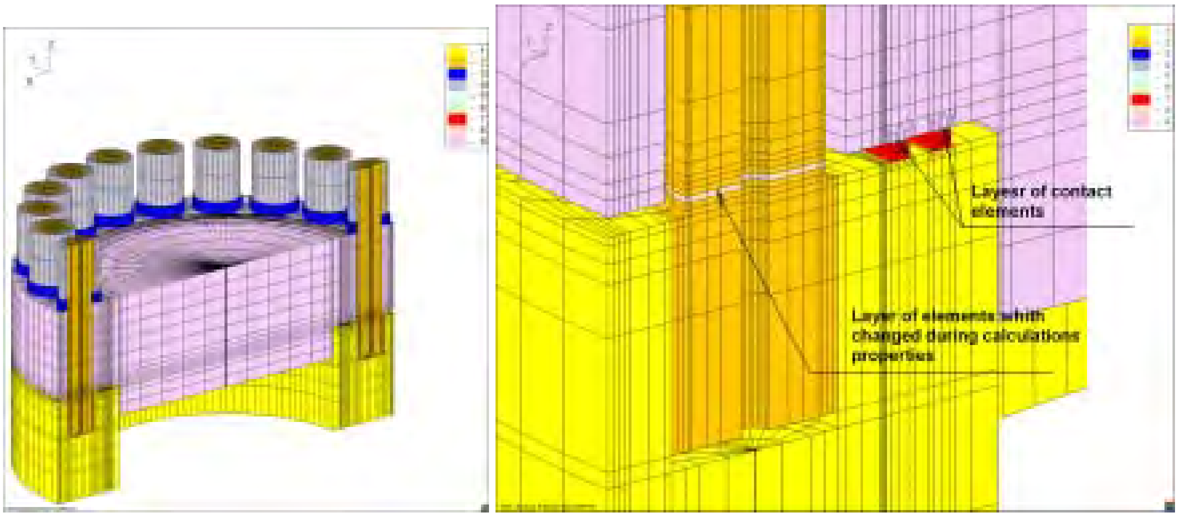


Fig.2 Finite element model of the cover/header flange joint.

It is a peculiarity of this calculations method that interaction of the flange and the cover can vary at different combinations of loading factors. As a result of small tightening force, even low pressure in the primary circuit can cause tensile stresses in the gasket. But this is physically impossible. So, contact elements on the surfaces of the both gaskets from the cover side (material 5, Fig. 1.4) are used in the finite element model (FEM). A series of iterations is performed at each step of the calculation procedure. The values of axial components of the stresses in the finite elements that belong to the contact layer are analyzed. If these stresses are greater than zero, it is assumed that the modulus of elasticity of this finite element is equal to a small value (E=0.1 MPa), the stiffness matrix is rearranged, the system of equations is solved, and stresses in the whole structure (including contact elements) are determined. If the properties of a contact element were equal to zero at the previous iteration, and they are less than zero for current iteration (compression), than the mechanical properties of nickel in this element are specified once again. Iterations go on until the sign of axial stresses in contact elements does not reverse.

This approach allows obtaining the estimation of real stresses in the studs in the case of failure of one (or several) of them, obtaining the estimation of the gap between the cover and the flange and equivalent parameter of the leak which is equal to the area of this gap.

It has been mentioned that different variants of break of one (or several) stud are analyzed in probabilistic calculation. In the case of such break the stresses are redistributed among the remaining studs. This rearrangement is non-uniform, the studs nearest to the failed ones, are stressed more. A layer of elements, where the modulus of elasticity close to zero can be specified (material number 8, Fig. 1), is included in the model to ensure performance of variant calculations. So, the break of one or several arbitrary located studs can be specified in each step of the calculations.

To simulate the stud tightening process, an initial constant value of axial deformation is specified for the working part of the stud (it is a smooth part of the stud with the diameter of 50 mm) in the first step of the calculation. The value of the axial deformation was chosen such that axial membrane (mean over the cross section) stresses are at the level of 260 MPa, i.e. the limiting value calculated by standard procedures.

The super element approach used in the described above task solution gives an essentiall computational advantages. The repeated on geometry fragments of the whole FE model, which included one stud, derived by planes, elapsed through OZ axis and rotated on the angle 18, 36, 54 …. degrees, are considered as super elements. It is needed in that case to calculate the matrixes of all the super elements on the first step of calculation only, but on the next steps we have to recalculate matrixes of the super elements only, where the contact condition of nickel gasket are changed or the destruction of corresponding stud is happened.

All these calculations were performed with the elastic approach with allowance of the dependence of mechanical properties on temperature (“Norms…”, 1989, Neymark B.E., 1967). The data base on stresses components values in studs depending on broken studs amount and loading condition has been created for a list of operation regimes of steam generator. This data base was used in a probabilistic analysis of leak and break away of header cover.

3. RESULTS OF THE STRESSED-STAINED STATE ANALYSIS OF THE HEADER COVER/FLANGE JOINT IN DIFFERENT OPERATING REGIMES.

Hydrostatic testing of the primary circuit is the most important for the analysis of failure and leak probabilities. In this mode the highest axial stresses occur in the studs holding the cover. The hydrostatic tests are performed at the temperature of 130 ^{o}C, primary circuit coolant pressure P1 = 24.5 MPa, and secondary circuit coolant pressure P2 = 0.5 MPa. The modes of “tightened state” and “heating to the hydrostatic test temperature” precede the hydrostatic test mode. Peculiarity of the “heating to the hydrostatic test temperature” mode is the uniform heating of all design elements to the hydrostatic test temperature of 130 ^{o}C.

Distributions of the axial stresses in a stud in the “tightened state” are given in Fig 3. The distribution functions and values of the stresses are the same in all studs.

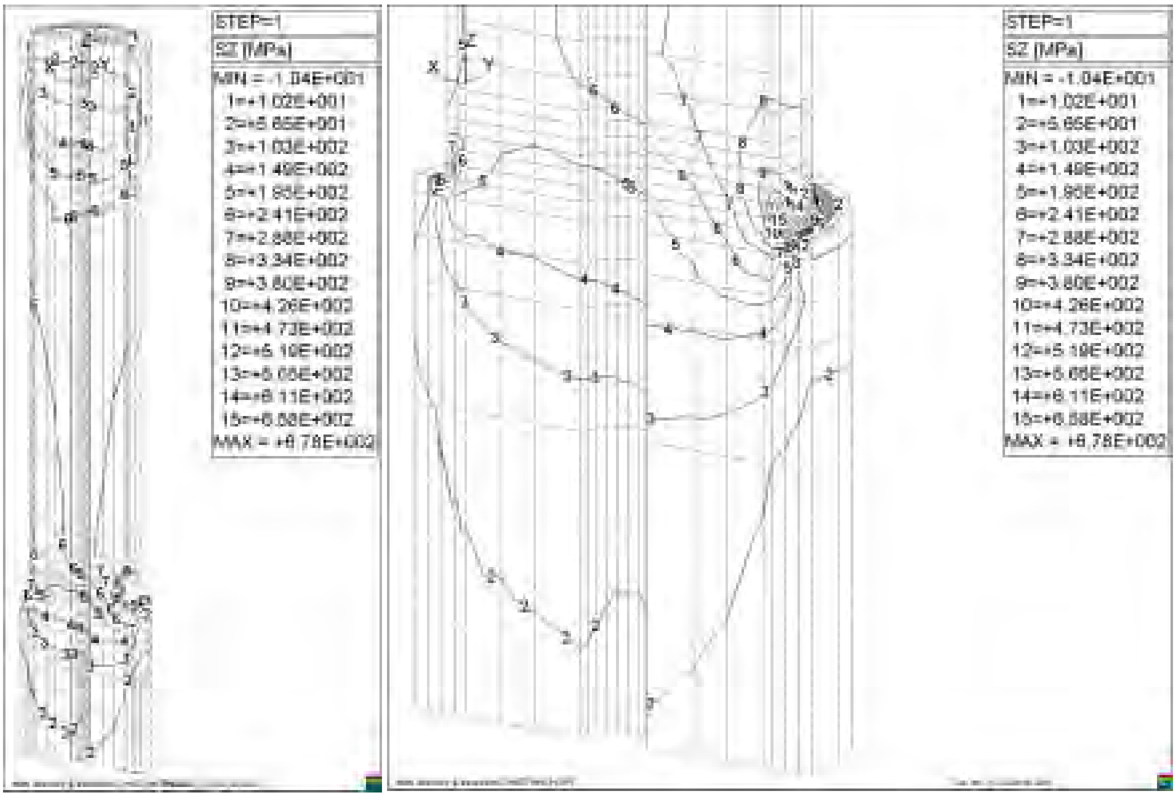


Fig.3 Distributions of axial stresses in a stud in the “tightened state”

Analysis of the calculation information shows that uniaxial stress state associated with the tension in axial direction and stud bending takes place in the middle part of the stud. In the lower part of the stud, in the jointing zone the stressed state becomes three-dimensional and concentration of the stress components appears near the outer surface of the stud

Therefore, the calculated stud stress distributions were reduced to three parameters: σ_m – membrane stress component in the middle part of the stud (or stresses averaged over the cross section), σ_Q – bending stress component calculated as the difference of the maximum axial stress over cross section and σ_m, K – stresses concentration factor showing how many times the axial stress component increases in the concentration zone. Those parameters were included in the data base for probabilistic calculations.

The values of listed above parameters for each of the studs, in the case of simultaneous breaks of several successively arranged studs (from 1 to 10) during the hydrostatic test of the primary circuit are presented in Table 1. Two several FE models were created for the calculations variants with even and odd amount of broken studs – Fig.4. The stud indices given in the table 1 are shown in the top views of the finite element models of the joint used in the analyses (Fig. 4b).

The similar calculations were performed for other operations regimes of steam generator header.

(a) **(b)**

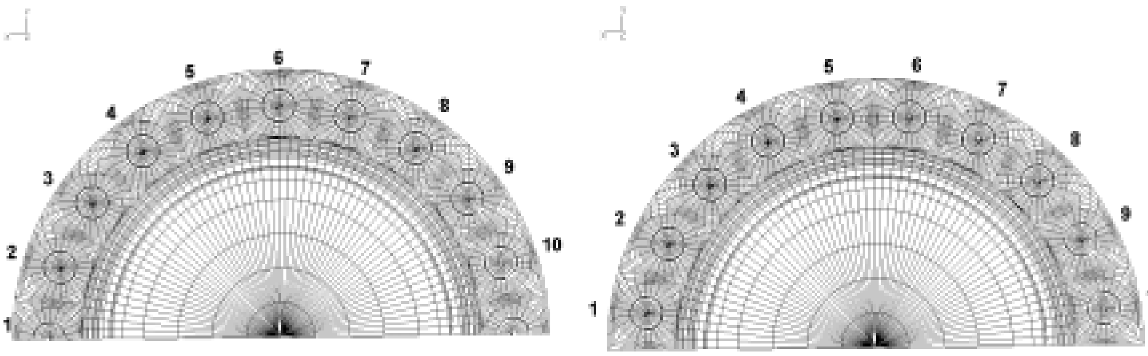


Fig.4 The stud indices in the finite element models of the header cover joint (a – in the case of break of odd number of studs, b – in the case of break of even number of studs).

Table 1. The membrane (σ_M) and bending (σ_Q) stresses [MPa], in the middle part of the stud and stresses concentration factor (K) during the hydrostatic test of the primary circuit in the case of the break of one or several successively arranged studs.

No. of stud	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Amount of broken studs	σm, σQ K	σm, σQ K	σm, σQ K	σm, σQ K	σm, σQ K	σm, σQ K	σm, σQ K	σm, σQ K	σm, σQ K	σm, σQ K
2	-	303 28 1.99	274 33 2.14	262 36 2.2	262 33 2.2	257 36 2.3	256 37 2.3	257 36 2.2	257 36 2.2	257 36 2.2
4	-	-	399 35 2.1	295 36 2.0	266 40 2.2	253 41 2.3	248 41 2.3	247 40 2.3	247 40 2.3	248 39 2.3
6	-	-	-	489 62 2.2	352 54 2.2	276 53 2.3	239 54 2.4	223 54 2.5	216 53 2.5	214 53 2.5
8	-	-	-	-	720 110 2.2	442 97 2.3	279 91 2.5	190 89 2.8	148 89 3.1	133 90 3.3
10	-	-	-	-	-	1055 38 2.3	355 96 2.6	199 183 3.2		

Without broken studs: $\sigma_M = 263$; $\sigma_Q = 37$; K = 2.3

Influence of the corresponding to considered regime of operation temperature distribution on stresses values is taken in to account. Temperature distribution in the cover joint zone, calculated for normal operating conditions, is given in Fig. 5 as an example. The conditions of convectional heat exchange with coolant of the first and second circuit were given on the inner and outer surfaces of the header cover. The temperature of the coolant of first circuit is equal to 320 ^oC, for the second - 278 ^oC

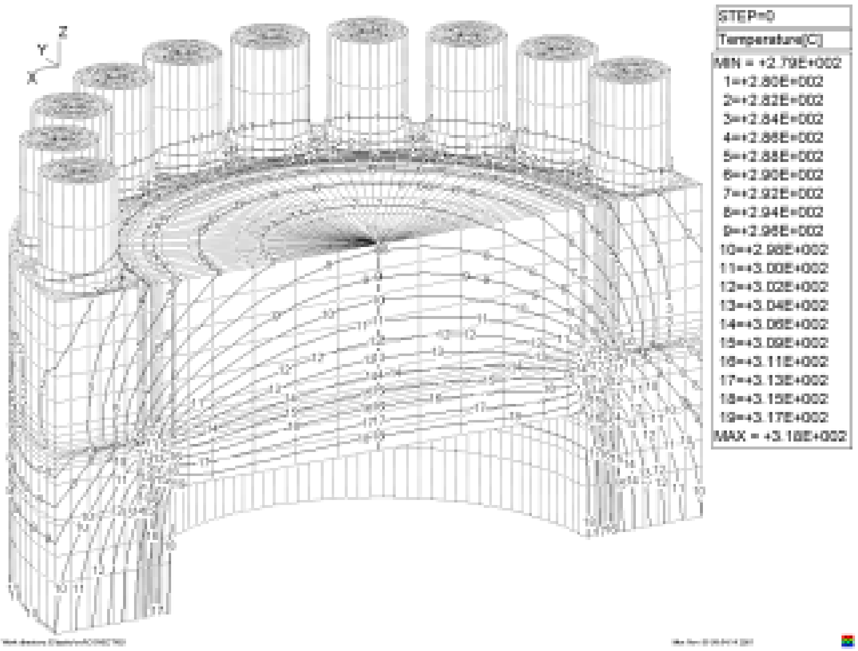


Fig.5 Temperature distribution in the header cover joint zone, calculated for normal operating conditions.

The plots of axial stress distributions in the middle part of studs No. 5 (Fig. 4a) when the studs are under load and one or several studs are broken are given in Fig. 6. These plots correspond to the following states of the studs: STEP1 - "cold tightened" state of the studs, STEP2 - "hot tightened" state of the studs (T=130 ^{o}C), STEP3 – hydrostatic test (Inner pressure is added), STEP4 – break of one stud (No. 1, Fig. 4a), STEP5 – breaks of three studs (No. 1 and 2, Fig. 4a), STEP6 - breaks of five studs (No. 1, 2, and 3, Fig. 4a), STEP7 - breaks of seven studs (No. 1, 2, 3, and 4, Fig. 4a).

After the break of studs No. 1 and No. 2, the stresses in the stud No. 5 increase slightly (Plots STEP4, STEP5 in Fig.6) because the studs, nearest to the broken ones, i.e. studs No. 3 and No. 4 mainly take up the overload. After the break of stud No. 3 (Plot STEP6) the stresses in stud No. 5 considerably increase, although stud No. 4 is still working. The jump of axial stresses in stud No. 5 (Plot STEP7) is observed during the break of stud No. 4, because this stud is the nearest unbroken one to the group of the broken studs and takes up the main part of the overload.

In the case of the breaks of more than eight studs, the axial stresses in the nearest unbroken stud averaged over cross section, exceed the stud steel yield strength.

The developed model and method of the SSS calculation of the header cover joint allows obtaining of leak size in the case of several studs break. For this purpose, displacement of the nodes at the edge of outer layer of contact elements is analyzed. By considering two nodes of the contact layer, located one under another and having the same radial and angular coordinate, it is possible to compare their axial displacements, obtained under different loads. If the vertical displacement of the node contacting with the cover surface is less than the vertical displacement of the node contacting with the gasket, it means that the gasket is compressed. If the difference between these displacements is positive, a gap between the cover and the gasket is formed. The area of this gap and associated equivalent diameter of the leak can be easily calculated.

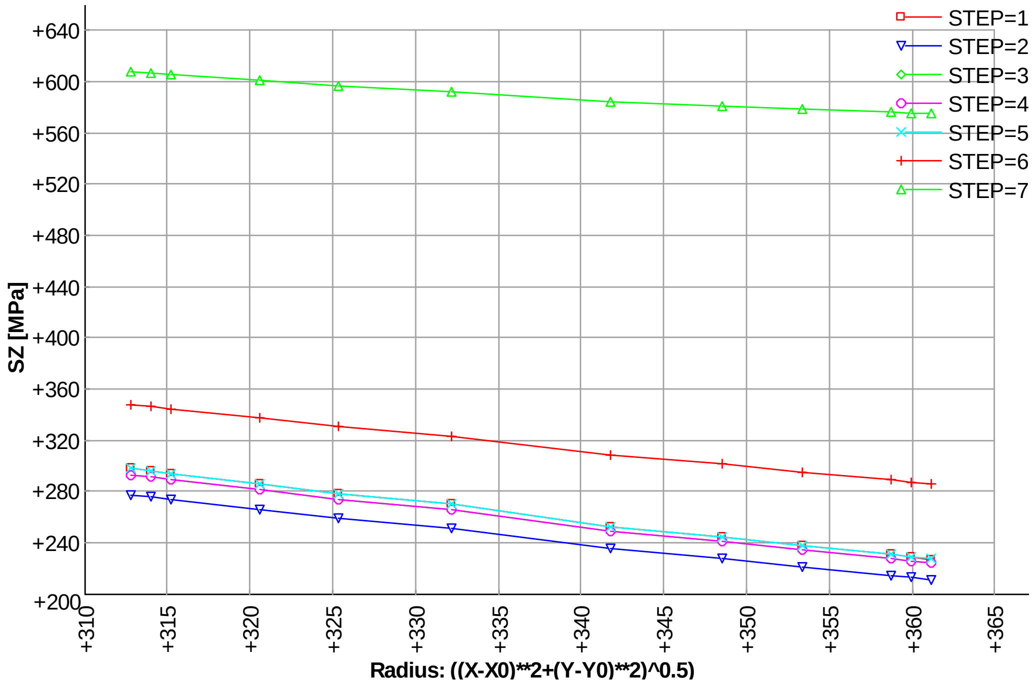
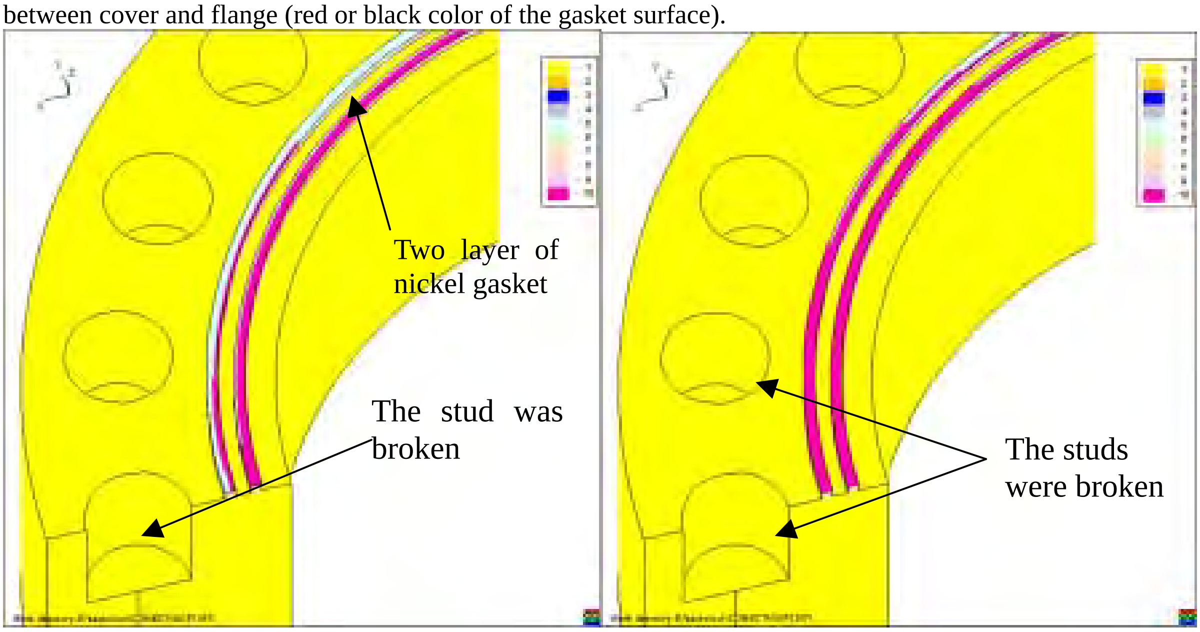


Fig. 6 Распределение осевых напряжений в средней части шпильки №5.

The state of the gasket and contact layer after the break of one stud is shown in Fig. 7a. As follows from the figure, the inner gasket does not contact with the cover surface in this zone, i.e., the gap is formed. Part of the surface of the gasket outer layer does not contact with the cover surface also (red or black color), but the joint is still tight (light blue or white colored area). A situation that takes place after the break of three neighboring studs is shown in Fig. 7b. In this case both gaskets loose tightness in the break zone, that causes development of a gap between cover and flange (red or black color of the gasket surface).



(a) (b)

Fig.7 The change of the gasket and contact element layer states under load and on the break of studs (a – break of one stud, b – break of three studs)..

To estimate the leak size, the area of the gap is determined with the plots of vertical displacements of the contact layer nodes located on the edge at the cover-side (upper edge) and on the edge at the gasket-side (lower edge). These plots for the case of three neighboring studs break are given in Fig. 8. The angular coordinate measured from the positive direction of the OX axis of the global coordinate system is laid off along the OX axis. Zero value of the angular coordinate corresponds to the center of the broken stud.

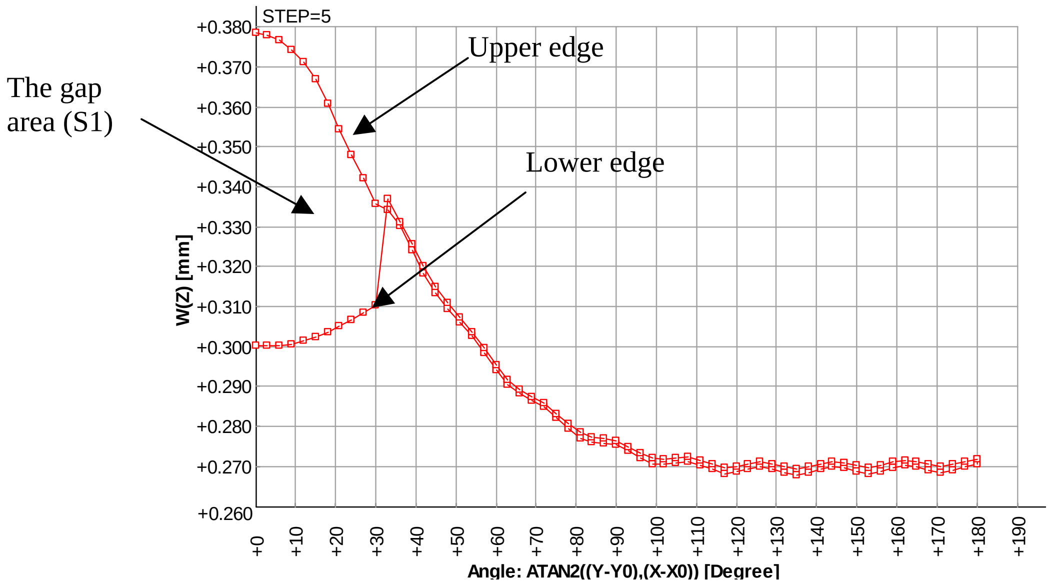


Fig.8 The vertical displacements of outer gasket contact layer edges on the break of one stud and under the hydrostatic test pressure.

The area of gap S1 is calculated on the basis of the presented plots and the fact that the radius of arc on which the nodes located on the contact layer edge are arranged is R=290 mm. As a result of symmetry, the value of S1 is doubled and the leak equivalent diameter is calculated as:

$$D = 2\sqrt{\frac{S1*2}{\pi}}$$

The values of gap area and equivalent diameter for the loading corresponding to the primary circuit hydrostatic test conditions (P1 = 24.5 MPa, P2 = 0.5 MPa, T = 130 ^{o}C) are given in Table 2.

Table 2. Parameters of Gaps and Leak Equivalent Diameter as a Result of the Break of One or Several Studs.

Number of Broken Studs	Maximum Gap Opening [mm]	Gap Area [mm^2] (2S$_1$)	Leak Equivalent Diameter [mm]
0	0	0	0
1	0	0	0
2	0.017	1.24	1.25
3	0.078	18.4	4.8
4	0.194	67.8	9.3
5	0.381	172.4	14.8
6	0.676	364.7	21.5
7	1.125	691.1	29.7
8	1.806	1219.4	39.4
10	4.367	3365.7	65.4

4. CALCULATION OF ONE STUD DESTRUCTION PROBABILITY

Assessment of the probabilities of leaks or cover break-away as result of a failure of jointing elements (studs) consisted of two stages. At the first stage, the probabilities of the break of one stud depending on the states of the other studs were calculated. At the second stage, the probabilities of different combinations of broken and unbroken studs were calculated. The probability of one stud destruction P(i,j) is calculated, where **i** and **j** amount of destroyed adjacent studs, with using of data base on stresses values in studs obtained on the firs stage of investigation described above. For example, P(0,2) means that one from adjacent to considered stud is unbroken, but two studs placed from other hand from considered stud are broken. The calculations are conducted with using of the computer code of MAVR series, which have been developed in Russian research center "Kurchatov institute" for a leak and break probability in equipment of the first circuit of nuclear power plants (NPPs). The stud is considered in that case as a thick walled cylindrical vessel working in the condition of complicated stresses distribution and under corrosive influence of the first and second circuit fluid. The algorithm of the MAVR series computer codes are based on the following principles (A.A.Tutnov and O.D.Loskutov, 1995):

- The fracture probabilities calculations predicted by means of the mathematical simulation of the defects generation and development kinetics including corrosion-fatigue damages;
- All possible scenario of cracks development are considered taking into account loads, appropriate to operating regimes, emergency regimes, maximal calculated earthquake and so on;
- The methodology of linear-elastic and non-linear fracture mechanics is used for the leak and break probability calculations;
- The history of the object operation is simulated using settings for various combinations of loading modes, their duration in time and various combinations of these combinations.

  Following parameters are taken into account:
  - Statistical scatter of the values of mechanical characteristics of steel and weld material;
  - Statistical scatter of the data on defects initial sizes, concentrations, sub critical development rate;
  - The efficiency of non-destructive testing systems.

Data on the brittle strength and admixture concentrations for the 38HN3MFA steel are given in Shur D.M., Rivkin E.Yu., Merinov G.N., Belikova R.V., 1990. The yield limit, strength, Young modulus and other characteristics are given in "Norms …", 1989. There is used the normal distribution law of listed above parameters. The distributions were bounded by normative data on guarantied values of strength and mechanical characteristics. It was supposed, that there are no initial defects in the studs jointing the header cover. The calculations of P(i,j) were conducted for loads corresponding to normal and emergency operation regimes for the time of operation up to 150000 hours.

5. THE CALCULATION OF PROBABILITY OF REALIZATION OF BROKEN AND UNBROKEN STUDS COMBINATION

The probabilities of appearance of several combination of broken and unbroken studs are calculated on the present stage of investigation. The condition of the header cover break-away is the following: the length of the arc corresponding to the combination broken studs is so large that the membrane stresses component in the nearest unbroken studs exceed the specified yield strength. This condition is satisfied from probabilistic point of view when break probability of any stud P(i,j) is equal to 1. It is possible if the membrane stresses component in the middle part of stud under hydro test or under any other regime of operation reaches yield limit of material.

The size of the gap between flange and cover and consequently the leak rate is determined by the length of slit arc, formed on the break of several adjacent studs. For example, the failure of one stud results in the arc length of two studs to stud spacing, etc. Let P(k) denote the probability of formation of a slit arc with the length of "**k**" stud to stud spacing or (which is the same) formation of a row of **k**-1 studs. For short, we will call formation of the arc with the "**k**" length as "**k**" event. Along the circle where 20 studs are located, several non-crossing arcs can be formed. These arcs are formed by rows of broken studs separated by one unbroken stud at least. In other words, each of the "**k**" (**k** =1,2,…,20) events can be realized several times and the maximal number of realizations of the "**k**" event is equal to the integer part of 20/**k**.

In this approach the probability of the event, when only arc k=2 is formed, is determined from the binomial distribution on the condition that only one of 20 studs will be broken. The arc of the $k \geq 3$ dimensions can be obtained by several ways, each is characterized by its own probability of realization depending on P(i,j). For example, the arc **k**=3 can be formed as a result of the simultaneous break of two adjacent studs or as a result of the break of one of the boundary studs of the arc **k**=2. With increasing k the number of ways by which the corresponding arc can be obtained, increases rapidly. The probability of the appearance of arc from **k** broken studs is calculated as the probability of events combination of arc appearance from **k-c** broken studs and destruction of **c** studs - probability $P^c(i,j)$:

$$P(k)= F\ [P^c(i,j),\ P(k\text{-}c);\ c =1,\ldots,k\text{-}1;\ i + j = 0,\ldots,k\text{-}2] \qquad k = 2,\ldots,20, \qquad \text{(Eq. 1)}$$

where

$$P(1) = [1 - P(0,0)]^{(20-k+1)} \qquad \text{(Eq. 2)}$$

The probabilities P(k) in the Eq. 1 are determined by the probability P(i,j) and probability P(k'), where **k'**<**k**. Therefore, (Eq. 1) is a system of the recurrent equations permitting to find P (k) for anyone **k** ≤ 21.

The problem is obfuscated by the fact that besides combinations of events of the same types, combinations of events with different "**k**" are possible. In general, probabilities of these events will be expressed in terms of products of factors of the P(k) type, where k are connected with each other by the number of studs. So, the number of such factors **n** or maximal number of independent trials that can be realized in the specified system of elements is limited by the maximal number of non-crossing arcs that can be located in the circle with 20 studs. The probabilities of joint realization of different k events, i.e. probabilities of different combinations of broken and unbroken studs, can be calculated with polynomial distribution (Sevastianov, 1982).

The maximal number of "leak-resulting" arcs located in the circle with twenty studs is equal to 6. Therefore, the exponent in polynomial distribution (2.2) n=6 allows covering all possible "leak-resulting" broken and unbroken stud combinations. The probability of realization of combination of different arcs from $\mathbf{k_i}$ broken studs by polynomial distribution is expressed as a function of products of probabilities $P(k_i)$ and factorials $\mathbf{k_i}$:

$$P_c = \Phi\left\{\prod_i^{n_{k_i}} [P(k_i)/k_i!]\right\} \qquad \text{(Eq. 3)}$$

The number of multiplicands n_{k_i} and sizes of arcs k_i in (Eq. 3) are attended by following condition:

$$\sum_i n_{k_i} \cdot k_i \le 20 \qquad i \le 6 \qquad \text{(Eq. 4)}$$

Pc is the probability of realization of the corresponding combination of arcs of broken studs, i.e. certain arrangement of broken and unbroken studs, i.e. of determined mutual disposition broken and unbroken studs. Each of thus combination corresponds to a leak size. Thus, the solution of the task is reduced to determination of probabilities P (k), which then are used in (Eq. 3). Substituting P(k) in (Eq. 3) with allowance for (Eq. 4) it is possible to calculate probabilities of possible combinations of mutual disposition of broken and unbroken studs, therefore, to calculate probability of leaks appropriating to these combinations.

It should be emphasized that in general, all of the mentioned probabilities depend on time, i.e. they are random functions. An estimation of the operating time influence was performed in presented paper with the method of one-step specifying of the initial probabilities P(i,j), i.e. the entire operating period was considered as one step of specified duration.

Some results of calculations of probabilities of leaks conditional diameters and of a cover break-away event due to destruction of studs are shown in the Fig..9-12. Each point corresponds to a certain combination of broken and unbroken studs. The spread of points in the presented figures indicates that different combinations of broken and unbroken studs produce equal or similar leaks. Each of these combinations has its own probability, and these probabilities can differ greatly.

As it was mentioned above, the condition of the header cover break-away is when a combination has an arc with the dimension at which stresses in the nearest unbroken studs exceed the specified yield limit of steel. The probability of realization of such events, interpreted as cover break-away probability, is presented in the figures by horizontal lines. So, all the leaks located above these lines are more probable than the cover break-away and vice versa. So, the magnification of a conditional diameter in two times results in a decreasing of probability on some of order. It is necessary to mark, that the probabilities of leaks by a conditional diameter more than 30 mm are less than probability of a cover break-away independently of operating time.

Indicated on a Fig. 10 dependencies of probability of leaks on their size for different times of operation show essential influence of this factor to a possibility of a leak appearance in the cover flange joint. The obtained results show, that the probabilities of leaks depend hardly on their sizes, but the relative dependence decreases with increasing of operation time. Possible minimum on sizes leak has an conditional diameter of 1.3 mm. This minimal leak has a maximal probability of realization.

The dependence of probability of a cover break-away on the operation time is shown on Fig.11. The probability of a cover break-away, at least for the considered conditions, is hypothetical. The calculations have shown, that the higher level of stresses under hydro tests load than under operational modes results in larger probabilities of leaks during hydro tests, if the time of operation between hydro tests is equal or less than 2 years (Fig. 12). Obviously, if the time of operation between hydro tests is 3 or more years, the influence of processes of cracks generation and development in operation period on probability of studs destruction can exceed an influence of short-term effect of higher stresses under hydro tests.

The results of calculations of probabilities of leak and break-away of header cover due to studs destruction are necessary for the estimation of steam generator reliability. The developed algorithm of calculation of probabilities of destruction of different combination of bearing elements can be used in an analysis of another design elements, particularly, for flange joint of a cover and reactor pressure vessel.

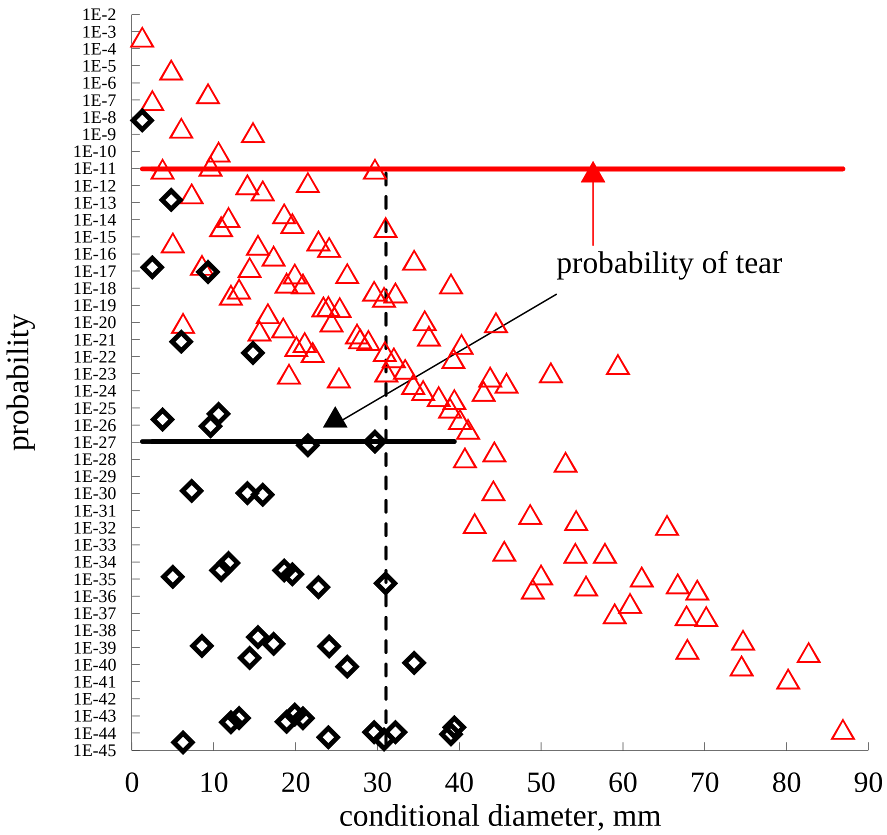


Fig. 9. Probability of leak vs. conditional diameter of leak. Operating time, hours: 10000 - black, 150000 - red.

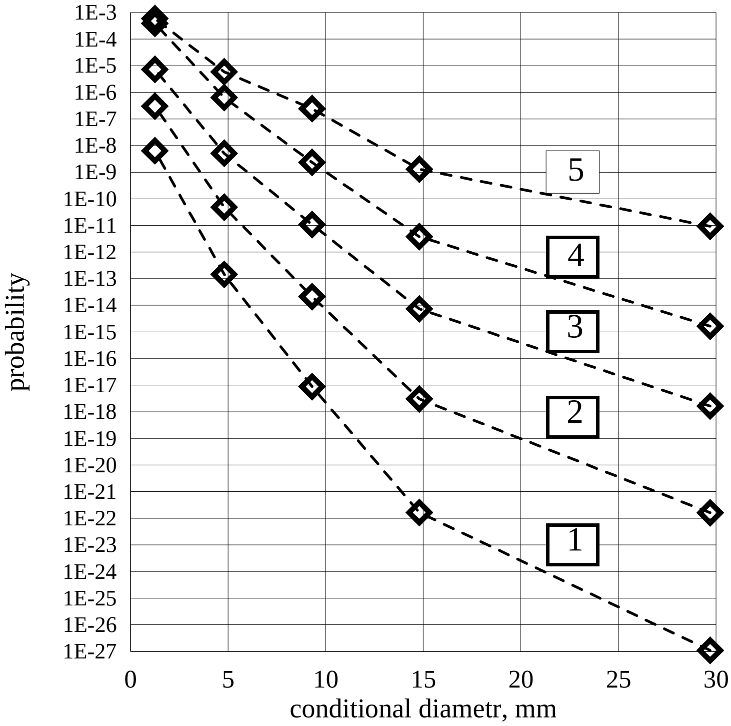


Fig. 10. Probability of leak vs. conditional diameter of leak. Operating time, hours: 1 - 10, 2 - 20, 3 - 50, 4 - 100000, 5 - 150000.

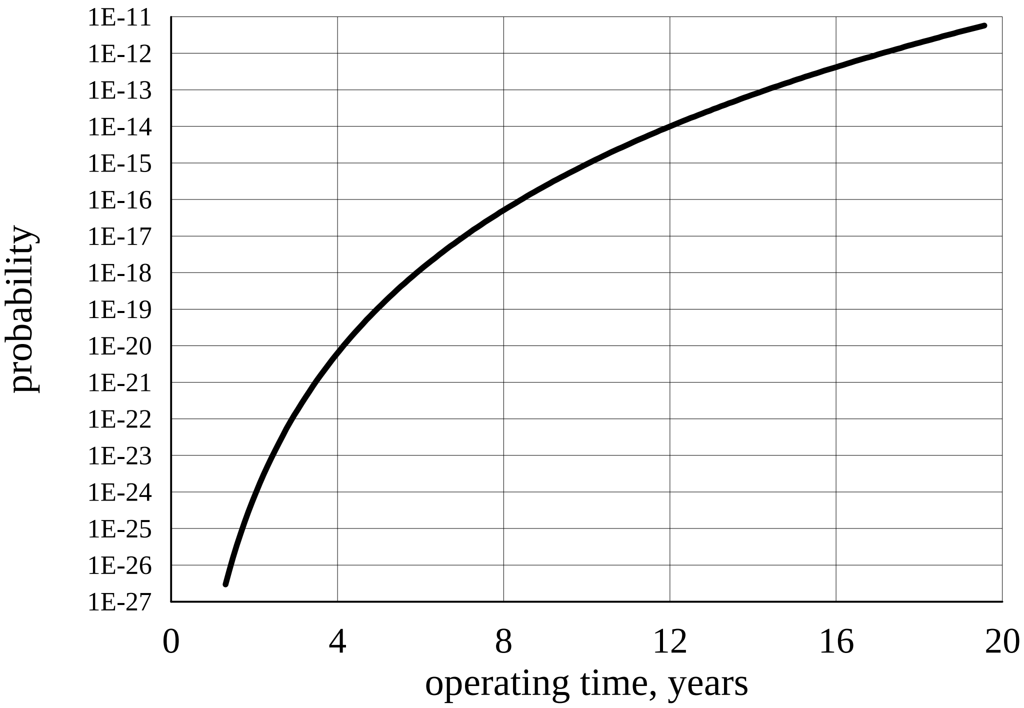


Fig. 11. Probability of covers tear vs. operating time.

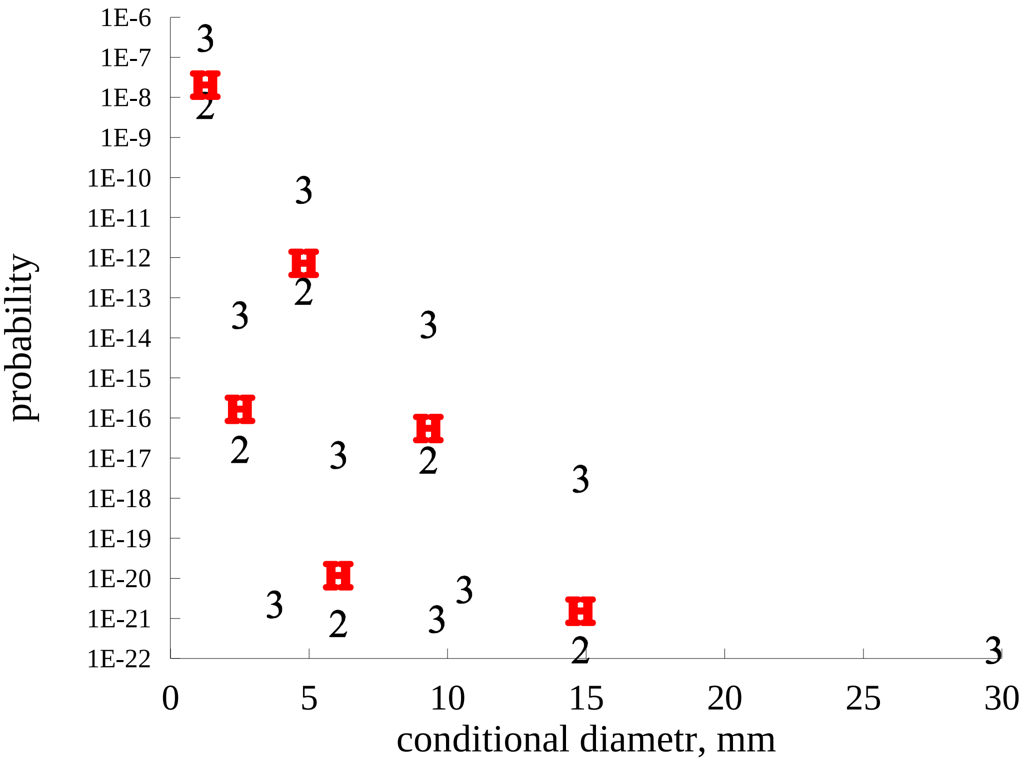


Fig. 12. Probability of leak vs. conditional diameter of leak. Operating time: 2 -2 years, 3 - 3 years, H – hydro test.

6. CONCLUSION

1. The detailed 3D model of flange joint of steam generator PGV-1000 header cover has been developed.. The calculations of stressed-strained state of the studs under load condition of different regimes of operation are conducted. The applied approach allows to obtain quantitative assessment of leak equivalent diameter depending on load condition and number of destroyed studs. The application of a super element algorithm for solution of the given problem has allowed essentially reduce task performance period. The data base on stresses values in studs under various modes of operation with destruction of various number of studs is created. This data base was used in the probability analysis of leaks and header cover break-away events. The analysis of obtained results has allowed to establish the following facts:
   - After destruction of one or several adjacent studs an essential overloading is realized in two unbroken studs nearest to destroyed studs;
   - There should be destroyed two studs as a minimum for a leak appearance.
2. The developed methodology of calculation of probability of a system of bearing elements (studs) destruction can be used in the reliability analysis of flange joints of various design elements of the reactor equipment, for example, for a cover and a vessel of reactor. The analysis of results of calculation of a leaks appearance in a zone of a steam generator header cover due to destruction of studs have shown:
   - The probability of a leak, which conditional diameter exceeds 30 mm, is less than probability of header cover break-away event;
   - The obtained dependence of cover break-away probability on time of operation has shown, that the probability of cover break-away does not exceed 10^{-7} in a Year for the time of operation equal to 30 Years.

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