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The Procedure for Determination of Special Margin Factors to Account for a Bow of the VVER-1000 Fuel Assemblies

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ABSTRACT

Starting from 1980s, the problem of bow of the VVER-1000 reactor FAs and the effect of that on the operational safety is being discussed. At the initial period of time, the extension of time for dropping control rods of the control and protection system associated with this bow posed the highest threat. Later on, new more rigid structures were developed for FAs that eliminated the problems of control rods.

However, bow of the VVER-1000 reactor FAs is observed up to now. The scale of this bow reduced significantly but it still effects safety. Even a minor bow available may lead to the noticeable increase of power of individual fuel pins associated with the local variation of the coolant amount. This effect must be taken into account on designing fuel loadings to eliminate the exceeding of set limitations. The introduction of additional special margins is the standard method for taking this effect into account.

The present paper describes the conservative technique for the assessment of additional margins for bow of FAs of state-of-the-art designs. This technique is employed in the VVER-1000 reactor designing. The chosen conservatism degree is discussed as well as the method for its assurance and acceptable ways for its slackening. The example of the margin evaluation for the up-to-date fuel loading is given.

1 INTRODUCTION

In the course of operation, different loads (a significant hold-down force, temperature stresses, pressure, radiation increase, and so on) affect FAs in the reactor core, which may lead to FA geometrical instability. One of the instability consequences is a FA bow that is observed in the LWR reactors of different types including VVER-1000 since 1980s. A noticeable bow of the VVER-1000 reactor FAs led at that time to the problems in moving control rods as due to the excessive friction, time of dropping emergency protection system controls exceeded the design rated value of 4 seconds that vitally deteriorated the reactor facility safety.

Considerable efforts were exerted in designing a more stable VVER-1000 reactor core. Development of more rigid structures for FA, that is TVSA type with additional stiffen angles [1] and TVS-2 type [2], was the result of the most importance. Their introduction into operation reduced significantly FA bows and resolved the problem of moving control rods. However, even with the reduction of FA bow it effects the operational safety of the VVER-1000 reactor core. This effect mechanism of the most importance is the following one: on bowing of the ensemble of FAs, a local area with the coolant varied amount may be produced in gaps between those. In fuel pins adjacent to gaps areas, energy release varies noticeably that may result in exceeding the design limitations in the local thermal flow.

To eliminate exceeding the design limitations by the variation of gaps between FAs, fuel loadings may be designed with a sufficient margin prior to the design limitations. Therefore, it is

necessary to assess the effect of undesigned gaps on energy release parameters and to evaluate the numerical values of additional margins for each studied fuel cycle basing on this assessment.

To obtain margin factors for the VVER reactor, the conservative approach was adopted assuming to use the combination of parameters to be worst for safety in this effect assessment. This approach must ensure (for example, with the specified probability of 95%) the observance of the design limitations in any design basis conditions and in the campaign any moment. Therefore, the technique for the calculation of margins taking into account FA bow was developed on the basis of wittingly conservative assumptions which would be justified in what follows.

The presented technique consists of several stages logically following one after another. At the first stage, the scales of FA bow in the course of the VVER-1000 reactor core operation are assessed. The calculations by combined thermal-mechanical codes allow determining bows of FAs and the variation of gap sizes between those. At the second stage, the effect of varied gaps on fuel pin power is evaluated by the exact methods of neutron calculations. The analysis of the calculation results allows choosing the conservatism measure in evaluations and establishing the relationship between FA shape variation and safety parameters. In the course of the third completion stage, the margin value providing for the necessary probability of limitations inviolation is determined on the basis of definite dependencies and with regard to gaps typical of the investigated fuel loading.

Further, the methods for the analysis at each of the stages are briefly discussed.

2 APPLICATION OF THE THERMAL-MECHANICAL CALCULATION RESULTS

The joint co-bending of the whole ensemble of FAs in the VVER-1000 reactor core may be calculated by the RRC “Kurchatov Institute” complex of codes consisting of the following codes: PULSAR-2 (fuel rods thermo-mechanics); UZOR-1 (spacer grid rigidity); Korall (fuel assemblies thermo-mechanics) and Labirint (in-core collective interaction calculation); or by the combination of codes TEREMOK-RENDEZVOUS developed by the IPPE [3,4]. With the calculation results available for neutron-physics and thermal-hydraulics characteristics of a fuel cycle as well as for the parameters of used FAs and reactor design, these codes may calculate three-dimensional distribution of joint co-bending of FAs in the investigated core. Figure 1 taken from the reference [3] presents the example of bowing of axes of FAs in one cross-section of the VVER-1000 reactor.

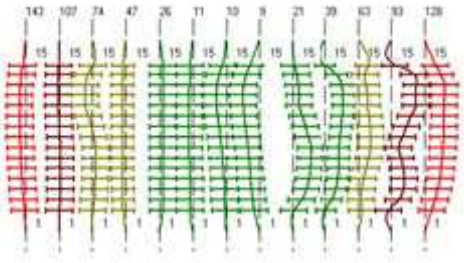

Figure 1. Example of the altitude distribution of deflection projection of a fuel assembly axis within a cross-section comprising axis of the most curved fuel assembly [3].

In the course of numerous calculations, it was established that FAs of the VVER-1000 reactor bend so that spacer grids relocate practically in one and the same plane, that is twisting of FAs is not observed. With this type of bending, gaps between FAs may only increase or reduce without changing their shape. The sizes of gaps vary along the core height achieving the maximum value in the cross-section close to the centre of that. Distribution of gaps between FAs in any chosen cross-section may be found with the help of described calculation codes. Figure 2 illustrates this distribution.

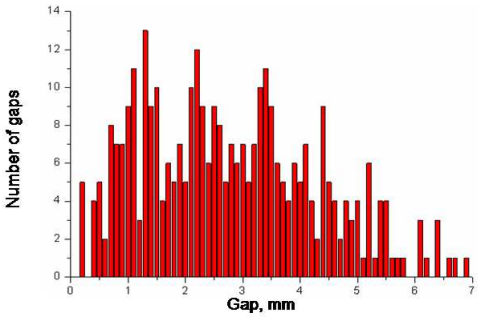

Figure 2. Example of distribution of gaps between FAs in the cross-section at the 50% height level of the VVER-1000 reactor core

The peculiar feature in the calculations of thermal-mechanical behavior of the FA ensemble in the core consists in the fact that this is a multifactor problem, and the system under investigation has a great number of degrees of freedom. The calculation result for the equilibrium position of all FAs in the core is sensitive to the variations of input data. In this case, the initial values of FA bows significant for the calculation are known only in the form of tolerances, that are the limiting values of some distribution. Therefore, the resultant calculated distribution of FA bows over the core volume is the realization of some random function. The analysis of a great number of similar realizations shows that the distribution along the gap size and the limiting values of this distribution are the same for all realizations.

This allows interpreting the result of a single thermal-mechanical calculation of gaps as the assessment of the probability to achieve the set value by the chosen gap. That is, the bar chart in Figure 2 after the appropriate normalization may stand for the distribution of a probability density of a single gap. From the plot of Figure 2 type, the limiting gap size may be determined which will be exceeded, for example, only in 5% of cases. This gap size may be used in the further evaluations of the margin factor if it is based on the principle of “95% probability”. Other approaches to the analysis of a single gap distribution are quite possible but the result as a whole will be the similar one.

3 THE METHOD OF NEUTRON CALCULATION, THE CALCULATION MODEL

Taking into account the special features of the effect under investigation precise MCU code [5, 6], a module code intended for the solution of heterogeneous transport equations for neutrons, photons, electrons and positrons by the analog and non-analog Monte-Carlo methods, was choosen for our calculations. For neutrons, the code also allows solving a homogeneous equation (problems of the criticality of systems multiplying neutrons), that is, the kinetic equation with the set boundary conditions is solved.

In the calculations by the MCU code, the DLC/MCUDAT database of nuclear-physics constants is used containing sections with the group and pointwise representation of neutronics constants which were formed on the basis of known libraries of evaluated data (for example, ENDF/B-VI) and of Russian data evaluations [7].

The MCU code geometric module allows modeling the systems of the practically arbitrary shape consisting of 3D elements. However, for the problem under consideration, a two-dimensional model was developed providing for the conservatism necessary degree. On developing, the opportunity was taken to preset periodic lattices produced by the multiplication of some initial elements set by the combinatorial analysis.

The chosen calculation model represents a cluster of 13 FAs of the VVER-1000 reactor with the boundary conditions of the mirror reflection at the exterior boundary. The model is presented in Figure 3. FAs are arranged in the cluster as in the VVER-1000 reactor core in the nodes of a hexagonal

lattice with a pitch of 236 mm. There are nominal gaps of 2 mm size between edges of FAs of 234 mm "turnkey" size.

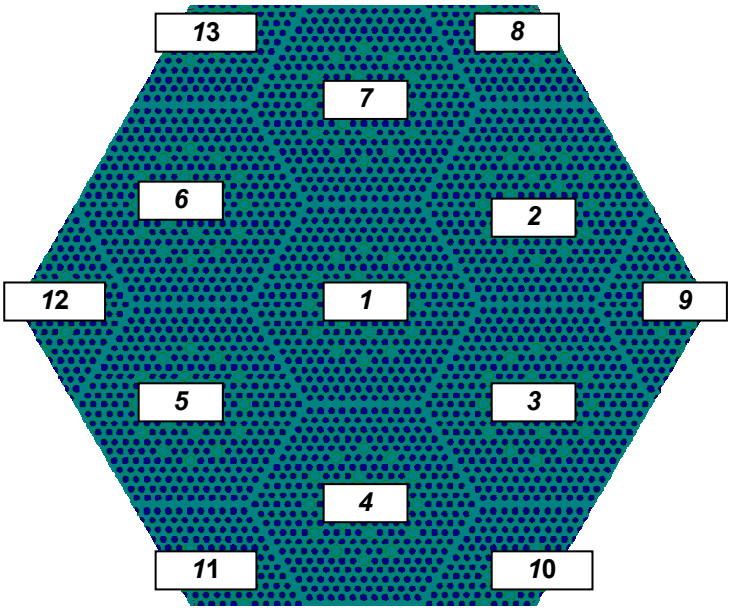

Figure 3. The calculation model to make evaluations by the MCU code

In the course of modeling, the critical problem is solved by the method of generations. Energy release is evaluated as a linear functional of a neutron flux

$$R_{18} = \int \Sigma_{18}(\mathbf{r},E)\, \Phi(\mathbf{r},\boldsymbol{\Omega},E)\, d\mathbf{r}d\boldsymbol{\Omega}dE,$$

where

$\Sigma_{18}(\mathbf{r},E)$ is a macroscopic cross-section of a nuclear reaction of fission either for an individual nuclide or for the whole composition in the given investigated area;

$d\mathbf{r}d\boldsymbol{\Omega}dE$ is the domain of integration in the phase space in which a particle coordinates are determined by the radius-vector r, by the rate direction Ω, and by the value of the particle energy E (this is a volume of each fuel pin in this model),

$\Phi(\mathbf{r}, \boldsymbol{\Omega},E)$ is the function of a particle flux distribution.

A typical number of investigated histories in the calculations of $3\div5\times10^7$ allowed obtaining of an acceptable level of the statistical error determined as a standard deviation $s = \sqrt{D}$ at the level of ~0.3% (D is a sample value of the variance of the random quantity used for the functional evaluation).

All functionals are normalized for the flux of one primary neutron in the generation.

4 THE CHOICE OF THE CONSERVATIVE OPTION

To determine the margin factors, it is assumed to use the model with the most conservative combination of parameters that means in this case the combination of parameters providing for the maximum possible increase of energy release on the variation of gaps between FAs. The employment of the model based on the conservative values of parameters also allows obtaining the results applicable for a wide range of fuel loadings.

The effect of different parameters is evaluated by the MCU code calculations within the calculation model (Figure 3).

4.1 Sizes and Geometry of Gaps

It is evident that the size of the gap between fuel assemblies (FA) is the most essential parameter effecting the variation of energy release in fuel pins of the FA under study. However, it was found out the positional relationship of gaps around the FA under study is also essential.

The preliminary analysis of results allowed selecting groups of fuel pins in which the energy release distortion is essential for the definition of margin factors. These are fuel pins of the peripheral row and of the second from the periphery row. In this case, the angle fuel pins in these rows and the rest fuel pins (to be called further as the “central” ones) should be investigated individually. The peculiar feature of angle fuel pins is associated with their location at the joint of three FAs, therefore, the coolant amount near these fuel pins is determined by sizes of three proximate gaps. The scheme of the joint of three FAs with to adjacent gaps increased presented in Fig. 4.

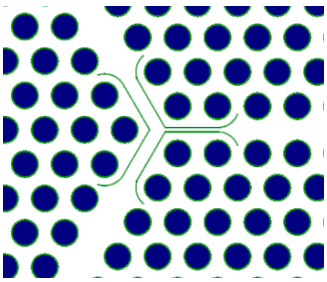

Figure 4. Scheme of three VVER FAs (TVSA type) joint area with two adjacent gaps increased

A series of calculations was performed in which sizes of gaps surrounding FA No.1 (Figure 3) were varied without any variations in the rest parameters. In this case, both practically observed unsymmetrical deviations of one or two adjacent gaps (Figure 5 and 6, correspondingly) were considered.

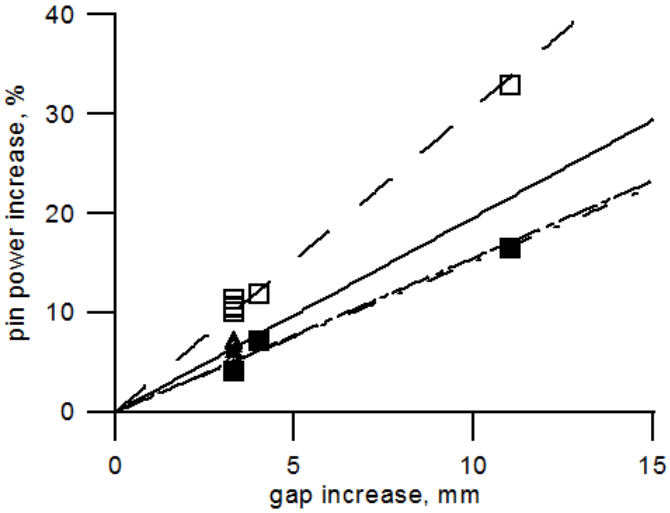

Figure 5. The effect of single gap size on pin power increase in chosen fuel pins (🗁 - peripheral row, corner pin; ☎ - peripheral row, central pin; 📎 - second row, corner pin; 🖂 - second row, central pin)

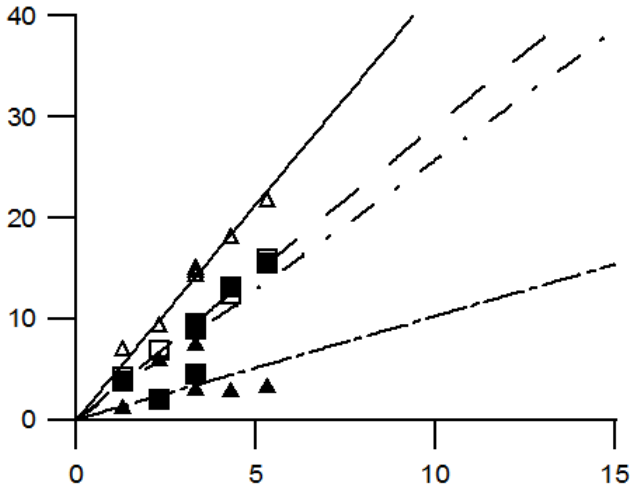

Figure 6. The effect of double gap size on pin power increase in chosen fuel pins (🗁 - peripheral row, corner pin; ☎ - peripheral row, central pin; 📎 - second row, corner pin; 🖂 - second row, central pin)

It may be reliably concluded from plots of Figure 5 and 6 that the increase of pin power burst is observed on the increase of the gap size (some deviation is observed in a series of calculations (b) of a double adjacent gap for fuel pins of the second row) within the range of practically implemented gaps for chosen fuel pins. The approximation of dependences in Figure 5 and 6 by straight lines coming from the point of origin in the range of gaps under investigation seems to be quite justified.

From the point of view of the highest increase of energy release, fuel pins of the peripheral row should be considered. Energy release in fuel pins of the second row is increased noticeably less.

We may conclude from the indicated above results that unsymmetrical geometries of gaps of the maximum possible values should be used in the calculations aimed at determining margin factors. Calculations for the central fuel pins should be performed with the increase of the single gap and for the angle fuel pins – with the increase of double gap.

In the course of real operation, adjacent gaps hardly increase equally. However, the results of calculations with the equal increase of adjacent gaps may be used if such a value as an combined

increase of adjacent gaps is employed. At the same time, both the combined increase of the double gap at adjacent edges and the triple gap at the joint of three FAs. Figure 7 presents calculated values of energy release increase in the angle fuel pin of the peripheral row (the same ones as in Figure 6) versus the combined increase of the double gaps.

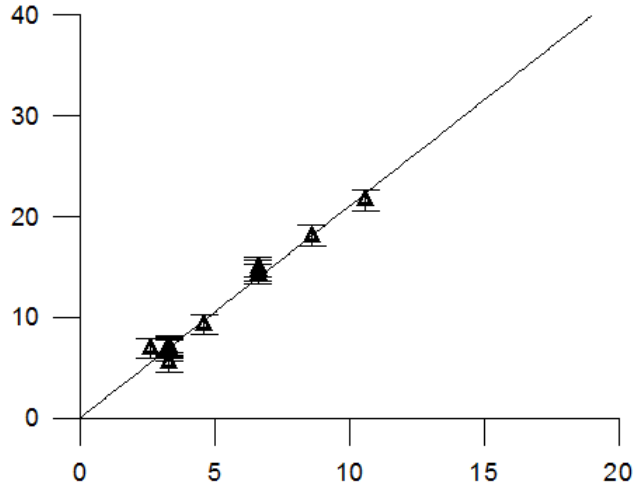

Figure 7. Pin power increase of the corner fuel pin of the peripheral row versus the combined increase of the double gaps

It may be concluded from the plots in Figure 7 that the dependence of pin power burst on the combined increase of the double gap is more reliable and this dependence is the linear one. with the double gap increase should be used.

It is necessary to point out that according to thermal-mechanical calculations, the gap between FAs may be also reduced down to zero. This results in energy release decrease in the chosen fuel pins as the appropriate calculations show. However, the results of these calculations are not presented in the plots, as energy release decrease does not effect the determination of margin factors. The use of those may be discussed in the assessment of coolant heating and of DNBR in the area of gaps' reduction.

4.2 Enrichment, Burn-up

The effect of enrichment on pin power burst with the variation of gap between FAs was studied in several series of calculations.

In the first series of calculations, the enrichment effect (with the rest invariable parameters) for the case of equal enrichment in all FAs in the calculation model (Figure 3) was investigated. Of course, the case of adjoined three and more fresh FAs of high enrichment is impossible in real fuel loadings, however, to reveal basic regularities and to obtain conservative results, this model justified. Figure 8 demonstrates the averaged results of this calculation series.

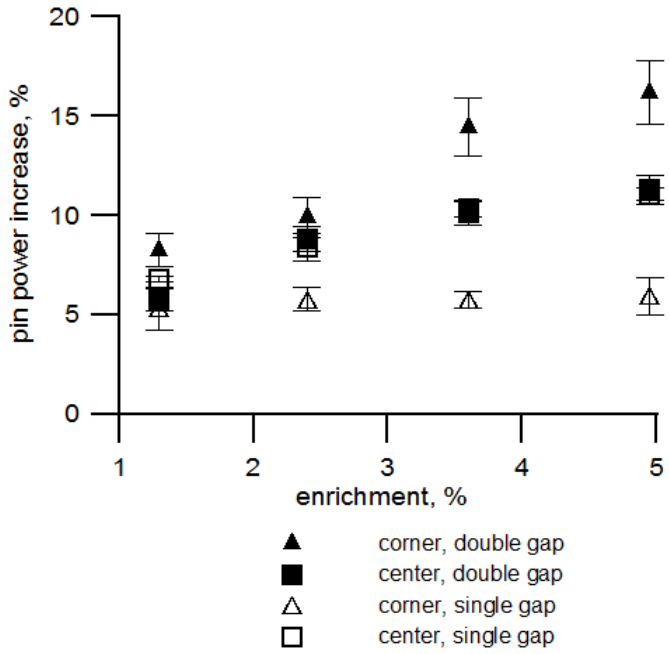

Figure 8. Pin power increase in fuel pins of the peripheral row versus enrichment of FAs (Enrichment of FAs is equal in this model)

The value of energy release in fuel pins of the peripheral row is increased with the enrichment increase though for high enrichments (>3%) this dependence is not so vital.

The similar conclusion may be made regarding burn-up. The increase of gap between the fresh and burnt-up FAs will result in the less effect than that occurring between two fresh FAs due to the less multiplication ability of burnt-up FA. Therefore, the use of the calculation model with all fresh FAs to estimate margin factor seems to be conservative.

The first fuel loadings of the VVER-1000 reactor represent the only case when three fresh FAs adjoin in one and the same junction, at the same time; their enrichment is most likely different. To analyze such cases as well as to seek the most conservative enrichment configuration, the following series of calculations was performed. Enrichment of all FAs in the calculation model was set equal (Figure 3) (3.6% and 4.95% in two series of calculations) and enrichment of FAs No. 2 and 3 was varied from 1.3% up to 4.95%. Figure 9 presents the calculation results for pin power burst in angle fuel pins of the peripheral row versus the average enrichment of adjoining fuel pins in the studied junction at the double gap increase. The available results for FA No.1 enrichments of 1.3% and 2.4% are also marked in the plot.

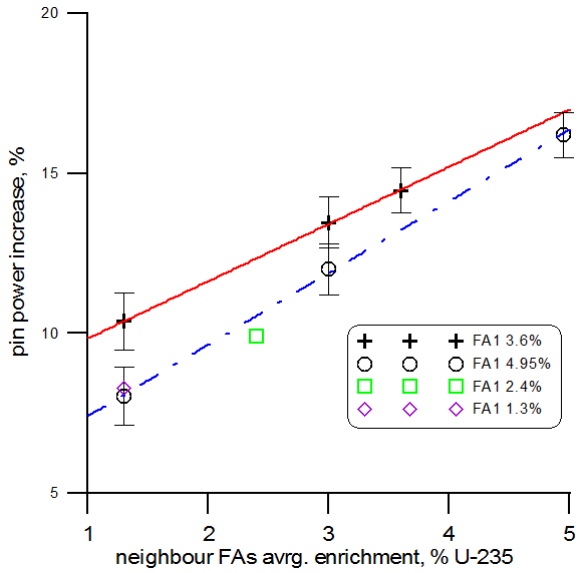

Figure 9. Pin power increase in the corner fuel pin versus the average enrichment of adjoining FAs

The highest energy release increase is observed in the case when enrichment of the central FA No.1 is not maximum possible and is equal to 3.6%, enrichment of adjoining FAs No. 2 and 3 is 4.95%. Therefore, to form the model for conservative calculations, just this enrichment configuration should be used.

4.3 The Coolant Temperature and Density, Boric Acid Concentration

The consistent variation of the coolant temperature and density in the gap between FAs affects the neutron spectrum and, consequently, energy release of fuel pins. Density effect on energy release variation at the gap size increase turned out to be less significant. In addition to that, the coolant density and temperature vary not much in the course of a normal operation. Therefore, it was decided to use in the calculations the values of temperature and density corresponding to average values of those over the VVER-1000 reactor core. In this case, the conservative deviation of integral active power and the coolant flow rate may be taken into account.

The presence of boric acid reduces the value of pin power burst near the gap between FAs. Besides, boric acid concentration is decreased in the campaign course down to zero. Therefore, a zero concentration of H_3BO_3 in the coolant was accepted as the conservative value.

4.4 May the Conservatism be Reduced?

The use of the calculation model based on the conservative values of parameters allows obtaining the margin factors covering assuredly all possible effects for a wide range of fuel loadings. On the other hand, the factor margins overestimated deliberately are not desirable from the point of view of flexibility in development of fuel cycles and in the NPP economy as a whole. To achieve the reasonable balance of the safety and economy interests, on the evaluation of margins, there may be a need to discard the “excessive” conservatism.

In this case, the model conservative combination of parameters may be revised aiming to abate those. It seems possible to eliminate the requirement of the simultaneous investigation of the model with all fresh FAs and with zero boron concentration as this combination is impracticable in real fuel loading of the VVER-1000 reactor. The use of a real value of one of these parameters (of course, the less influential one) may be quite sufficient.

The requirement for all FAs to be of high enrichment in the studied cluster is another conservative assumption, which may be discarded. As it was noted above, three fresh FAs might be located in one joint only at the first loading, in this case, their enrichment may not be the maximum possible one. The implementation of more realistic combinations of FA enrichments in the calculation model will allow discarding the excessive margins without a significant deterioration of the safety level.

Authors also consider the idea to use more accurate 3D Monte-Carlo calculations that involve information about axial distribution of the gaps. It seems such model will help to obtained less conservative results.

5 THE EXAMPLE OF THE MARGIN FACTOR CALCULATION

Let's give some results demonstrating the application of the described technique as an example. A fuel cycle was formed for one of new VVER-1000 reactors on the basis of FAs with reinforced frame. The patterns for reloadings were chosen, the preliminary characteristics (fields of energy release, of temperatures and so on) of fuel loadings were calculated from the first loading up to the steady-state one that is to be realized after the fifth reloading. These data were used in the thermal-mechanical calculations that allowed obtaining the distribution of single and double adjoining gaps at the most dangerous cross-section along the core height. These distributions are demonstrated in Figures 10 in the form of bar charts, 95% quantile limit are marked in each plot. According to the plots, 95% of single gaps are less than 5.0 mm and 95% of double gaps are less then 8.3 mm.

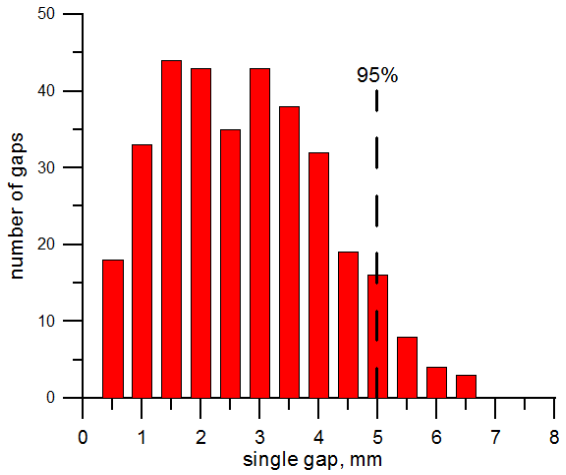

Figure 10. Distribution of single in the maximum cross-section at 50% height from the core bottom of the VVER-1000 reactor, steady-state fuel cycle.

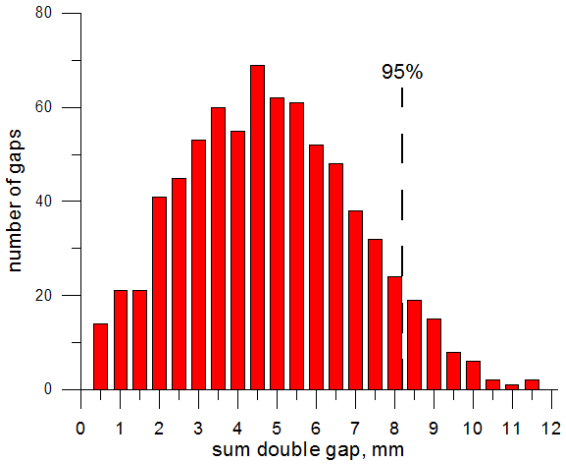

Figure 11. Distribution of sum double gap in the maximum cross-section at 50% height from the core bottom of the VVER-1000 reactor, steady-state fuel cycle.

Taking into account peculiar features of FA design a model was formed for the neutron calculations by the MCU code (Fig. 3). It is necessary to repeat these calculations for each fuel loading only in case of some FA design peculiarities. Dependencies for characteristic fuel pins are formulated according to results of a series of pin power calculations with different sizes and geometries of gaps. Figure 12 shows the plots of these dependencies for fuel pins of the peripheral row.

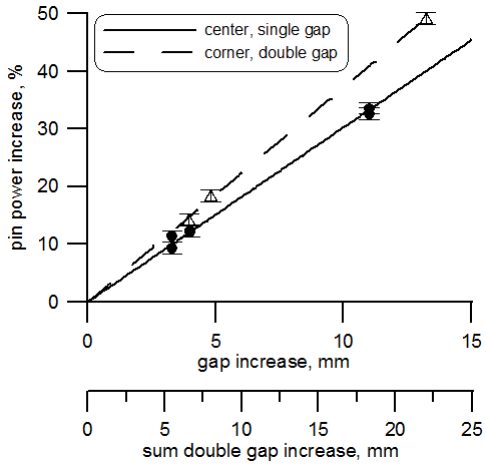

Figure 12. Pin power increase of the characteristic fuel pins versus the value of gaps between FAs

As it was established above, energy release varies most considerably exactly in fuel pins of the peripheral row on the variation of gap between FAs. Therefore, the calculation of margin factors according to the calculation results for the peripheral fuel pins and application of these factors also for fuel pins of the second row will be the most conservative approach. Here we will not go beyond this case.

According to the data of Figure 12 dependencies of pin power increase on the values of appropriate gaps are linear ones. Using a value of the single gap increase of 3.0 mm (5.0–2.0 mm) to

calculate the margin in the central fuel pins and that of 4.3 mm (8.3 – 4.0 mm) of the double gap for angle pins we obtain the following evaluations for ql = linear thermal loading:

$$\left[\frac{\Delta q_l}{q_l}\right]_{gap}^{center} = 9.1\ \%\quad \textit{or the margin factor}\ f_{gap}^{center} = 1 + \left[\frac{\Delta q_l}{q_l}\right]_{gap}^{center} = 1.091$$

$$\left[\frac{\Delta q_l}{q_l}\right]_{gap}^{angle} = 9.6\%\quad \textit{or the margin factor}\ f_{gap}^{angle} = 1 + \left[\frac{\Delta q_l}{q_l}\right]_{gap}^{angle} = 1.096.$$

While calculating net engineering margin factors for the VVER reactors, it is usually assumed that their components (the mechanical and methodical components are also included) are independent of each other, and each component is calculated based on the principle “95% of probability”. Then the use of the engineering margin factor calculated by the formula

$$F^{eng}(q_l) = 1 + \sqrt{\left(\left[\frac{\Delta q_l}{q_l}\right]_{gap}\right)^2 + \left(\left[\frac{\Delta q_l}{q_l}\right]_{mechanic}\right)^2 + \left(\left[\frac{\Delta q_l}{q_l}\right]_{method}\right)^2},$$

will provide for not exceeding of design limitations with the probability of 95% as it is accepted in the safety analysis.

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