Experimental Studies of Resistance Fretting-Wear of Fuel Rods for VVER-1000 and TVS-KVADRAT Fuel Assemblies

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Abstract

The paper covers the results of the studies performed to justify the wear resistance of fuel rods in contact with the spacer grids of TVS VVER-1000 fuel assembly and TVS-KVADRAT square fuel assembly of Russian design for PWR-900 reactor. The presented results of three testing stages comprise:

Testing of mockup fuel rods of VVER TVS fuel assembly for fretting wear under the conditions of the water chemistry of VVER reactor;

Testing models of different design embodiments of the fuel rods for VVER TVS fuel assembly for fretting wear in still cold water;

Testing mockup fuel rods of TVS-KVADRAT square fuel assembly for PWR reactor for fretting-wear under the conditions of PWR water chemistry.

The effect of structural and operational factors was determined (amplitudes, fuel rod vibration frequencies, values of cladding-to-spacer grid cell gap for the depth of fuel rod cladding wear etc.), an assessment was made of the threshold values of fuel rod vibration parameters, which, if not exceeded, provide the absence of the fuel rod cladding fretting wear in the fuel rod-to spacer grid contact area.

Key words: fretting wear, fuel rod, spacer grid, VVER, PWR

1. Introduction

The vibration loads a FA is subjected to in the course of reactor operation can cause anticipated operational occurrences and might even lead to radioactivity release through damaged fuel rod claddings. One of the main causes of the fuel rod damage ending up in coolant radioactivity and the personnel dose commitment increase, as well as FA unloading ahead of time is the fretting-corrosion of the fuel rod claddings under the spacer grids.

Despite the high achieved indices of FA reliability according to the international assessments the fretting-corrosion of the fuel rod claddings under the spacer grids is one of the main causes of FA damage in light-water pressurized reactors. The fraction of failures due to fretting-corrosion in the fuel rod-to-spacer grid mating units exceeds 50 %. One of the top priority directions in the zero failure concept is the assurance of FA fretting-wear resistance. In this respect one of the practical tasks in new FA designing is the assurance of their vibration strength at the stage of detailed project report elaboration on the basis of the criterion of no fretting-wear, since there are no failures caused by the cladding fatigue damage.

The paper covers the results of the studies performed to justify the wear resistance of fuel rods in contact with the spacer grids of TVS VVER-1000 fuel assembly and TVS-KVADRAT square fuel assembly of Russian design for PWR-900 reactor. The presented results comprise three different investigations:

- Testing the fuel rods of VVER TVS fuel assembly mockup for fretting wear under the conditions of the water chemistry of VVER reactor; [1];
- Testing models of different fuel rod design embodiments for VVER TVS fuel assembly to study the fretting wear in still cold water [2,3];
- Testing the fuel rods of TVS-KVADRAT FA mockup for PWR reactor for fretting-wear under the conditions of PWR water chemistry.

2. Experimental Studies of the Fretting-Wear Process of the Fuel Rod Cladding in Contact with the SG of VVER-1000 Advanced and Standard Fuel Assemblies

The purpose of the given work was to elaborate the methods of experimental studies, assess the margin of wear resistance of the fuel rod-to-SG mating units of different designs, determine the conditions of fretting corrosion-induced damage, rate of the process development, investigation of the mechanism of the fuel rod cladding wear in the spacer grids, comparison of the sensitivity of SGs of different designs to fretting-corrosion, obtaining of the assessments of the wear coefficients in zirconium-to-zirconium and zirconium-to-stainless steel friction pairs.

The experimental studies of fretting-corrosion were realized with specially developed models and investigation methods:

- A model of a 9-rod FA fragment to study the process of flow-induced vibration in longitudinal and cross flow;
- A model to study the process of fretting-corrosion of the fuel rod-to-SG mating unit specimens in standard coolant;
- A methods to determine such frequency response characteristics of a fuel rod as dynamic stiffness, determined as transverse force (per a unit of motion) applied to the middle of the fuel rod span depending on the frequency. The frequency response characteristics are used as the criterion of dynamic similarity of the dummy fuel rod to a standard one.

In the course of the studies of the flow-induced vibration the dependences were determined of the fuel rod vibration versus the rate of the longitudinal-transverse flow, the structural and process parameters of the design.

The maximum root-mean-square values of the measured parameters at longitudinal-cross flow at the cross-flow rate of 1,4 m/s did not exceed:

- 5,3 m/s^2 – vibration acceleration of the fuel rod at the level of the grids;
- 6,1 m/s^2– fuel rod vibration acceleration at the level of the middles of the spans between two adjacent spacer grids;
- 41·μm – fuel rod vibration-induced movement;
- 26·μm – spacer grid vibration-induced movement.

The values of the vibration accelerations of the middle of the fuel rod spans obtained at the instrumentation-equipped FAs in the course of the commissioning tests did not exceed 1 m/s^2.

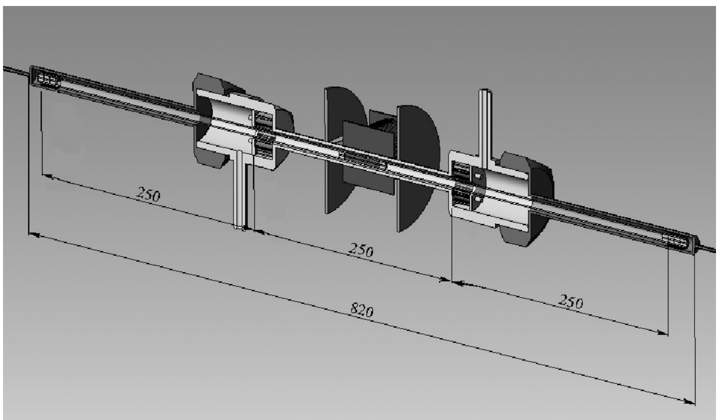


Figure 1. Model to investigate fuel rod cladding fretting wear.

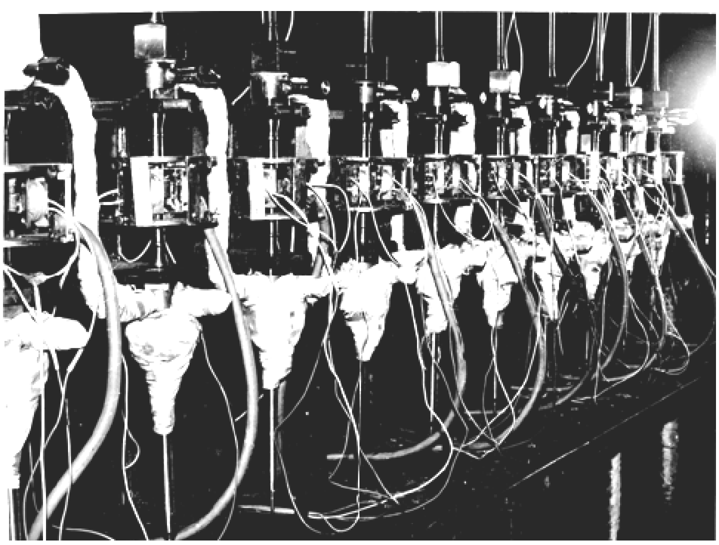


Figure 2. Models installed in the test bench

Figures 1 and 2 show the scheme of the fuel rod model and 10 models mounted on the test bench specially built to study the fretting-corrosion of the fuel rod cladding. The model contains a three-span fuel rod specimen, a casing, spacer grid fragments, electromagnet shaker. A fuel rod specimen contains a fragment of a standard cladding, molybdenum pellets, ferromagnetic insertion and accelerometer. The electromagnet shaker fastened on the external surface of the casing with the control unit generates an alternating magnetic field at assigned frequency and amplitude which, when interacting with the ferromagnetic insertion, generates an alternating transverse force applied to the middle of the middle span of the fuel rod specimen. The vibration of the specimen leads to relative vibration-induced displacements and specimen turnings relative to the mating spacer grid elements. The vibration accelerations of the middle of the span of the specimen are controlled in two mutually perpendicular planes with two-component accelerometer. The quality (water chemistry) of the coolant (temperature, composition, velocity of flow) is close to standard.

Two stages of endurance tests were performed on the 10 fuel rod models, each stage in the scope of 750 hours with 20 specimen pairs tested. At the first stage specimens of standard stainless steel grid were installed in the model in a pair with a zirconium spacer grid of UTVS-type fuel assembly. Vibration parameters (amplitude and frequency of vibration accelerations of forced oscillations) varied. In the course of inspection on 19 pairs of the fuel rod specimens and spacer grids with vibration acceleration levels up to 30 m/s^2 in the fuel rod-to-spacer grid mating units both with interference fit and with a gap no wear was detected, except for traces of contact. One fuel rod specimen mated with a gap at vibration acceleration not less than 30 m/s^2 there was actually complete specimen wear both on the par t of the stainless SG and on the part of the zirconium SG. Figure 3 shows a worn specimen of the post-test fuel rod cladding. The worn traces reproduce the geometry of the bulgings that are a transverse support of the fuel rods as it passes the SG cell. The central cell of a seven-cell specimen of the zirconium SG was worn till destruction and major wear was also observed on the central cell of the stainless steel specimen. By the test results a conclusion was made that the conditions sufficient and necessary for fretting-damage to appear are the vibration acceleration levels that exceed 30 m/s^2 and the presence of play in the fuel rod-to-SG mating units. No wear in 19 pairs of specimens at fuel rod-to-spacer grid mating both with gaps and with interference fit show that even very high vibration levels (up to 30 m/s^2) do not lead to fretting-wear. Therefore, the parameters that control the fretting-wear are the value of vibration acceleration in the middle of the fuel rod span. The conclusion was made by analogy with the one previously made by the results of testing the steam generator tubes with liquid-metal coolants for vibration wear.

Considering the maximum measured levels of fuel rod vibration acceleration at FA mockups in the course of commissioning tests at a NPP (up to 1 m/s^2) and experimental studies of the nine-rod model (up to 6,1 m/s^2) it is evident that the tested specimens of fuel rod mating with zirconium and stainless steel SG possess sufficient margin of stability against vibration and fretting-corrosion.

One of the main requirements for the FA design is the assurance of the fuel rod mating with the SG without considerable relative vibration-induced displacements during the entire service life of the FAs at vibration loads created by the reactor plant. As these two conditions change the FA shall be experimentally checked up for resistance to fretting wear.

The materials of the fuel assemblies in the form of specimens were tested for fretting-wear in 5 models with fretting-wear contact of 2 pairs of the specimens from standard materials under standard conditions of coolant water chemistry (temperature, composition, flow velocity). The specimens were the fuel rod cladding parts about 40 mm long. The mating specimen was cut out of a standard SG cell (a bulging in contact with the cladding) or turned from the SG material in the form of a finger with a flat edge contact surface. The controlled parameters of the endurance tests were the amplitude and frequency of relative displacements of the specimen and its mating part, the normal constant contact force. In the course of the tests part of the fuel rod cladding specimens was damaged, some of them up to through penetration of the cladding specimen wall. Some specimens were not worn which corroborates the conclusions on the existence of the threshold values of vibration-induced displacement amplitudes and contact pressures below which the rates of fretting-wear are insignificant and are technically acceptable. Metallographic studies of 17 pairs of fuel rod and SG specimens have shown that the microstructure of the material of which the specimens were manufactured was not damaged; the layers deep under the wear platforms were not deformed. The dependences of the wear depth versus time at the stage of wear-in were of parabolic nature and later they became linear with constant wear rate. The wear rate in the fuel rod cladding specimens in friction pairs E110/E110 and E110/08X18N10T was the same and the wear rate of the mating specimens from steel 08X18N10T is by an order smaller than the mating specimens from E110 alloy. By the results of the profile metering and metallographic studies a conclusion was made that the wear mechanism in zirconium-stainless steel and zirconium-zirconium are different with the processes of adhesion prevailing in the pair E110/E110 and corrosion-mechanical wear in

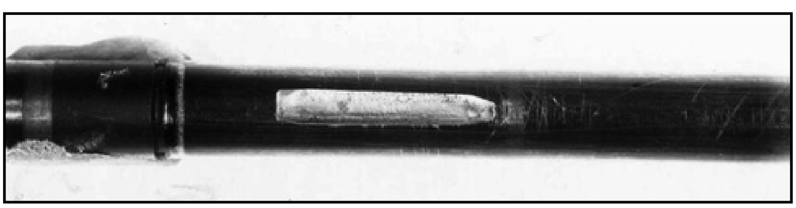


Figure 3. Worn specimen of fuel rod cladding

the pair E110/08X18N10T. By the test results the assessments of the wear coefficient were made by Archard formula for material pairs E110/E110 and E110/08X18N10T, that can be used in design development activities for the calculational assessments of the wear intensity of components made from these materials.

3. Experimental Studies of Dynamic Characteristics of Failed Fuel Rods and Endurance Vibration Tests of Fragments of a Fuel Assembly Lower Part with Unfastened Fuel Rods

At the end of the 90-s – beginning of 2000-ies there were incidents of loss of fuel rod fastening in the lower grid, which caused the wear of the lower fuel rod plugs at two NPP units with VVER-1000. In the units of fuel rod fastening in the lower grid that became loose the dovetail connection was used. The dovetail connection unit was modernized to increase the fuel rod longitudinal fuel rod fastening by introducing the conical recess on the fuel rod lower plug. Also a number of fuel assembly designs were developed with collet-type fastening units and also without longitudinal fuel rod fastening.

Within the framework of the advanced fuel rod design free from fastening in the lower part of the support grid comparative tests of FA lower part fragments of the available and advanced designs were performed. The tests contained two stages:

- determination of the natural frequencies of vibrations and fuel rod dynamic stiffness in different design versions of the lower spans;
- a study of vibration wear in the place of fuel rod-to-spacer grid cell contact.

The investigations of the dynamic characteristics (natural frequencies and dynamic stiffness) were performed on a vertically installed FA mockup in the air at (20±3) °C. The dynamic characteristics were determined in the three lower spans of 9 periphery fuel rods both fastened inside the lower grid and shifted upwards from the initial position by 25, 50, 75 and 100 mm (without fastening in the lower grid).

The frequencies of spans No. 3 (SG number counting from the bottom) with the fuel rod extraction from the lower grid actually did not change (Figure 4). Some of the fuel rods in span No.3 experienced the excitation of vibration with frequencies of about 200 Hz, typical of the second span, but with an amplitude lower by an order than the amplitude of the harmonics characteristic of span No.3. Therefore, the vibrations of each span are weakly transferred to the adjacent spans.

It was found as a result of the investigations that the absence of the support in the lower grid reduces several times the natural frequencies and dynamic stiffness of a fuel rod in the lower span a few scores of percent in the second span and does not influence the dynamic characteristics of the third span. As the length of the console section of the fuel rod below SG1 varied within 0 to 75 mm the change in the dynamic characteristics in all the spans is comparable with the error of their determination.

In the course of the comparative accelerated endurance vibration tests the fragments of the standard FA lower part fastened in the lower grid were tested along with the advanced (fastening-free) FA design. The fragments of the FA lower part for vibration endurance tests (Figures 5 and 6) included fuel rod dummy, three or four SG cells and lower grid dummy for the models with the fuel rod installed into the lower grid. The fuel rod dummy is a fragment of the cladding with the lower plug

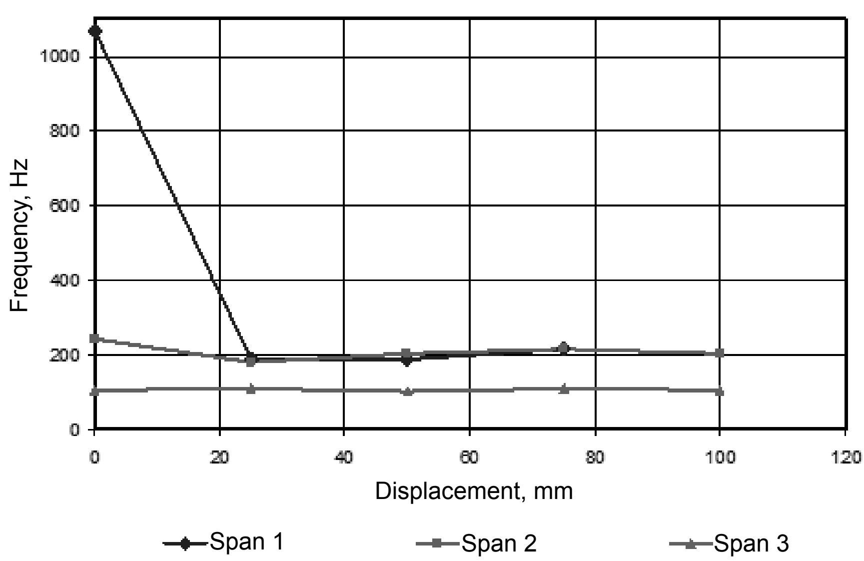


Figure 4. Dependences of natural frequencies of fuel rods on the value of displacement upwards

filled up with mockup lead fuel pellets to model the linear mass of the fuel rod. The lead pellets were compressed by the upper plug connected to the cladding with welding.

The tests were carried out on the fragments of the FA lower part on four design versions. Two types of fragments (version 1 and 2 in Figure 5) were not fastened in the lower grid and had the length of the console span below SG1 of 45 and 55 mm, respectively. The fuel rod with the consol span 45 mm long was in the standard position, the console span 55 mm long corresponded to the lower utmost position of the rod. In the specimens of type 3 the fuel rod was installed into the lower grid without the longitudinal fastening. Version 4 deals with the specimens that have passed the tests within the framework of the activities on TVS-2M that had collet fastening units in the lower grid.

In the course of the tests the model was loaded with inertia loads that considerably exceeded the in-vessel loads in order to obtain considerable wear within the acceptable time lag. The tests were performed in still water at (20±3) °C at the test facility in Figure 7. The model, covered with a plexiglass cover was filled up with water, the fuel rods were installed in the model vertically, the vi-

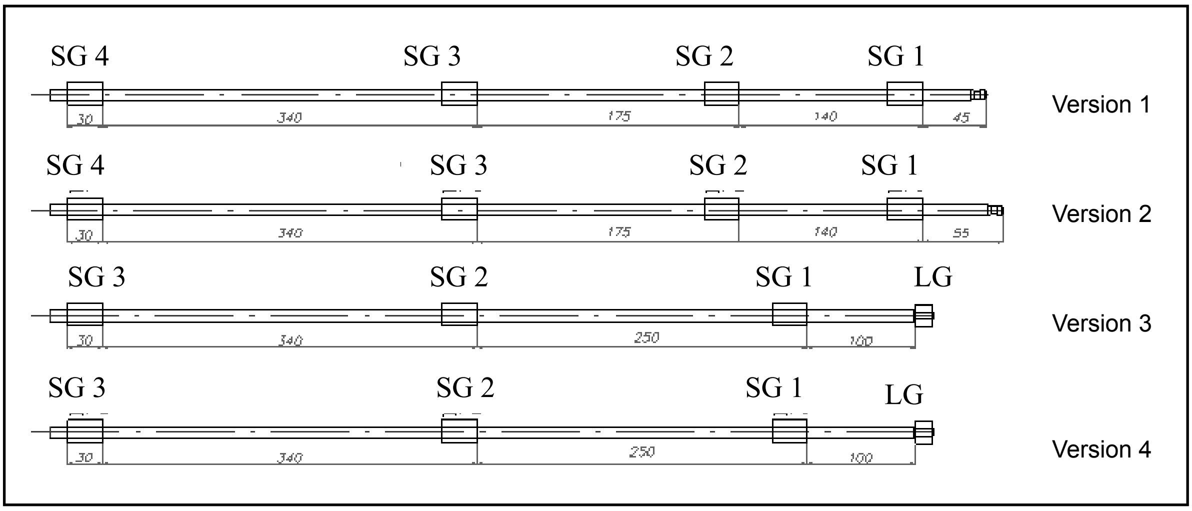


Figure 5. Fragments for vibration endurance tests

1 – plate; 2 – fuel rod dummy; 3 – pipe-sleeve with SG cell; 4 – stop; 5 – lower grid dummy

Figure 6. Model for endurance vibration tests of the FA lower part fragments

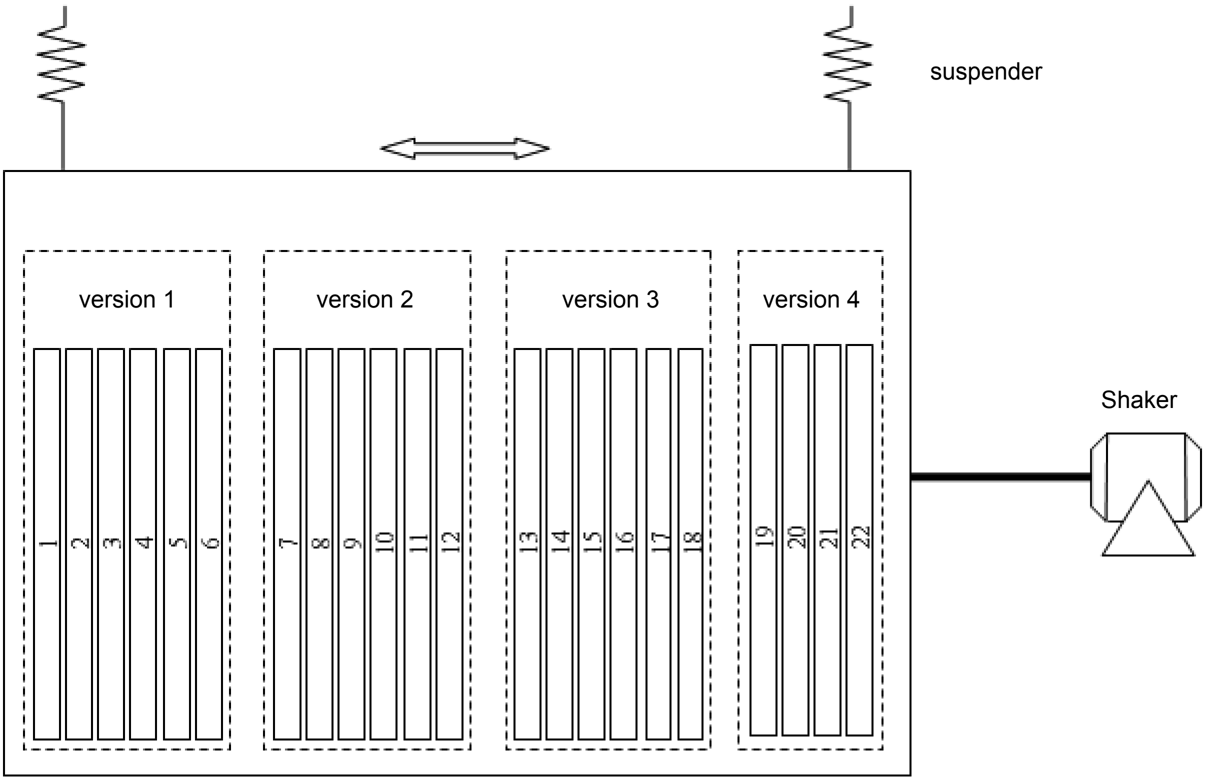


Figure 7. Test bench and model scheme

bration load was applied in the horizontal direction. The tests comprised four stages 50 h long each, after each stage was over there was a check of the play in the in the fuel rod-to-cell contact area and random (100% after the last stage) profile metering of the contact areas with laser profile meter. In the course of the tests the vibration frequency was assigned equal to 16,5 Hz (the rotation frequency of VVER-1000 reactor coolant pump) the amplitude of the model acceleration was up to 21 m/s^2, which is by an order higher than the level measured at the power units in the course of commissioning tests.

In the course of the studies wear curves were obtained (the dependence of the wear depth of the fuel rod cladding and SG cells on the quantity of the loading cycles) for the specimens without fuel rod fastening and the earlier wear curves for the specimens fastened inside the lower grids obtained within the framework of TVS-2M validation studies, were also complemented and specified. After the accelerated cladding wear tests the wear was observed in 141 out of 222 (64 %) units of fuel rod-to-bulging contact. The maximum wear depth was 0,34 mm. The largest number of the contacts with wear were observed under the SGs that limit the 340 mm span.

Thus, it is seen that even in the absence of fuel rod fastening in the lower grid the fuel rod cladding wear remained considerably less than in the middle FA spans 340 mm long. At this, the dynamic stiffness and natural frequencies of the console ends of the fuel rods in the lower span as well as the degree of fuel rod cladding and SG cell damage actually do not depend on the length of the console ends. For the justified conclusion on the resistance to fretting-wear it is necessary to perform fuel rod testing without fastening in the lower grid under the conditions of standard water chemistry since the wear mechanisms at 20 ^oC and 320 ^oC in standard coolant flow are different.

4. Experimental Study of Vibration and Fretting-Wear of Fuel Rods in FA-KVADRAT Fuel Assembly

The work was carried out in order to validate the resistance to fretting-wear of the fuel rods in TVS-KVADRAT of Russian design. Brand new engineering judgment was used in the TVS-KVADRAT design as well as new water chemistry typical of PWR-type reactors. In this respect the investigation program included two stages:

- a study of flow-induced vibration of fuel rods

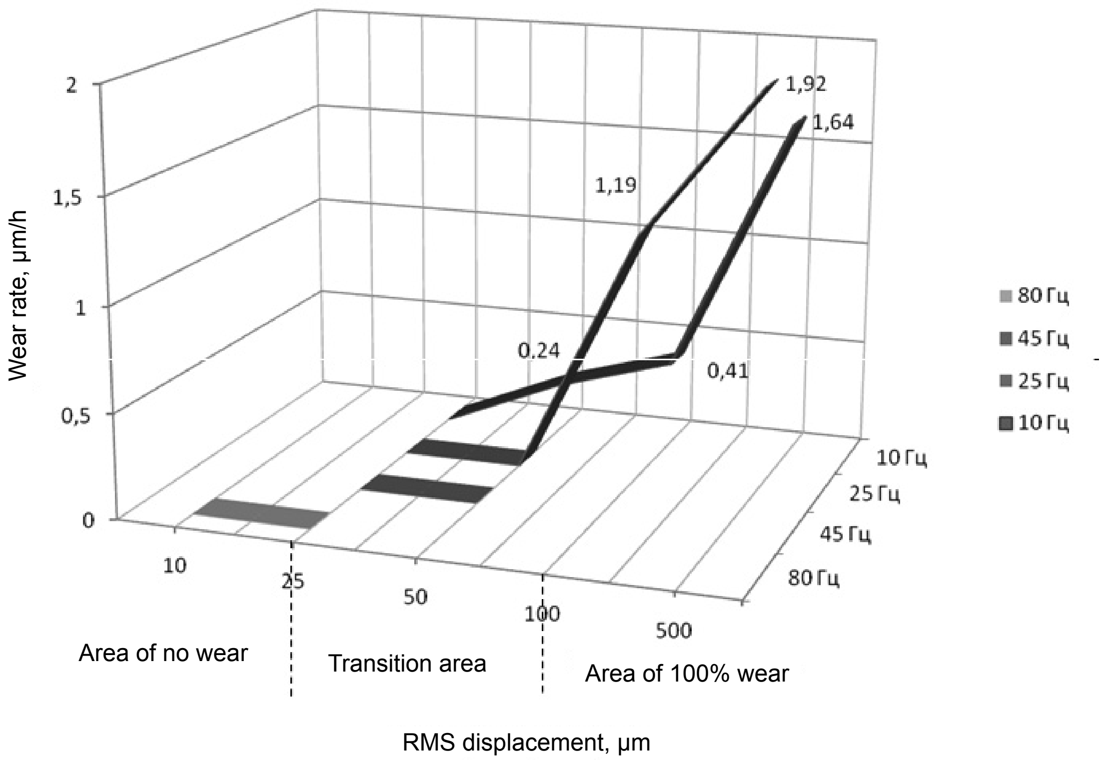


Figure 8. Dependence of the average wear rate versus RMS displacement

as a part of a full-scale mockup at thermal-hydraulic parameters of coolant close to the parameters of normal operation of PWR reactor;

- determination of the boundary of fretting-wear by the results of long-term tests of three-span models of TVS-KVADRAT fuel rods using the electromagnet way of inducing transverse vibration and at thermal-hydraulic parameters of coolant close to those of PWR reactor normal operation.

Due to the unavailability of the information on the levels of fuel rod vibration in PWR-900 reactor, the vibrations of TVS-KVADRAT fuel rods were measured in a single-assembly test bench of hot run in coolant flow at the parameters close to the reactor ones. In the course of the investigations the following tasks were being solved:

- determination of the acceleration of the middles of the fuel rod spans at vibration flow-induced vibration;
- determination of the effect of the thermal-hydraulic parameters of coolant (temperature, flow rate, dynamic pressure) on the vibration response of fuel rods;
- determination of the effect of the lengths of the spans on the vibration level.

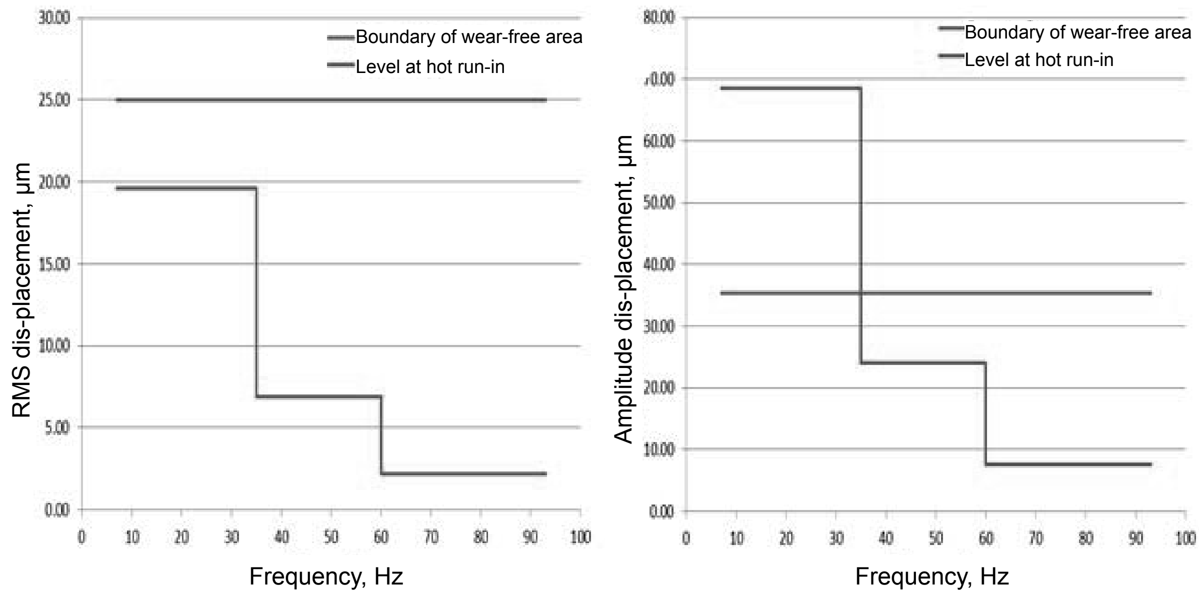
The source of vibration in the longitudinal flow of coolant were the hydrodynamic instabilities of the flow created by the circulation pump, acoustic vibrations and flow turbulence as well as cross-flows.

By the results of the first stage of the full-scale TVS-KVADRAT mockup the levels of fuel rod vibrations were determined under the thermal-hydraulic parameters of coolant close to standard for PWR reactor and also the effect of the structural and process factors on the level of the vibrations.

The tasks of the second stage of the studies were:

- the determination of the effect of the amplitude, frequency of fuel rod vibration on the wear depth of the fuel rods at standard coolant parameters;
- assessment of the threshold value of vibration displacement depending on the frequency of fuel rod vibration which, when exceeded develops the vibration-induced cladding wear.

The studies were performed in the test bench areas dedicated to corrosion-resistance study. The main investigation area components are: a section of the hydraulic circuit, fuel rod dummies, vibration loading system and vibration measurement system. The scheme of the model is similar to the one presented in Figure 1.



a b

a - Diagram of the level of fuel rod vibrations and boundary of wear-free region (based on RMS values)

b - Diagram of the level of fuel rod vibrations and boundary of wear-free region (based on amplitude values)

Figure 9. The boundary of the wear-free area and the level of the fuel rod vibrations of TVS-KVADRAT mockup at a single-assembly hot run-in test bench

The endurance tests of the dummies were performed at water circulation through the fuel rod dummies with the parameters maintained close to the standard ones for a PWR reactor. The tests were planned to be performed in two stages, each stage lasting 750 h. Due to the wear of the specimens and further loss of the dummy tightness the first stage was reduced and only lasted 127 h.

To study the fretting-wear processes the frequency interval up to 200 Hz was divided into four ranges: 7-15 Hz, 15-35 Hz, 35-60 Hz, 60-200 Hz. The first two ranges contain the frequencies of acoustic standing wave and rotation frequency of the circulation pump. The last two ranges contain natural frequencies of the spans 394 mm and 522 mm (the second and the third spans from the bottom, respectively). Broad-band vibration in the indicated ranges was replaced by the vibration equivalent at recorded frequencies out of these ranges. The selected frequencies were: 10 Hz (close to the frequency of the standing acoustic wave), 25 Hz (rotation frequency of the circulation pump), 45 Hz (natural frequency of the 522-mm span), 80 Hz (natural frequency of the 394-mm span).

At the first stage the variable parameters included the distance between the bulgings, however, no dependence of the wear rate on the factor was observed and at the second stage the distance was set in the same range for all the models.

By the results of the tests for each "frequency-amplitude" combination the wear ranges average in all the contact units were determined. Figure 9 provides the dependence of the average wear rate versus the RMS displacement for frequencies 10 Hz and 25 Hz. It is seen in the plot that at RMS displacements less than 25 µm there is no specimen wear. The area of 100% can be found at RMS displacements above 100 µm. The transition area is in the range from 25 µm to 100 µm.

On the basis of the values of displacement of the dummy span middle parts that left no wear, the boundary of the absence of wear was plotted. Taking into account the fact that at testing the TVS-KVADRAT in a single-assembly hot run-in test bench the vibrations were of random nature and the amplitude values of the displacements are 3,5 times as large as the root-mean-square values and at testing of the dummies the excited vibration was to the law of sines and the amplitude values are 1,41 times as large as the root-mean-square, a comparison of the levels of displacements was performed by both the root-mean-square and by amplitude values.

The flow-induced fuel rod vibrations (in anti-fretting grid-to-SG1 (394 mm) and SG1-SG2 (522 mm) spans) are at frequencies close to natural and are observed in the frequency ranges from 80 to 90 and from 45 to 60 Hz, respectively. In these ranges the signal/noise ratio is acceptable and allows estimating correctly the level of fuel rod vibration. In the other part of the spectrum the level of the noise is comparable with the level of the measured signal. In this respect the curve of the level of vibrations in the single-assembly hot run-in test bench at frequencies below 20 Hz was assumed conservatively by the integral level of displacements (RMS value of the time signal in the entire frequency band was assumed), and at frequencies 45 Hz and 80 Hz was reduced to the frequency, as the main contribution into the integral level of displacements was made by the noises at low frequencies.

Figures 9 provides the boundaries of the wear-free region and the level of the fuel rod vibrations of the TVS-KVADRAT mockup at the single-assembly hot run-in test bench in root-mean-square and amplitude values.

Within the frequency ranges 35-60 Hz and 60-200 Hz the margin for the level of the fuel rod vibration in TVS-KVADRAT as far as the wear-free region is 1,5 and 4,6 times, respectively.

To justify the vibration strength of the TVS-KVADRAT in the range below 35 Hz it is necessary to specify the data on the level of flow-induced vibration of the fuel rods in this range. The purpose can be reached by applying the measurement channels with the level of the noise of the order of 0,01 m/s^2. By the available experience in vibration measurement the level of noise can be reached due to the application of the piezoelectric accelerometers.

It is worth emphasizing that the known calculations are not convincing enough. For example, the attempts of a comprehensive description of the process of fretting-corrosion /3,4/ resulted in intricate formulae poorly applicable for practical use. The only and widely known Archard formula (or its modification Preston formula) is simple and explicit since it connects the value of wear with the work of the friction forces (or the wear rate and friction power), but the dimension of the wear coefficient considerably limits its application. Besides, the main parameters of the formulae, the relative displacement and contact force are difficult to determine. The experimental modeling of FA fragments providing similarity and transportability of results on a standard FA is nowadays an only way to give the designer the obvious and reliable data that allow coping with fretting-wear. A similar method is applied world-wide /5/.

5. Conclusion

The paper covers the results that accumulate the experience of operation of OKB “GIDROPRESS” in the area of investigation of the fretting-wear of VVER-1000 FA fuel rods:

1. Methods were developed and investigations carried out of the process of fretting-corrosion of the structural materials and the fuel rod-to-spacer grid mating units by physical modeling under the conditions close to standard. It was experimentally proven that the tested designs of the fuel rod-to-spacer grid mating units of the advanced FA for VVER-1000 possess a sufficient margin of vibration strength at operation under design-basis conditions.

2. The fragments of the fuel rod-to-spacer grid mating units for the FA design with fuel rods free from fastening in the lower grid with the console rod section from 0 to 100 mm long tested in still water have shown a considerable specimen resistance to fretting. For a founded conclusion on the resistance to fretting-wear under standard conditions it is necessary to test the FA of this design under the conditions of standard water chemistry since the wear mechanisms at 20^{o}C and 320^{o}C are different in the standard coolant flow.

3. In the course of the experimental studies of the fuel rod vibration and fretting-wear in TVS-KVADRAT an up-to-date testing methods was developed and experimental data obtained that were required for the verification and specification of the mathematical model of fretting-corrosion of the fuel rod claddings in contact with the SG. Vibration strength of TVS-KVADRAT was justified in the frequency range above 35 Hz.

4. The method of experimental physical modeling of fretting-wear in FA fragments providing similarity and transportability of results on a standard FA gives the designer the obvious and reliable knowledge that allows successful coping with fretting-wear.

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Abbreviations

NPP -	Nuclear power plant
VVER -	Water-cooled and water-moderated power reactor
RCP -	Reactor coolant pump
SG -	Spacer grid
RMS -	Root-mean-square value
FA -	Fuel assembly
TVS-KVADRAT -	Fuel assembly for PWR reactor
UTVS -	Advanced fuel assembly
PWR -	Pressurized Water Reactor
LG -	Lower Grid