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FEATURES OF FUEL PERFORMANCE AT HIGH FUEL BURNUPS

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ABSTRACT

Some features of fuel behavior at high fuel burnups, in particular, initiation and development of rim-layer, increase in the rate of fission gas release from the fuel and increase in the inner gas pressure in the fuel rod are briefly described. Basing on the analysis of the data of post-irradiation examinations of fuel rods of VVER-440 working FA and CR fuel followers, that have been operated for five fuel cycles and got the average fuel burnup ≈ 50 MW·day/kgU, a conclusion is made that the VVER-440 fuel burnup can be increased at least to average burnups of 55-58 MW·day/kgU per fuel assembly.

Calculation results for fuel rods of VVER-440 FA intended for six year operation are given. For the analysis the hottest fuel rods were chosen. The calculation was carried out by the TOPRA code with a significant degree of conservatism. It is shown that the fuel rods of these FA remain fully available.

The studies show the possibility of ensuring the availability of VVER-440 fuel rods intended for six fuel cycles.

INTRODUCTION

In connection with the transition to the five- and six-year fuel cycles the reaching of superhigh fuel burnups, up to 60-64 MW·day/kgU over a fuel pin and higher are now expected. Therefore forecasting of the characteristics of fuel pin behavior at these fuel burnups is important, and first of all for fission gas release (FGR) from the fuel. The FGR from the VVER fuel pins to the cladding wall at fuel burnups exceeding ≈ 45-50 MW·day/kgU over a fuel pin is mainly of adiathermal character. This release is associated with the formation and development of surface the so-called rim-layer whose width and porosity increase with fuel burnup.

In [1] it is said, concerning the FGR from the fuel pins with superhigh fuel burnups: "With the rate of FGR from the fuel maintained at ~ 2.5% per 10 MW·day/kgU with the range up to 75 MW·day/kgU, the FGR will not exceed 10% and the inner gas pressure in the fuel rod will not reach critical values. However the supposition on the above mentioned dependence of gas release on fuel burnup at values exceeding 55 MW·day/kgU needs an experimental support. Proceeding from the assumption that the FGR from VVER fuel pins to the cladding wall is mainly due to adiathermal mechanisms and, first of all, to the release from the rim-layer, the increase in the FGR with increased fuel burnup can be forecast.

As at present no data on the FGR from the VVER fuel pins with superhigh fuel burnups are available, the information on the FGR from the fuel of such fuel pins becomes important. In addition to the analysis of experiments performed on the MIR and MR reactors and foreign data, the information on the behavior of just the normal VVER fuel pins (with their power, operation conditions and neutron spectrum). The post-reactor rests of VVER fuel pins having the fuel burnup 65 MW·day/kgU over the fuel pin allow the necessary information on the FGR to be obtained. This information can be used for substantiation of the availability of fuel pins intended for operation up to the superhigh fuel burnups, by generalizing the data of post-reactor tests and verification of calculation codes including refinement of the models of adiathermal FGR.

In the present report the data used in the substantiation of the possibility of pilot operation of fuel assemblies up to fuel burnups 58 MW·day/kgU are given. The substantiation was performed basing on:

- generalization of the data of operation and post-reactor tests of VVER-440 fuel pins and fuel assemblies having worked for five years (including the comparison of these data with those for the fuel pins having lower fuel burnups) and forecasting of serviceability of VVER-440 fuel pins intended for the pilot operation for six years;
- calculation substantiation of serviceability of these fuel pins (check of meeting the criteria of thermal-physical serviceability under normal operation conditions).

By the present more than seven million fuel rods had been tested in the VVER-440. Fuel burnups higher than 50 MW·day/kgU on the average in the fuel assemblies were reached. In the period 1993-1998 the fraction of damaged fuel pins was on the average (1-1.3) $x10^{-5}$ per one fuel cycle, and in some years – $5x10^{-6}$ [2]. It should be noted that among the causes resulting in fuel pin failure there were practically no causes of technological character. This can be due to both the design technological approaches used in the development of fuel pins, and, first of all, to the central hole provided in the fuel pellet and facets at its ends, and due to the properties of zirconium alloy used for the fuel pin claddings, which demonstrated high corrosion resistance and mechanical strength. The VVER-type fuel pins were tested and are being tested in the MR, MIR and HBWR (Norway) reactors when fulfilling a number of experimental programs (SOFIT-1, RAMP, FGR-1&2, IFA-503, 1&2 etc.).

For the VVER fuel pins there is a large set of data on post-reactor in-chamber investigations and tests of spent fuel, performed on the research reactors and high-temperature test facilities. Up to 1987 fragments of fuel pins and elements of fuel assemblies had been tested in the protection chambers. Since 1987, upon starting-up a specialized complex of post-reactor tests of fuel assemblies [1], eight VVER-440 and 20 VVER-1000 fuel assemblies (in all about 7000 fuel pins) with the maximum fuel burnup per fuel pin up to 50 MW·day/kgU have been tested. The pilot fuel pins produced from the normal ones having a high fuel burnup, which upon prefabrication were burnt up to high fuel burnups in the MIR reactor were also investigated. This level of tests representation permits a sufficiently full picture of the states of fuel pins and fuel assemblies at average fuel burnups per fuel assembly up to 50 MW·day/kgU and higher upon their operation in the VVER reactors to be obtained.

The experience of operation, data of post-reactor tests and calculations make it possible to forecast with sufficient certainty that the VVER fuel rods would remain available in the increase in the fuel burnup average per fuel assembly up to 55 MW·day/kgU and higher. The post-reactor test data show that with increase in the fuel burnup:

- the mechanical properties of claddings do not practically change and remain at a high enough level;
- cladding deformation (both in the radial and axial directions) including that induced by the cladding-fuel interaction should not result in exhaustion of their serviceability;
- development of cracks in the cladding is not observed, accumulation of damages in the cladding should not make them inoperable;
- corrosion and hydrogeneration of claddings should not lead to a considerable deterioration of their operability;
- FGR from the fuel and reduction in the free space under fuel rod cladding should not be such as the inner pressure in the fuel cladding would exceed the coolant pressure.

1. GENERALIZATION OF THE DATA OF POST-REACTOR INVESTIGATIONS OF VVER-440 FUEL ASSEMBLIES AND FUEL RODS [1-8]

The post-reactor investigations showed that the size of the VVER-440 fuel assemblies remain practically unchanged: the fuel bundle remains integer; the fuel pin arrangement does not change. The investigation results permit the following conclusion to be made [1].

The long success fuel experience of operation in commercial reactors, post-reactor tests of VVER fuel spent to high fuel burnups in the protection chambers show that the existing design of VVER fuel pin reliably ensures reaching the rated fuel burnups under steady-state and transient operation conditions. By their main parameters (including by stability of size, corrosion resistance, mechanical characteristics of claddings, FGR from the fuel, and change in the fuel microstructure) the VVER fuel rods meet the safe operation requirements, licensing requirements and permit the average fuel burnup per fuel assembly to be increased up to 55-60 MW·day/kgU without operation restrictions.

Below the generalized results of post-reactor investigations of VVER fuel rods are given (see, e.g., [1]).

Elongation of fuel pins (under normal conditions upon removal from the reactor). The fuel pins elongate proportionally to fuel burnup at a rate ≈ 0.1% per 10 MW·day/kgU. No deviations from this dependence are observed up to burnups ≈ 50 MW·day/kgU. It can be supposed that at the fuel burnups averaged per fuel assembly up to 55 MW·day/kgU and higher the elongation of fuel elements of this design would not exceed the maximum permissible values (25 mm for the VVER-440 fuel pins).

Change in fuel pin diameter (obtained under normal conditions as the difference between the diameter average over the fuel pin area in the core section and the fuel pin diameter in the area of gas collector). Up to fuel burnups 35-40 MW·day/kgU:

- The fuel pin diameters decrease because of radiation creep of claddings induced by the coolant pressure. At high burnups the rate diameter reduction is slowed down (which can be accounted for by the beginning of the fuel-cladding interaction) and, at fuel burnups ≈ 43(38-45) MW·day/kgU the diameter begins to increase (which can be accounted for by intense fuel-cladding interaction by the pattern of "rigid" contact and by that the fuel begins to interact with the cladding practically in the whole height).

At the fuel burnups higher than ≈ 43 MW·day/kgU:

- under the pressure of swelling fuel the cladding begins to increase in the diameter because of radiation creep. In the most burnt sections the corrugation ("bamboo effect") of cladding with a pitch equal to the fuel pellet length and amplitudes up to 50 μm is observed. Metallographic studies show that the coordinates of cladding deformation peaks coincide with the coordinates of pellet ends.

Fuel-cladding gap. The fuel-cladding gap reduces with increase in the fuel burnup and, at fuel burnups ≈ 40 MW·day/kgU is fully reduced under the working conditions. At fuel burnups ≈ 50 MW·day/kgU the gap is also practically equal to zero under normal conditions.

Fuel cladding corrosion. As a rule, the external surface of all the irradiated fuel pins studied is covered with uniform oxide film less than 8 μm in thickness. The film is tightly adhered to the base metal. In the area of welded joints the oxide film thickness reaches 10-12μm.

On the inner cladding surfaces at fuel burnups up to ≈ 35-40 MW·day/kgU the oxide film with the thickness, which may vary even in one, cladding cross section from 0 to 10 μm (which can be accounted for by fuel-cladding axial asymmetry because of to fuel cracking). At fuel burnups higher than ≈ 45 MW·day/kgU, in the conditions of full fuel-cladding contact, the oxide film is more uniform over the perimeter and reaches 15 μm in thickness. Sometimes an interaction layer up to 15μm in thickness, containing mixtures of the type U- (Pu)-Cs-O or Zr-Cs-O are observed on the inner cladding surface. A slight dependence of thicknesses of oxide films on the VVER fuel claddings on fuel burnup permits one to assume that no change in the film thickness should be also expected at higher fuel burnups.

Hydrogenation of fuel claddings. In the claddings of some spent fuel pins removed from the power units a small quantity of lamellar zirconium hydrides with a size not exceeding 100 μm, is observed. The hydrogen content in the irradiated claddings of all sealed fuel pins is ≈ $(3\text{-}8)\cdot 10^{-3}$ mass %.

Mechanical properties of VVER (440, 1000) fuel claddings are practically equal for all the fuel assemblies investigated and do not depend on either fuel burnup or the place in fuel pin height where the sample was cut off. Within the studied range of average burnups (from 13.1 to 50.5 MW·day/kgU per fuel assembly) the mechanical properties are characterized by high strength and rather high plasticity. The reason of this stability of mechanical characteristics of Zr 1% Nb alloy is explained by ordered distribution of dislocation loops, whose formation is completed at relatively low neutron fluences (0.4 MeV $\approx 10^{19}$ neutron/cm^2).

This makes it possible to state that at fuel burnups higher than 55 MW·day/kgU per fuel assembly, the Zr – 1% Nb cladding will maintain its high mechanical properties.

Macro- and microstructure of fuel for up to five years upon operation can be described in the following way:

- the pellets are fragmented into four and more parts (mainly by radial cracks) but maintain their initial configuration. The diameter of central hole remains practically unchanged;
- the average grain size in the pellet basis does not change;
- at low fuel burnups (up to ≈ 3MW.day/kgU) the fuel density increases due to the radiation densification. At high fuel burnups the fuel begins to swell and, at fuel burnup over pellet 63 MW·day/kgU the swelling reaches ≈ 4 vol. %.

At fuel burnups higher than 45 MW·day/kgU over the cross section:

- heating of cracks (or parts of radial cracks) at the periphery of fuel pellets is observed. This can be accounted for by increased fuel swelling in this area because of high fuel burnup at the pellet periphery comparing with the average one over the cross section (by ≈ 50%).
- a clearly distinguished changed microstructural area begins to develop at the fuel pellet boundary, the so-called rim-layer that has a higher fuel burnup (higher than 75 MW·day/kgU), high plutonium content, and higher porosity.

The rim-layer is characterized by the presence of a lot of small gas bubbles, disappearing of the initial grain structure and formation of new subrains of considerably smaller size (smaller than 1 μm). At fuel burnup ≈ 63 MW·day/kgU the width of this layer reaches up to 150 μm.

FGR from the VVER-440 fuel pins increases with increase in fuel burnup. At low burnups the FGR is small. For the fuel pins with a high fuel temperature (high linear heat generation rate) the FGR is also determined by this temperature. A sufficiently sharp rise in the FGR begins at fuel burnups over the fuel pin burnups higher than 45-50 MW·day/kgU, which corresponds to the burnup over the fuel pin higher than 40 MW.day/kgU. The FGR growth is accounted for by supersaturation of the matrix with fission products and surface rim-effect. This growth has an athermanous character in many respects and occurs even at rather low fuel temperature.

For the VVER-440 fuel pin investigated the FGR from the fuel is about 0.4-1% of those occurred before 40-45 MW·day/kgU and increases at a rate ≈ 2.5% per 10 MW·day/kgU at high fuel burnups. The maximum FGR for the RK-222 (see below) fuel pin was 6%.

Free space in the fuel pin (reduced to the normal conditions) decreases in the course of fuel burnup, which is accounted for by both the reduction in the cladding diameter because of radiation creep (up to fuel burnups ≈ 45 MW·day/kgU) and fuel swelling. The minimum free space for the VVER-440 fuel pins studied was 8.1 cm^3 for the fuel pin from the RK-222.

Inner gas pressure (under normal conditions) for the VVER-440 fuel pins at low fuel burnups corresponding to the filling pressure 0.5-0.7 MPa. With the increase in fuel burnup this pressure rises, which is accounted for both by the decrease in the free space and increase in the amount of gas at the cladding wall because of FGR to the gas medium. At fuel burnups 35-50 MW·day/kgU the pressure is 0.8-1.4 MPa. The maximum measured inner gas medium pressure in the fuel pin was 1.84 MPa for the RK-222 fuel pin having abnormally high FGR was 5.2%. The inner gas pressure in the VVER-440 fuel pin under normal operation conditions should be not more than by ≈ 3-3.5 times higher than the pressure after unloading (under the normal operation conditions). Therefore it can be forecast that before the fuel burnups over a fuel rod lower than ≈ 60-65 MW·day/kgU, even in the sharp increase in the FGR the inner gas medium pressure in the fuel pin will not exceed the coolant pressure.

2. RESULTS OF POST-REACTOR TEST OF VVER-440 FUEL ASSEMBLIES UPON OPERATION IN THE FIVE-YEAR FUEL CYCLES [1-8]

To show the characteristics of VVER-440 fuel assemblies and fuel pins after operation for five years the results of post-reactor tests of fuel rods of RKK-22 (non-profiled) with 4.4% enrichment and some results of post-reactor tests of fuel rods of another fuel assembly will be shown. Basing on the results of post-reactor tests of fuel rods of these fuel assemblies a conclusion was made that the operation life of the VVER-440 fuel pins spent to burnup ≈ 50 MW·day/kgU over a fuel assembly was not depleted.

2.1. Data of RK-222 post reactor tests

The working assembly RK-222 had been operated in the fifth-nineth fuel cycles at the unit 3 of Kola NPP. In the unloading the average fuel burnup was 49.3 MW·day/kgU [3,4]. The fuel failure detection of RKK-222 fuel pin claddings showed that there were no failed fuel pins.

No traces of mechanical interaction of the claddings with the spacing grid cells were found on any fuel pin. The fuel pin elongations are within the range from 7.5 mm to 14.8 mm with the average value 11.3 mm. No defects were found in the claddings of fuel pins investigated.

The measured diameters of claddings are in the range from 9.05 mm – 9.2 mm. The average reduction in the cladding diameter is from 30 μm to 80 μm with the average value 60 μm. The corrugations in the areas with fuel burnups 45 MW·day/kgU did not exceed 50 μm.

All the weld joints examined were in a reasonable state. There were no incomplete penetrations voids or other defects.

The average fuel burnup of RK is 47.6-48 MW·day/kgU, the average fuel burnups over a fuel rod are from 43.9-55.4 MW.day/kgU the maximum fuel burnups over a fuel assembly are from 50.9 MW·day/kgU to 64 MW·day/kgU.

The oxide film on the cladding surface is: on the external side up to 8-17 μm. The hydrogen content in the fuel cladding material is $(3\text{-}8)\cdot10^{-3}$ mass % (in one of the sections of single fuel pin – $13\cdot10^{-3}$ mass %).

The results on the mechanical properties of fuel claddings little differ from the results of tests of fuel pin cladding samples of the earlier tested fuel assemblies having a lower fuel burnup.

The parameter of gases inside the fuel pin was measured on the laser puncture device. First one batch of RK fuel pins then the other one. It was found that:

- FGR from the fuel of 22 RK fuel pins, where it was measured, was from 0.69% to 6.04%. As before puncturing of the second batch of fuel pins the FGR was preliminary estimated (using the non-destructive method) and as the fuel pints with maximum activity were punctured, it can be stated that among the non-punctured fuel pins of this RK there can be not fuel pins having a high FGR;
- The inner gas pressure in the fuel pins, under the normal conditions, was within 0.95-1.89 MPa with the average value 1.15 MPa;
- Free space in the fuel pins was 8.1-12.6 cm^3 (the initial free space ~ 17 cm^3).

Fig.1. shows the values of FGR to the cladding wall of 22 punctured RK-222 fuel pins, as a function of fuel burnup in the fuel pin. Also, in the figure are give the values on the FGR from the fuel follower (see below). It should be pointed out that the FGR in the fuel pins of followers having the burnup higher than 50 MW·day/kgU was lower than that of the similar fuel pins of RK-222.

It is seen that the data on FGR of 19 fuel pins are in good agreement with the data obtained in the post-reactor investigations of fuel pins of other fuel assemblies. a higher FGR in three fuel pins with fuel burnups 48-51.6 MW·day/kgU cannot be reasonably accounted for by the known mechanisms.

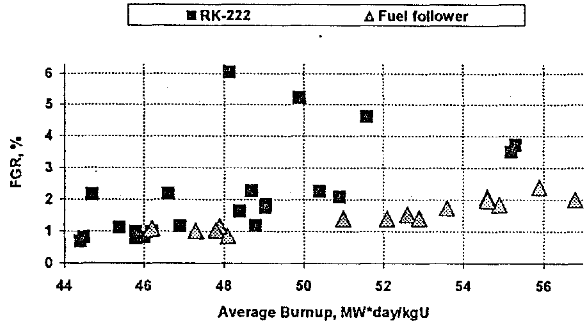

Fig. Values of FGR in the puncture fuel pins of RK-222 and fuel follower as a function of fuel burnup averaged over the fuel pin.

As a result of material-testing analysis with the quantitative treatment of the parameters of fuel microstructure, performed using the samples with fuel burnups up to 63.8 MW·day/kgU it was found:

- the pellets cracked into 5-8 fragments but their initial configuration remained unchanged. At fuel burnups over a pellet higher than 45 MW·day/kgU radial cracks do not come to the pellet surface, the fuel tightly contacting with the cladding;
- cesium migration in the fuel stack length is not observed in any fuel pin investigated. In the center of fuel; pellets no changes in the grains were noticed, the grains are equated. The grain size is 6-15 µm with the average one 6-8 µm. The central hole diameter did not practically change (all this indicates that the maximum fuel temperature did not exceed ≈ 1500°C during the operation);
- beginning from the fuel burnup ≈ 41 MW·day/kgU the formation of rim-layer is observed. The size of rim-layer of the pellet and its porosity increase with fuel burnup. The thickness of rim-layer for the most burnt fuel is ≈ 75-150 mm with the void concentration 15-25%. The void concentration reduces (first sharply, then smoothly) with distance from the edge of the pellet and in the pellet base is ≈ 3-4%.

2.2. Data of post-reactor investigations of fuel followers.

The fuel follower considered had been operated in the core of unit 4 of NovoVoronezh NPP for five years and in unloading it had fuel burnup 50.48 MW·day/kgU .The maximum calculation value of the average fuel burnup over fuel pins is 60.15 MW·day/kgU. The maximum linear heat generation rate of fuel pins was reached in the second year of operation and was 208 W/cm. In the third year of operation the fuel follower was operated in the CPS-bank of control rods. The results of fuel failure detection show that the fuel follower did not contained failed fuel pins. The corrosion state of fuel claddings slightly changed in the height of fuel pins investigated.

On the largest part of external cladding surfaces the thickness of oxide film did not exceed 5 μm, on the internal side it is reached 15 μm on some sections. In the weld area no cracks, voids or thinnings of the cladding was noticed. The hydrogen content in the cladding of fuel pins investigated was $5\text{-}12 \cdot 10^{-3}$%.

The fuel pin elongation was from 10.9 mm to 14.4 mm with the average value 12.76. The reduction in the fuel-cladding diameter was from 55 μm to 90μm with the average value 72 m. In the middle part of all the measured fuel pins the diametral fuel-cladding gap was 0-6 μm. The gap increased up to 80-100 μm as approaching the ends of the fuel kernels.

The average fuel burnup of 69 measured fuel pins was 50.9 MW·day/kgU. The fuel pin burnup was within the range from 46.2 to 56.8 MW·day/kgU. The maximum reached fuel burnup "at the point" was 62.3MW.day/kgU.

The free space in the fuel pins changed from 10.3 cm^3 to 11.9 cm^3 with the average value 11.2 cm^3. The inner pressure in the fuel pins (under the normal conditions) was within the range 0.92-1.19 MPa with the average value 1.05 MPa. The FGR in 20 investigated fuel pins was from 0.85% to 2.39% with the average value 1.53%.

A conclusion was made that the claddings kept the strength and plasticity margins in the whole fuel pin height.

The fuel pin kernels were fragmented, mainly by the radial cracks, into 4-8 parts. The central hole diameter was 1.3-1.6 mm. The grain size does not practically change over the cross section and in the height of fuel pins and is 5-8μm (without the rim-area). The width of rim-layer in the most spent fuel pin did not exceed 55 μm. The porosity in the rim-layer reached 18% while in the rest of pellet's sections it did not exceed 5.4%. The minimum density of fuel in the fuel pins (in the large fragments of pellets) was ≈ 10.2 g/cm^3, which corresponds to the maximum change in the fuel density amounting to 4%. The value is observed in the area of maximum fuel burnup.

A conclusion made as a result of generalization of VVER-440 fuel pin post-reactor investigation data

The data of post-reactor investigations of RK and fuel follower fuel pins having operated for five fuel cycles and having the average fuel burnup ≈ 50 MW·day/kgU and their comparison with the data of post-reactor investigations of fuel assemblies with lower fuel burnups shows that in the increase in fuel burnup over a FA up to ≈ 50 MW·day/kgU there is no drastic deterioration in the VVER-440 fuel pin serviceability. In the fuel pins no exponential changes in the parameters, determining their serviceability with the increase in fuel burnup are observed. This permits a conclusion on the possibility of the increase in fuel burnup of the VVER-440 fuel pins up to the average fuel burnups 55 MW·day/kgU and more over a FA, to be made.

3. DATA TO THE CALCULATION SUBSTANTIATION OF THE AVAILABILITY OF RK DESIGNED FOR SIX-YEAR OPERATION

It was planned to use 12 RK (in the 60O symmetry sector) for operation in the sixth year. For the subsequent calculation analysis 17 fuel pins were chosen from these RK. The choice was made basing on the calculation results using the BIPR-7A, PERMAK-A code data by the criteria: maximum fuel burnup; over a fuel pin and maximum linear heat generation rate at various fuel burnup's in the layer where the linear rate is realized. it is assumed that the chosen fuel pins would be the most reactive ones among the fuel pins of the considered RK (from the viewpoint of their serviceability).

The comparison of the maximum linear rates the considered fuel pins with the dependence of permissible rates shows that the most reactive fuel pins of the RK considered have (taking into account the safety factors) the linear rate values lying below the dependence of permissible rates.

In calculation study the thermal-physical calculation code TOPRA [8,9] intended for modeling the behavior of fuel pins and tvegs of the VVER-type reactors in quasistationary regime was used. The code accounts for the change in the operation conditions (linear heat generation ate, coolant temperature, cooling methods, fast neutron flux), structural and process parameters as well as the main processes occurring in operation and affecting the fuel pin behavior.

Because of the spread of the structural and geometric parameters of fuel pellets, claddings and fuel pins as a whole the calculation was carried out for four versions by the initial effective fuel-cladding gap (gap with allowance for the possible, reduction in the pellet diameter because of fuel radiation densification), covering all the possible states of actual fuel pins.

The preliminary analysis of calculation results showed that, in accordance with the criterion of maximum fuel temperature, all the fuel pins considered are far from the limited values (fuel melting temperatures) even with allowance for the factors of deviation from the model of solid cylinders (i.e. taking into account the inconstantancy by angle of the volume heat rating in the fuel, fuel cracking, spacings between the pellets etc.) in the plane of fuel pin cross section). therefore, among the thermal-physical criteria of serviceability, that of not exceeding the coolant pressure by the maximum pressure inside the fuel pin cladding must be met. For the fuel pins of the variant which area the most dangerous from the viewpoint of violation of this criterion (set of geometric and structural parameters) the calculations were made, with a higher degree of conservatism, with the safety factors 1.04 by the linear rate and burnup.

It should be specially noted that in the calculations the model of FGR from the fuel pin fuel, whose coefficients for accounting for athermanous FGR from the rim-area were chosen so that the rate of FGR, 2.5% per 10 MW·day/kgU, experimentally obtained in 1995-1997 in the RK-222 fuel pins, would be accounted for in the range 50-55 MW·day/kgU. The data on the FGR obtained in dismantling the fuel follower pins show that the athermanous FGR from the rim-layer may lead to much lower rate of FGR. Therefore it may be supposed that the calculation results presented have a considerable conservatism with regard to the FGR and inner gas pressure.

As illustration some calculation data for the maximum spent fuel pin (65.3 MW·day/kgU over a fuel pin) of the "medium initial parameters'variant: maximum fuel temperature - 958°C, FGR - 9.15%, maximum inner pressure in the cladding - 7.37 MPa. Under the normal operation conditions, upon unloading from the reactor, the inner pressure in this pin was 2.71 MPa. For this fuel pin, maximum unfavorable with respect to the fuel-cladding gap with allowance for the safety factor 1.04 by power and fuel burnup, the calculated data are: maximum fuel temperature - 1053°C, FGR - 13%,. maximum inner pressure in the fuel cladding - 11 MPa.

Analysis of results

The average change in the radius of the external surface of fuel cladding at the core section (under the normal operation conditions) for three fuel pins (the most spent ones) became positive. in some axial zones the positive change in this radius was up to 18 mm.

In the most spent sections, central in the height, the radius of fuel cladding exceeded the initial one, under the working conditions, by about 30 μm for fuel pins (on the average in the height-up to 16μm). Note that the TOPRA code accounts for the reduction in the degree of mechanical fuel-cladding interaction because of formation of a softer (than the fuel) surface rim-layer. With account for this, the increase in the cladding radius should be less.

The maximum temperature of fuel in the fuel pins decreases on the whole in the process of operation. This is due to both the decrease in the linear rate and to the processes occurring in the fuel pin. For the fuel pins considered the maximum fuel temperature does not exceed 1100°C.

For the fuel pin considered, which are characterized by a relatively low temperature by a high fuel burnup, the FGR, according to the gas release option used in the calculations, is mainly of athermanous character and does not exceed 14 %. Here it should be again pointed out that the calculation results presented are considerably conservative by the FGR and the inner gas pressure in the fuel cladding.

The rise in the inner gas pressure is due to the reduction in the free space in the fuel pin and FGR and takes place even in the reduction of the average linear rate of fuel pin. For the fuel pins considered the pressure of gas medium at the cladding wall does not exceed 11 MPa, i.e. even:

- with allowance for superposition of the power and burnup safety factors;
- the use of conservative values of initial parameters, and
- the use of conservative enough FGR model it remains lower than the coolant pressure.

As far at the mechanical criteria of fuel pin serviceability are concerned the fuel-cladding interaction by the "rigid'contact '(the fuel-cladding contact with reduced cracks in the fuel) for the fuel pins of minimum gap variant begins at fuel burnups ≈ 30 MW·day/kgU. At these burnups, under the relatively low linear rates, this interaction has no essential influence on the deterioration of fuel pin serviceability. It has been found that the VVER fuel pins of the fuel cycle considered intended for six year operation fully maintain their serviceability. The investigations performed show the possibility of ensuring the fuel pin operability during the whole fuel cycle.

At present the fuel assemblies are loaded into the unit 3 of Kola NPP. the forecast fuel burnup of six fuel assemblies is 59.2 MW·day/kgU.

CONCLUSIONS

1. The operation experience, post-reactor investigation and calculation data allow to forecast that the VVER fuel pins would remain operable with the increase in the fuel burnup average over a fuel assembly up to 55-60 MW·day/kgU. With the increase in the fuel burnup, no exponential changes in the parameters of fuel pins, determining their serviceability are observed. For example, the data of post-irradiation investigations of the fuel pins of VVER-440 fuel assemblies having the average fuel burnup ≈ 50 MW·day/kgU and their comparison with the data of post-irradiation investigations of VVER-440 fuel assemblies having a lower burnup do not show any drastic deterioration's of the VVER fuel pin serviceability with the increase in fuel burnup over the RK up to ≈ 50 MW·day/kgU.
2. The comparison of maximum linear rates of fuel pins of VVER-440 fuel assemblies, intended for operation for six years, with the dependence of maximum linear rates of VVER-440 fuel pins was carried out. The comparison results shows that the maximum linear rates (with allowance for the safety factors) are lower than the limited permissible ones.
3. The calculation results for the fuel pins of VVER-440 fuel assemblies, intended for six-year operation remain fully operable: the fuel temperature does not exceed 1100°C and does not reach the melting temperature with a great margin; FGR does not exceed 14%; maximum inner gas pressure in the fuel cladding remains lower than the coolant pressure.

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