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OPERATION EXPERIENCE OF WESTINGHOUSE NUCLEAR FUEL AT UKRAINIAN NPPs

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To ensure compatibility with the more robust design of TVSA manufactured by TVEL JSC, a modification of the Westinghouse FA, referred to as RWFA, was announced in 2013, which was designed to be more robust. Since 2015, RWFAs has been in pilot operation and since 2019 in commercial operation in Ukraine. The supply of Westinghouse FAs to Ukraine was under constant supervision and integrity control at all stages of operation and after its end. From the very beginning of the implementation of the WFAs, specialists of SE "NNEGC "Energoatom" and Westinghouse Company with the scientific support of NFC STE NSC KIPT carried out the annual inspections of the fuel assemblies. Based on the inspection results of 86 WFAs/RWFAs after 1-3 years of operation, it was concluded that the obtained values of the parameters characterizing the integrity of WFAs/RWFAs did not exceed the limits set during the FA design and safety substantiation of the core loading where those FAs were operated. All FAs that were subjected to scheduled inspections were loaded in the subsequent fuel cycles.

Keywords: *VVER-1000; Bow; Inspection; Growth; Twist; Fuel Inspection and Repair Equipment; Fuel assembly; Nuclear fuel*
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INTRODUCTION

Modernization and improvement of FA and fuel rod design, optimization of their operation modes is a complex task that includes a large set of design and experimental works. An important place among these works is taken by the examination of fuel assemblies and fuel rods during and after operation in the reactor core. At present, trends in nuclear fuel examination are largely focused on the need to promptly obtain statistically significant data on its condition after operation in a particular fuel cycle, while minimizing the time and cost of such examination. The efficient application of the results of post-irradiation examination depends on the completeness and reliability of the information on the technical condition and performance of the fuel, which in turn depends on the methodological and technical support of the examinations.

Obtaining actual information on the condition of fuel assemblies during and after operation is becoming increasingly important due to the requirement to introduce new fuel cycles with higher burnup and extended lifetime, to ensure the reliability of Rod Cluster Control Assembly (RCCA) operation, to control the quality of fuel assembly manufacturing, and to repair leaking assemblies. For these purposes, foreign countries have experience of using inspection and repair equipment at operating NPPs to monitor and repair leaking fuel assemblies for further use [1-3].

The FIRE (Fuel Inspection and Repair Equipment) for Ukrainian NPPs was designed and manufactured by Westinghouse company to control the technical condition of nuclear fuel, which was provided by the RWFA Licensing Program during its implementation at Ukrainian NPPs since 2014. In that year, a conceptual technical solution was developed for the implementation of advanced design of fuel assemblies (RWFA) at SUNPP Unit 3, and in 2015 the first reloading batch of RWFAs was loaded into the core in the pilot operation mode. The RWFAs are the result of the modernization of the WFAs, which were first loaded in 2010 and also had a more robust design compared to the first trial batch of 6 Lead Test Assemblies (LTAs) loaded in 2005 [4].

It should be noted that fresh nuclear fuel (hereinafter referred to as FNF) for VVER-1000 power units of Ukrainian NPPs was supplied under long-term commercial contracts with TVEL JSC and Westinghouse company. At present, due to the armed aggression of the Russian Federation against the people of Ukraine, the supply of fuel produced by TVEL JSC has been cancelled, but the operation and loading of the already supplied FAs will continue for some NPP units. Thus, RWFAs and WFAs produced by Westinghouse company are gradually replacing TVSAs produced by TVEL JSC at Ukrainian NPPs with VVER-1000 V-320 reactors (units capable of installing FIRE) [5].

The authorized organization for the implementation and operation of the FIRE, including the full range of activities for its development, nuclear fuel inspection and repair at all Ukrainian NPPs, is the SS Atomremontservis (SS ARS) of SE "NNEGC "Energoatom" [5]. The personnel of SS ARS, trained and certified by Westinghouse, carried out nuclear fuel inspections under the supervision of Westinghouse specialists in 2015-2016. Since 2017, the personnel of the SS ARS independently carried out nuclear fuel inspections. Since 2018, the NFC STE NSC KIPT has been processing the nuclear fuel inspection results using independently developed alternative and verified methods that were approved by SE "NNEGC "Energoatom" and Westinghouse company.

The results obtained during fuel inspections by means of the FIRE equipment are necessary to assess the technical condition of the fuel assembly components and to provide additional information to confirm compliance with the

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mechanical (strength, deformation), thermal, physical and corrosion design criteria for fuel rods and FAs, which determine their integrity [6-9]. From the scientific point of view, the results obtained by means of the FIRE equipment can be applied to understand the processes occurring in fuel rod and FA materials under irradiation conditions in VVER-1000 core, to assess the stability of geometric parameters of fuel rods and FAs, to predict their further performance, and to substantiate the safe operation of FAs in the next fuel cycles [10].

1. EXPERIENCE Of WESTINGHOUSE FUEL ASSEMBLY IMPLEMENTATION AT Ukrainian NPPs

Westinghouse company designed, developed and manufactured 6 LTAs, which have been operating as part of a mixed core of the South Ukraine Unit 3 since 2005, in order to diversify the nuclear fuel supply for the Ukrainian VVER-1000 type reactors. After the successful completion of the LTAs trial operation, the pilot operation was started and the first full refueling batch of 42 WFAs was loaded into the core of the South Ukraine Unit 3 in 2010.

A more robust design of Westinghouse fuel assemblies, referred to as RWFA, was announced in 2013 to ensure compatibility with the competitor TVSAs, with higher level of structural stiffness, manufactured by TVEL JSC. RWFA has been in operation at Ukrainian NPPs since 2015 in pilot mode and since 2019 in commercial mode. Since that timeWestinghouse enterprises produce only a modified design of RWFA for the needs of Ukrainian NPPs.

Here are the main chronological stages of Westinghouse nuclear fuel implementation at Ukrainian NPPs:

- 2005 – loading of the first 6 Lead Test Assemblies (LTA-1) as part of the mixed core of SUNPP Unit 3;
- 2010 – pilot operation of 42 modernized WFAs started in the core of SUNPP Unit 3;
- 2011 – pilot operation of 42 modernized WFAs started in the core of SUNPP Unit 2;
- 2012 – difficulties in testing WFAs in a mixed core with TVSA fuel assemblies;
- 2013 – announced a more robust design of Westinghouse fuel assemblies (RWFA) compatible with TVSAs in the mixed core;
- 2014 – approval of the Conceptual technical decision on the implementation of RWFA fuel assemblies with improved design at the SUNPP Unit 3;
- 2015 – pilot operation of the first refueling batch of RWFAs in the core of the SUNPP Unit 3 started.

Main key dates of Westinghouse nuclear fuel implementation at Ukrainian NPPs:

- In 2018, SUNPP Unit 3 was the first in Ukraine to fully switch to Westinghouse nuclear fuel after the fourth refueling batch of RWFAs;
- Since December 2019, SUNPP Unit 3 has become the first to receive SNRIU's permission for commercial operation of nuclear fuel from an alternative supplier, Westinghouse company;
- No sooner had the pilot operation of RWFAs been completed than the "Conceptual technical decision "On expansion of pilot operation of RWFAs of advanced design at Ukrainian NPP power units with VVER-1000 reactors (type V-320, V-338)" (KTR-M.13.18-244.15) was approved;
- In accordance with the Conceptual technical decision KTR-M.13.18-244.15, RWFAs have been operating at ZNPP Units 1, 3, 4, 5 since 2016;
- 42 RWFAs started operating at RNPP Unit 3 in 2022.

7 out of 13 VVER-1000 power units operate with Westinghouse nuclear fuel as of 2023, and six power units have already been fully switched to this manufacturer's nuclear fuel.

Table 1. Main periods of Westinghouse fuel implementation at Ukrainian NPPs

No.	Power Unit	First loading of WFA/RWFA*, year	Switch to Westinghouse fuel, year
1	SUNPP-2	2011	2020
2	SUNPP-3	2005	2018
3	ZNPP-1	2017	2021
4	ZNPP-3	2017	2021
5	ZNPP-4	2017	2021
6	ZNPP-5	2016	2020
7	RNPP-3	2022	2025
8	RNPP-4	2024	2027
9	KhNPP-1	2024	2027
*WFAs operated only on SUNPP-2 and SUNPP-3			

2. MAIN DESIGN DIFFERENCES BETWEEN RWFA AND WFA

The design of RWFA is almost similar to that of the WFA, but with higher robustness. Below is a list of designe changes that have been made to the spacer grids (SGs), the lower part of the top and the bottom nozzles [11].

Changes in the SG design:

- SG outer strap tabs were modified to increase stiffness and the number of tabs was increased (every fuel rod location);

- The shape of the outer strap was changed, the thickness of the outer strap and its width in the corners were increased, and a beading along the length of the outer strap was added;
- The material of the midgrids was changed to Inconel (Alloy 718);
- 8 inner straps were added, which were absent in previous design of the midgrids and the top grid.
- Grid width envelope was reduced by 0.25 mm.

Changes in the top nozzle design:

- Sharp edges on legs were smoothed out;
- The top of the adapter plate includes six guiding side plates (Figure 2b) or deflectors (Figure 2c) located along the perimeter to eliminate axial interaction of the top nozzle with the bottom nozzle of an adjacent FA being loaded.

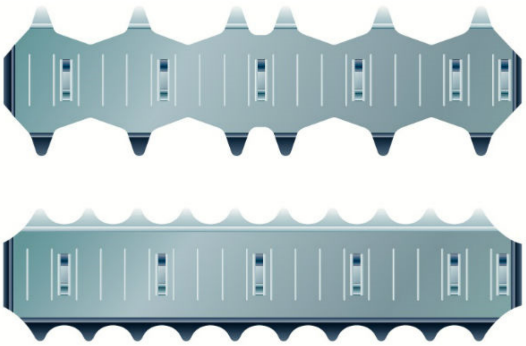


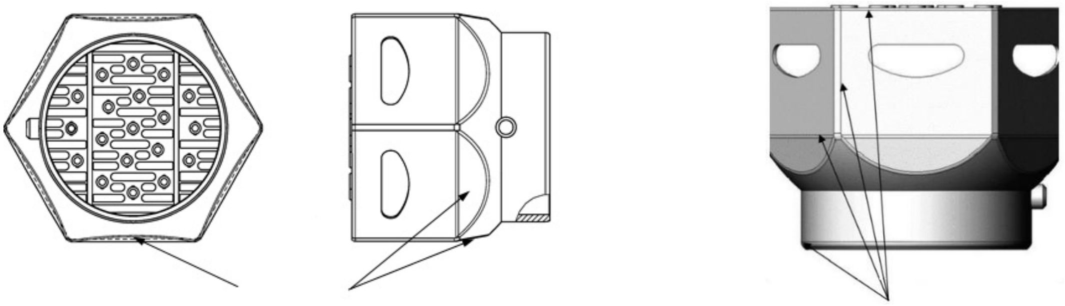
Figure 1. SG outer straps of the WFA (top) and the RWFA (bottom) [11]

a *b* *c*

Figure 2. Lower casting machined part of the WFA top nozzle (a) and the modified RWFA (b, c) [11]

Changes in the bottom nozzle design:

- Flat chamfers were tapered on all 6 faces at the hexagonal plane transition to a hemispherical surface to exclude the formation of local loads in the central part of the SG straps in the case of hard contact interaction of the FA with the surrounding FAs under core loading;
- Edges and corners were chamfered.



a) Tapered chamfers *b) Chamfered eges*

Figure 3. Changes of RWFA bottom nozzle [11]

Fuel rods, guide thimbles, and the barrel assembly of the FA top nozzle remained unchanged. The changes made by the developer increase the robustness of the FAs and facilitate their contact with FAs of other designs during vertical moving, which facilitates transportation and technological operations with FAs. This aspect is very important when loading the core, since the gap between fuel assemblies is only ~ 1 mm.

3. POST-IRRADIATION EXAMINATION OF FAS

From the very beginning of WFA implementation at all stages of its operation and after its completion, specialists of the SE "NNEGC "Energoatom" and Westinghouse company with scientific support of NFC STE NSC KIPT carried out annual examinations and inspections of irradiated FAs. Also, the process of manufacturing, transportation and receiving inspection of fresh fuel assemblies was carried out at Ukrainian NPP sites under constant supervision of Energoatom specialists and representatives of Westinghouse.

In most cases, only measuring systems are used during scheduled inspections, which are specified in the Nuclear Fuel Inspection Schedule and do not involve FAs disassembling. Further processing of the data obtained by means of these systems allows obtaining values of parameters characterizing the technical condition of FAs (the list of parameters is given in Table 2). In accordance with the technical specification, the measuring systems of the FIRE provide measurement of the main parameters of FAs with an error not exceeding the values given in Table 2.

Table 2. FIRE measuring systems error [5]

No	Parameter, unit	Measuring error
1	FA length, mm	± 0.127
2	FA bow, mm	± 2.54
3	FA twist, deg	± 1.25
4	RCCA drag force, kgf	± 0.5
5	Axial gap, mm	± 1.0
6	Fuel rod growth, mm	± 1.0
7	Fuel rod to rod gap, %	± 10
8	Oxide film thickness on fuel rod cladding, μm	± 5
9	Spacer grid width, mm	± 0.127
10	Diameter of fuel rod cladding, mm	± 0.0051

NFC STE NSC KIPT specialists developed and verified methods for processing measurement results to obtain parameters characterizing the technical condition of fuel rods and FAs. These methods are alternative to the methods used by Westinghouse specialists in their calculations. The error in processing the inspection results does not exceed the error specified in Table 2. This allowed the inspection of nuclear fuel with subsequent processing of the results without involving Westinghouse specialists.

4. MAIN SUMMARIZED RESULTS OF FUEL INSPECTIONS

Starting from 2018, Ukrainian specialists have inspected 56 W/RWFAs at SUNPP Unit 3, ZNPP Units 3 and 5 since the time of systematization of the material and writing this article. At the same time, the Ukrainian specialists processed the results obtained during the fuel inspection at ZNPP Unit 5 in 2017. Thus, the total number of fuel assemblies inspected in the FIRE is 64, and taking into account the inspections performed by Westinghouse specialists during the 2013-2017 refueling outages, it is more than 86 FAs.

Each measurement, the results of which are shown in the graphs, was carried out in the appropriate order during the refueling outage after the end of a particular fuel cycle.

4.1. Visual assessment of FA components condition

Visual assessment of the general FAs condition is carried out on the basis of an assessment of the following FA components appearance:

- spacer grids;
- peripheral rows of fuel rods on six faces along the entire height of FA;
- top and bottom nozzles.

Criteria for visual assessment of FAs are developed by fuel manufacturers and presented in technical specifications, fuel design documentation, substantiation of safe operation, developed and summarized within the framework of scientific and technical support and given in the Methodological Guidelines for Nuclear Fuel Control for NPPs and the Proprietary standard of the SE "NNEGC "Energoatom" [12].

Visual assessment of the FA condition is carried out by visual inspection of the half-width or full width of the assembly face along the entire length. In the process of such an assessment, the fuel assembly is inspected from the top to the bottom nozzle with video recording of the image obtained. Next, the data obtained is processed and their compliance with the design and operational criteria is determined to assess the condition of FA components. The video recording materials are used to monitor the general condition of FAs, in particular, the SG outer straps, the presence of deposits and abnormal corrosion on the surface of fuel rod claddings, debris, and mechanical damage of FA structural components.

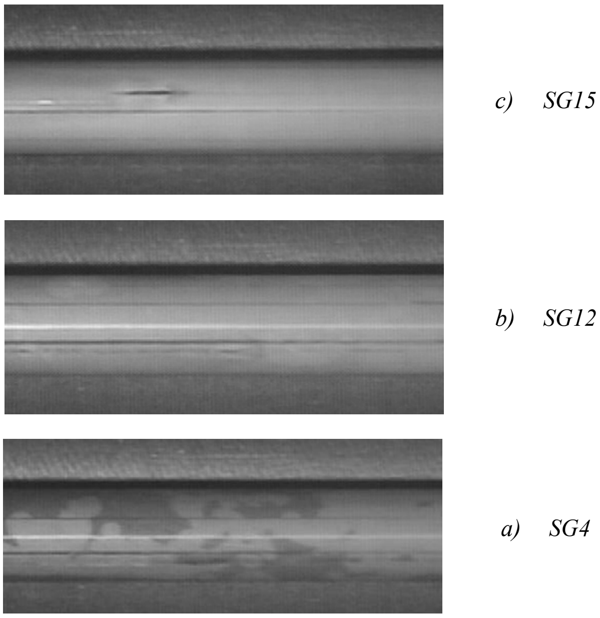
A visual inspection of the cladding surface of six fuel rods after four years of operation, removed from different rows of RWFA at SUNPP Unit 3, was performed with the support of the NFC STE specialists. The visual inspection of fuel rods is performed to obtain data to confirm the presence and nonexceedance of the design value of fretting wear in the places of contact of SG dimples and SG springs with fuel rod claddings. The cladding surface condition was analyzed to detect cladding defects that appear during operation in the VVER-1000 core.

The visual inspection results of six fuel rods revealed that after four fuel cycles, traces of interaction in the form of narrow elongated oval-shaped dark-colored strips 0.5-0.7 mm wide and 4-6 mm long located along the fuel rod axial line were observed in the upper part of all fuel rods that were inspected.

Interaction traces the "fuel rod - SG cell" are clearly visible at the levels of SG12-SG16 (Figure 4). Starting from SG8, it was rather difficult to determine the exact location of the "fuel rod - SG cell" contact. In the lower part of the fuel rod (including the area of the bottom end plug), it was almost impossible to identify the area of contact "fuel rod - SG cell".

No fuel rod cladding damage, corrosion damage (pitting, debris, fretting), or deposits of structural materials corrosion products of the primary circuit on the surface of fuel rod claddings were detected during the entire period of scheduled fuel inspections. The spacer grid outer straps surface was free of deformation, mechanical and corrosion damage. Some SGs had single and numerous longitudinal scratches formed as a result of transportation and technological operations with FAs.

No debris was found stuck between SGs and fuel rods or between fuel rods. Some FA top and bottom nozzles had single longitudinal minor scratches. No significant inhomogeneity of the surface of all inspected FA top and bottom nozzles was detected.


c) SG15

b) SG12

a) SG4

Figure 4. Segments of fuel rods in areas of contact with SGs [5]

4.2. FA growth

When operating in the core, as a result of intense neutron irradiation, WFAs/RWFAs are being subject to the combined effects of radiation growth and radiation-thermal creep, which manifest themselves in the form of an increasing length of guide thimbles made of zirconium alloys. The length change of the guide thimbles also depends on the axial loads acting from the FA top nozzle springs. Figure 5 shows the dependence of the change in the nominal length on the average burnup of all FAs inspected by means of the FIRE.

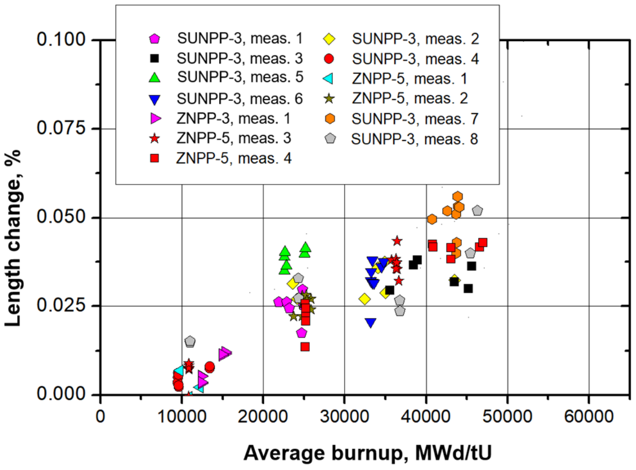


Figure 5. Generalized dependence of the nominal length change on the average burnup of WFAs/RWFAs [5]

According to the data obtained, there is a quasi-linear increase in fuel rod length throughout the entire period of operation. For FAs with a maximum burnup of ~ 46 GW·day/tU (after four years of operation), the average elongation is

0.05%. The growth rate of WFAs/RWFAs is comparable to the growth rate of FAs of other designs with ZIRLO® guide thimbles.

These measurements made it possible to confirm that the growth of the WFA/RWFA guide thimbles is below the expected value and does not exceed the design limit used in the safety analysis to calculate the stress-strain state of the guide thimbles and the FA top nozzle springs.

4.3. FA bow and twist

The deformation and bow of FAs in the core depend on the transverse stiffness of FA, the strength of its skeleton, and operating conditions. The bow deformation and bow shape of FAs with the same design and the same service life may differ significantly. Such differences are mainly due to the following factors: thermal load, location in the core, and design of the adjacent FAs.

Bow and twist are among the most important parameters that affect the reliable and safe operation of a particular FA design. These parameters also affect the drag force of RCCAs in FA guide thimbles and the drag force when inserting/removing FAs in/from the core.

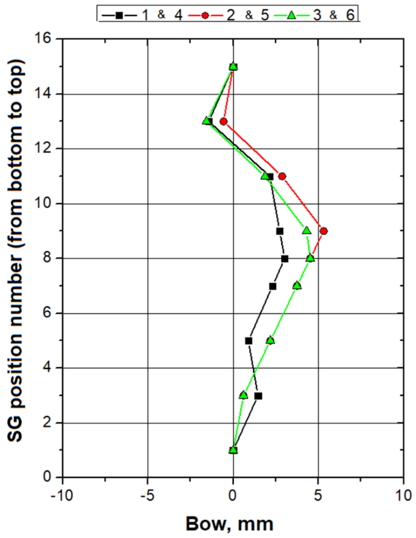
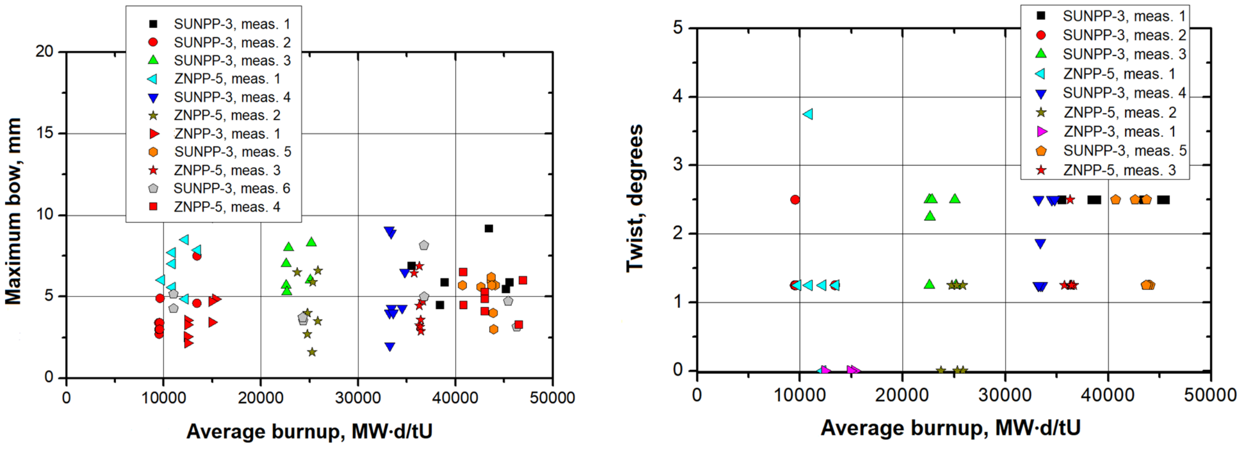


Figure 6. The RWFA bow measurement results [5]

The FIRE equipment and developed methods make it possible to obtain the values of the FA bow with regard to the top and bottom nozzle of the FA along three faces and with visualization (graphical representation) of the bow depending on the height of the FA assembly (see Fig. 6) [13].

The bow of Westinghouse FAs, as well as TVEL FAs, is characterized by a "C" or "S" shape. FAs can simultaneously have both "C" and "S" bow shapes in the core.

When designing the FA and substantiating its safe operation, the maximum bowing parameter (≤ 30 mm) and the maximum twist angle (≤ 5 degrees) were used, which guarantees the movement of the RCCA in the guide thimbles and the insertion of FA in the core with forces that do not exceed the design value.



a b

Figure 7. Generalized dependence of the change in maximum bow (a) and twist angle (b) on the RWFAs average burnup that have been inspected by means of FIRE [5]

Figure 7 shows the dependence of the change in maximum bow (a) and twist angle (b) on the average burnup of RWFAs that were inspected by means of FIRE.

Based on the results of measuring the WFAs/RWFAs geometric parameters, it was found that the deformation (bow and twist) of FAs does not depend on burnup (see Fig. 7) and is dependent on the stiffness of the FA skeleton. According to Figure 7, the bow of WFAs/RWFAs within the burnup range of 9000-46000 MW·day/tU remains constant and varies from 1.6 mm to 9.86 mm, and the twist angle averages 2.5 degrees.

4.4. RCCA drag force when loading/unloading into/from the FA

The RCCA drag force in guide thimbles is a characteristic of the stability of FA geometric parameters. The maximum RCCA drag force in FA is established and substantiated by the fuel manufacturer based on operational experience, while meeting the regulatory requirements for the RCCA fall time. This value should not exceed 8 kgf for WFAs and 14.7 kgf for RWFAs. Exceeding the design limit of the RCCA drag force may result from FA deformation (large bow or twist, complex bow shape) and, when the emergency protection is tripped, may lead to an increase in the RCCA insertion time, incomplete insertion, and even jamming in guide thimbles.

The RCCA drag force is measured when the RCCA simulator is dragged along almost the entire height of the FA guide thimbles [13]. The drag force has a different value at different FA heights with a maximum at the bottom part of FA (the RCCA is inserted along the entire length of FA). Also, the drag force differs when the RCCA moves up and down. For FAs that have been inspected, the RCCA drag force is higher when inserting the into the guide thimbles than when withdrawing it.

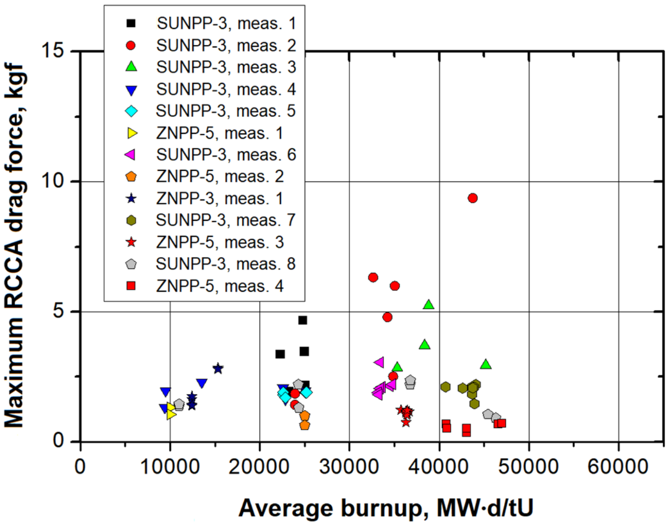


Figure 8. Generalized dependence of the RCCA maximum drag force in the guide thimbles on the WFAs/RWFAs average burnup [5]

The dependence of the RCCA maximum drag force in the guide thimbles on the average WFAs/RWFAs burnup based on the data obtained by means of the FIRE is shown in Figure 8.

The maximum drag force when the RCCA being inserted into the WFA/RWFA guide thimbles is in the range from 1 kgf to 7 kgf, which is significantly lower than the maximum design limit (14.9 kgf) [12]. In most cases, the drop time of the RCCA does not exceed 1.5 s.

4.5. Axial gap between fuel rod end plugs and the adapter plate of top nozzle and the top plate of bottom nozzle

The axial gap in WFAs/RWFAs is the total gap between the fuel rod end plugs and the adapter plate of top nozzle and the top plate of bottom nozzle. The size of the gap depends on the change in the length of the FA guide thimbles and the change in the fuel rod length due to radiation-thermal creep and radiation growth. For all designs of FAs, the axial gap should be maintained within the limits that exclude jamming, further bow and damage of fuel rods during the entire service life and fuel storage (or other fuel operations). The design limit specifies that during a four-year fuel cycle, radiation and thermal growth of WFA/RWFA components (guide thimbles, fuel rods/burnable absorber rods) should not result in a decrease in the axial gap of less than 20.5 mm.

The FIRE systems are designed to estimate the axial gap for all fuel rods/burnable absorber rods and measure it for the peripheral row [13]. Figure 9 shows the dependence of the average axial gap between fuel rods and the adapter plate of top nozzle and the top plate of bottom nozzle on the WFA/RWFA average burnup. As the burnup increases, the axial gap decreases linearly.

The data obtained during the inspections indicate that the minimum axial gap for fuel WFAs/RWFAs is at least 34-37 mm, which is significantly higher than the design limit set for a 4-year fuel cycle (20.5 mm) [13]. This measurement allowed to confirm that for all FAs that were inspected, the axial gap will remain within the limits that exclude jamming, further bow and damage to the fuel rods throughout their entire service life.

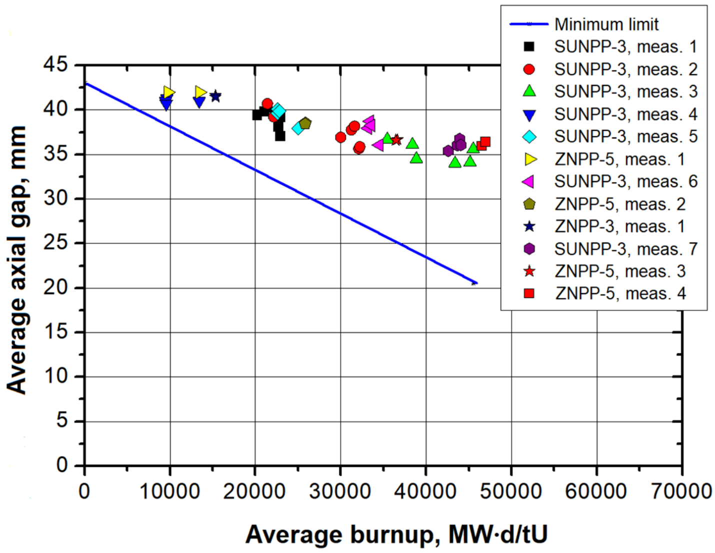


Figure 9. Dependence of the average axial gap between fuel rod end plugs and the adapter plate of top nozzle and the top plate of bottom nozzle on the WFAs/RWFAs average burnup [5]

4.6. Fuel rod growth over 6 faces of FAs

An important aspect under operation is the deformation of zirconium alloy components, which determines the performance of the entire core. Fuel rod growth is caused by radiation effects, which occur as radiation-thermal creep and radiation growth. Therefore, when licensing fuel, one of the criteria is deformation, which sets the limit values for the diameter change and fuel rod/burnable absorber rod growth. With this purpose, the diameter change and fuel rod cladding length are calculated at the design stage, and measurements performed by means of FIRE should confirm the correctness of the calculations. The limit value of the cladding deformation for the stationary fuel rod operation at the end of the fuel cycle should be less than 1%.

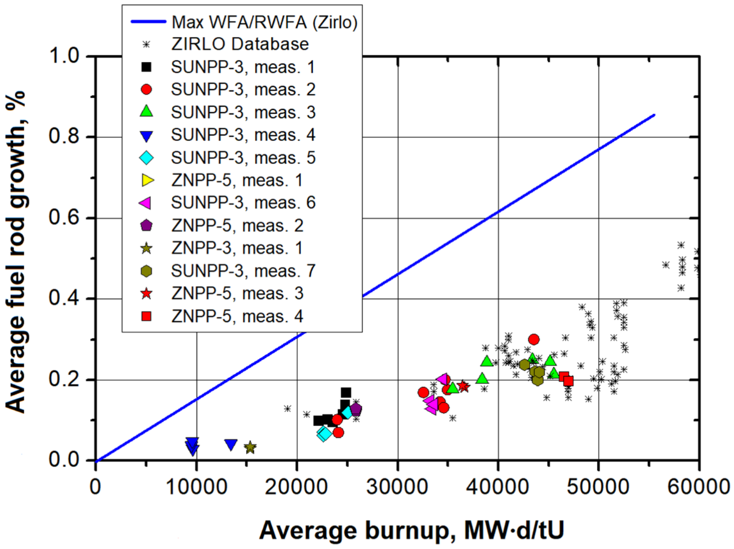


Figure 10. Dependence of the average fuel rod growth in WFAs/RWFAs on the average burnup [5]

The FIRE systems allow estimating the growth of all fuel rods/bunable absorber rods and measuring it for the peripheral row [13]. Figure 10 shows the dependence of the average peripheral row fuel rod growth on the average FA burnup in comparison with the values of the Westinghouse database. According to the data presented (see Fig. 10), in the burnup range of 9000-46000 MW·day/tU, a linear increase in fuel rod length occurs with an increase in burnup. Based on published information, when burnup is reached, above which there is a tight contact of the fuel pellet with the cladding, this fuel rod deformation trend may change [6, 7].

According to the accumulated experience of nuclear fuel inspections at Ukrainian NPPs, the average fuel rod growth in WFAs/RWFAs with a burnup of ~46 GW·day/tU is within 0.21...0.30%. Such growth does not lead to a decrease in the axial gap below the expected value for a given burnup depth (~ 34...37 mm) and, accordingly, is below the safety limit for FAs operation.

The use of the FIRE made it possible to confirm that the maximum value of cladding deformation for the standard operating mode of fuel rods at the end of the fuel cycle does not exceed the safe operation limit for each FA type operating at Ukrainian NPPs.

4.7. Profilometry of RWFA fuel rod claddings

Under reactor core irradiation, an increase in the burnup is accompanied by a decrease in the fuel rod cladding diameter due to radiation and thermal creep. Upon reaching a certain burnup depth, when the cladding-fuel pellet gap disappears, the cladding diameter begins to increase again due to fuel pellet swelling.

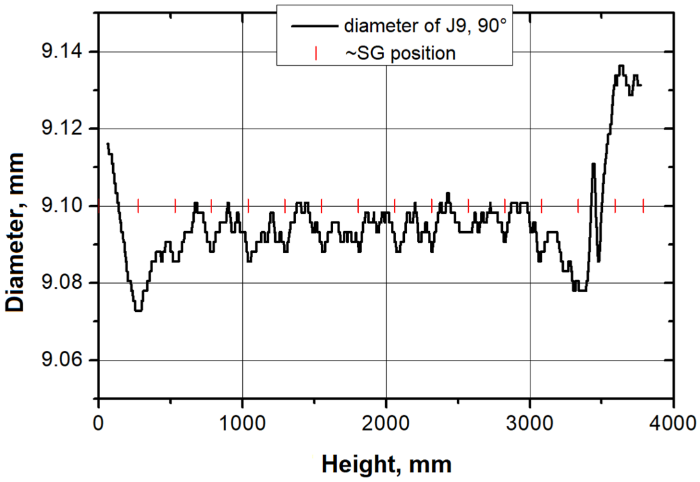


Figure 11. Distribution of the cladding diameter in mutually perpendicular directions along the height of the fuel rod J9 [5]

Measurements of the diameter of a single fuel rod are performed with the fuel assembly disassembled and the fuel rod removed. In most cases, to substantiate the fuel rod operability, it is necessary to determine not the diameter of the fuel rod at a certain height, but the change in diameter along the entire length of the fuel rod (profilometry). The profilometer head is equipped with two linear variable differential transformers (LVDTs). The fuel rod is placed between the tips of the LVDTs and the roller guides opposite the LVDTs. The outer diameter of the fuel rod causes the relative displacement of the linear transformer and generates a voltage corresponding to the size of the fuel rod with an accuracy of 5 µm (see Table 2). At the time of this article writing, profilometric measurements were performed only for 6 fuel rods/burnable absorber rods of one RWFA after the fourth year of operation.

The diameter of fuel rod/burnable absorber rod claddings in RWFAs before irradiation in the core is 9.144 mm and may differ from the specified size by +0.037/-0.038 mm. The tolerance for fuel rod/burnable absorber rod ovality is 0.025 mm.

In all cases, for the inspected FAs, the maximum change in the cladding diameter did not exceed 0.66% (see Fig. 11), which is below the design limit of 1% [13]. The maximum ovality is 0.020 mm and almost coincides with the design value, but is below the design limit obtained during the substantiation of the operation of these FAs (> 0.050 mm).

The FIRE provided a confirmation that the maximum value of the fuel rod cladding diameter changes at the end of the fourth fuel cycle did not exceed the safe operation limit.

4.8. Fuel rod to rod gap on 6 faces along the entire height of FA

The results of the fuel rod to rod gap estimation are necessary to confirm compliance with the thermophysical criteria and to prevent overheating of fuel rods. The maximum value of the reduction of the rod-to-rod gap should not exceed 50% for WFAs/RWFAs. If the value exceeds the maximum value, overheating of fuel rod cladding or localized power increase may occur.

The FIRE systems provide the capability to estimate the rod-to-rod gap on 15 spans between the SGs [13], but only for the visible (11 rods) rods of the peripheral row along all 6 faces.

According to the accumulated experience of fuel assemblies' inspection at Ukrainian NPPs, the maximum value of the rod-to-rod gap reduction for all designs of FAs operated at Ukrainian NPPs does not exceed 13-15%. In one case, a 33.7% reduction of the rod-to-rod gap was detected for WFA with a burnup of ~ 46 GW·day/tU. At the same time, no dependence of the rod-to-rod gap on the burnup was observed. The obtained values made it possible to confirm the meeting of this criterion.

4.9. Oxide film distribution on the fuel rod cladding along the height

For Westinghouse fuel rod claddings made of ZIRLO, the meeting of thermophysical and mechanical criteria is ensured at an oxide film thickness not exceeding 101.5 µm within the design life [12]. The local thickness of the oxide film on the fuel rod cladding, calculated for a unilateral confidence level of 99%, should not exceed 152.4 µm.

The FIRE oxide film thickness measurement system provides measurements on the fuel rod section between successive SGs along the entire FA height [13]. Figure 12 shows the dependence of the oxide film thickness on the cladding surface of the six inspected fuel rods after the fourth year of operation on the height coordinate of the fuel assembly. As can be seen from the dependence, the thickness of the oxide film varies with the height coordinate of fuel rods. The maximum oxide thickness is observed in the upper part of FAs.

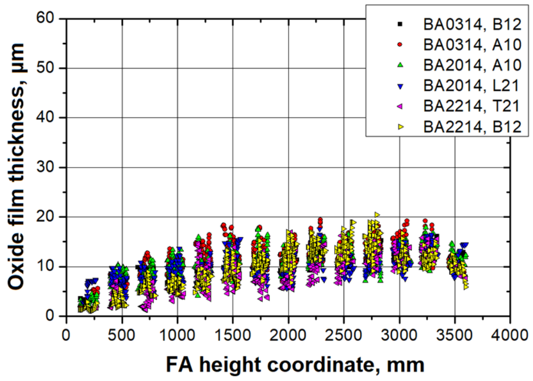


Figure 12. Distribution of oxide film thickness along the height of six inspected fuel rods of different FAs after four years of operation [5]

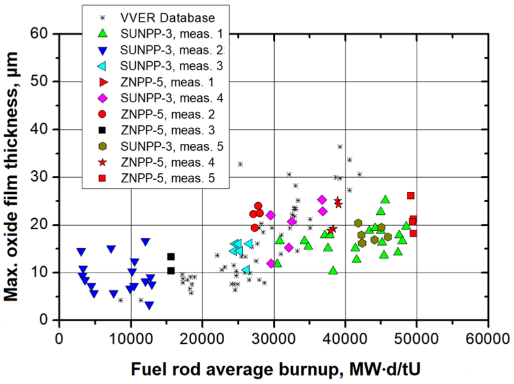


Figure 13. Dependence of the maximum oxide film thickness on the average burnup of fuel rods [5]

Figure 13 demonstrates the dependence of the maximum oxide film thickness on the average fuel rod burnup. The maximum oxide thickness on the fuel rod claddings after the fourth year of operation is in the range of 13...25 µm. Oxide film was dense, without cracks and delaminations, and exhibited good reflectivity at all height coordinates. The color of the cladding surface varies from dark gray in the lower part to light gray in the upper part of the fuel rod. Also oxide spots and contours of varying contrast and size are observed.

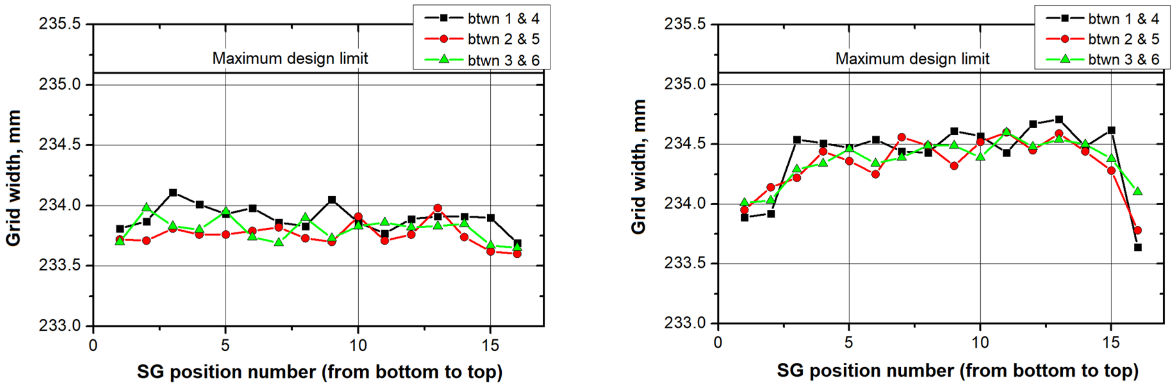
The obtained results of thickness measurements on the fuel rod surface are significantly lower than the maximum design limit (< 101.5 µm) set at the design stage and when obtaining a license for fuel operation in the core. Accordingly, the use of FIRE allowed to confirm the meeting of this criterion.

4.10. Spacer grid width

The change of the spacer grid width, caused mainly by radiation growth, depends on the neutron fluence, irradiation exposure time, FA position in the core, and the material of the spacer grid (zirconium alloy, Inconel). For SGs made of zirconium alloys, the width increase is caused by two mechanisms: radiation growth and volume increase as a result of hydrogenation. The maximum increase of SG width is limited by the gap between the adjacent FAs. For WFA/RWFA, the maximum grid width should not exceed 235.1 mm. Two modifications of FAs manufactured by Westinghouse are in operation at Ukrainian NPPs:

- up to 2015, WFAs with SGs made of Zircaloy-4 and Alloy 718 (Inconel 718);
- after 2015, RWFAs with SGs made of Alloy 718;
- starting from 2019, the operation of two designs of Westinghouse FAs with two types of SGs continued at SUNPP Unit 3.

The FIRE [13] and the methodology for calculating the growth hexagonal SGs allow obtaining the minimum, maximum, average, and absolute values of SG width. The SG width is calculated between two parallel faces of the SG. Figure 14 shows the width of each of the SGs of one RWFA (a) after four years of operation and one RWFA (b) after three years of operation.



a *b*

Figure 14. Dependence of the average SG width for mutually parallel faces on the height position of RWFA (a) and WFA (b) after four and three years of operation, respectively [5]

As expected, there is almost no change in the width of RWFA SGs made of Alloy 718 under irradiation. Grid width measurements of four FAs were performed for four years. The dependence of 16 SGs width change of one of these FAs on the burnup is shown in Figure 16. The results obtained during the inspection period are within the measurement accuracy of the ultrasonic inspection system and reveal that the SGs made of Alloy 718 do not change their width under the influence of irradiation during four fuel cycles.

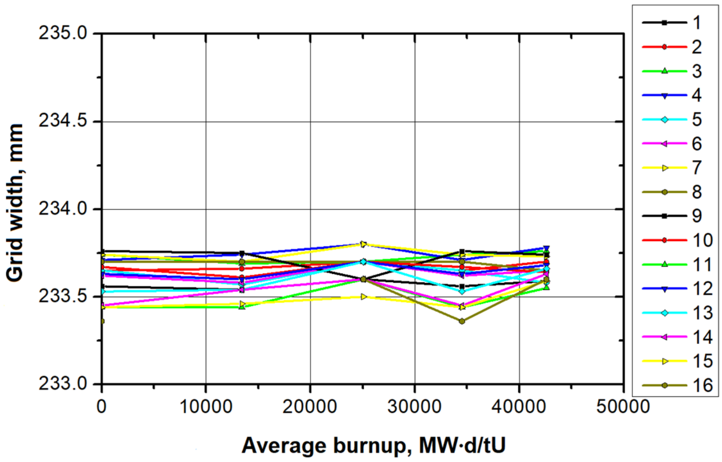


Figure 15. Dependence of the change in the average spacer grid width on the average burnup for one of the inspected RWFAs [5]

For WFAs, after three years of operation, the distribution of width for SGs made of zirconium alloy along the height of the fuel assembly (see Fig. 14.b) shows a maximum in the upper part of FA. The change of grid width is comparable to the FA burnup profile, which indicates the influence of radiation growth on the change of SG dimensions. At the time of systematization of this material, there is no data on the width of the above mentioned SGs after four years of operation, which does not allow to plot the dependence of SG width on the WFA average burnup similar to that shown in Figure 15.

During the inspection, the results of the grid width measurements confirmed that the SG width of both RWFAs and WFAs is below the design limit of safe operation (235.1 mm) [12], which was established at the design stage and when obtaining a license for fuel operation in the VVER-1000 core.

CONCLUSIONS

1. As of 2023, 7 out of 13 VVER-1000 power units operate Westinghouse nuclear fuel. Six power units have already been fully implemented the nuclear fuel from this manufacturer, and RNPP Unit 3 started operating with RWFAs in 2022.

2. The main differences between RWFAs and WFAs that were introduced in the modification are as follows: spacer grids (the shape and thickness of the outer strap were changed, 8 inner straps were added, and the material of the middle grids was replaced with Alloy 718); top nozzle (chamfers were made on sharp edges and guiding side plates or deflectors were added); bottom nozzle (pyramidal tapers were added on all 6 faces, sharp edges were chamfered). These changes increase the stiffness of the fuel assemblies and facilitate interaction with FAs of other designs during their vertical movement, which facilitates transport and technological operations with FAs.

3. The supply of Westinghouse nuclear fuel to Ukrainian NPPs was performed under constant supervision and inspection of its condition during operation and after its completion. From the very beginning of WFA implementation, annual inspections of FAs were carried out by SE "NNEGC "Energoatom" and Westinghouse specialists with scientific support of NFC STE NSC KIPT.

4. The results of nuclear fuel inspections during the 2017-2021 refueling outages at ZNPP Units 3 and 5 and SUNPP Unit 3 were accumulated and systematized. The values of parameters characterizing the technical condition of more than 86 WFAs/RWFAs with a burnup of up to 46 GW·day/tU were calculated.

5. The obtained values of the parameters characterizing the technical condition of WFAs/RWFAs are demonstrated to not exceed the limits set when designing the fuel and substantiating the safety of the fuel loading. All fuel assemblies inspected after 1-3 years of operation were loaded in subsequent fuel cycles. The values of the parameters characterizing the technical condition of WFAs/RWFAs after four fuel cycles indicate that the nuclear fuel did not exhaust its resource and has a sufficient margin of controlled parameters to achieve higher burnups.

6. Based on the results presented in the paper, the main conclusion was made that the technical condition of WFAs/RWFAs manufactured by Westinghouse and operated in Ukrainian VVER-1000 reactors fully meets the safety requirements that were set out in its design and substantiation of safe operation. In the case of damage or leakage of fuel rods in the Westinghouse fuel assemblies, they can be repaired due to their removable design and repair tool such as the FIRE, and are much more maintainable than TVSAs manufactured by TVEL JSC.

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ДОСВІД ЕКСПЛУАТАЦІЇ ЯДЕРНОГО ПАЛИВА ВЕСТІНГХАУЗ НА АЕС УКРАЇНИ

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Для забезпечення сумісності з більш жорсткою конструкцією ТВЗА компанії АТ “ТВЕЛ” у 2013 році було анонсовано модифікацію ТВЗ компанії Westinghouse під назвою ТВЗ-WR також з більш жорсткої конструкції. ТВЗ-WR експлуатується в Україні з 2015 року в режимі дослідно-промислової експлуатації, а з 2019 року – в промисловій експлуатації. Підприємства компанії Westinghouse виробляють тільки ТВЗ-WR для потреб АЕС України. Постачання ТВЗ Westinghouse для України відбувалося під постійним наглядом та контролем на всіх етапах експлуатації та після її завершення. З самого початку впровадження ТВЗ-W, спеціалістами ДП «НАЕК «Енергоатом» та компанії Westinghouse при науковій підтримці НТК ЯПЦ ННЦ ХФТІ, проводились щорічні обстеження паливних збірок. За результатами обстежень близько 86 ТВЗ-W/WR компанії Westinghouse після 1-3 років експлуатації було зроблено висновок, що отримані значення параметрів, які характеризують технічний стан ТВЗ-W/WR, не перевищують межі, закладені при проєктуванні палива та обґрунтуванні безпеки паливних завантажень, в яких експлуатувалися зазначені ТВЗ. Всі ТВЗ, планова інспекція яких проводилася після 1-3 років експлуатації, використовувалися у наступних паливних завантаженнях.

Ключові слова: *ВВЕР-1000; вигин; інспекція; подовження; скручування; стенд інспекції і ремонту палива; тепловидільна збірка; ядерне паливо*