Performance of the Westinghouse WWER-1000 Fuel Design

***J. Höglund*[1], *R. Latorre*[2], *D. Davis*[3], *A. Jansson*[4]**

[1] Westinghouse Sweden, Västerås, Sweden
[2] Pacific Northwest National Laboratory, Richland, WA, USA
[3]Westinghouse Columbia, Columbia SC, USA
[4]Westinghouse Sweden,Västerås, Sweden

Abstract

In 2005, six (6) Westinghouse WWER-1000 Lead Test Assemblies (LTAs) were loaded in South Ukraine Unit 3 (SU3). The LTAs completed the planned four cycles of operation and reached an average assembly burnup in excess of 43 MWd/kgU. Post Irradiation Examination (PIE) inspections were performed after completion of each cycle and it was concluded that the 6 Westinghouse LTAs performed as expected during their operational regimes.

In 2010, a full region of 42 assemblies of an enhanced WWER-1000 fuel design for Ukrainian reactors, designated WFA, was loaded in SU3. The WFA includes features that further mitigate assembly bow while at the same time improving the fuel cycle economy. In 2015, 26 WFAs completed their planned four cycles of operation reaching an average assembly burnup in excess of 42 MWd/kgU. Currently 36 WFAs continue operating their fourth cycle in SU3. In addition, South Ukraine Unit 2 (SU2) has been loaded with WFAs and 27 assemblies have completed two cycles of operation reaching an average assembly burnup above 24 MWd/kgU.

PIE for the WFAs has been completed after each cycle of operation. All assemblies have been examined for visible damage or non-standard position of fuel assembly components during unloading and reloading. All WFAs have also been subject to the standard leak testing process, with all fuel rods found to be hermetically sealed and non-leaking.

Each outage, six WFAs have been subject to a more extensive inspection program. In 2012, 2013, and 2015, the Westinghouse Fuel Inspection and Repair Equipment (FIRE) workstation were used for the SU3 inspections.

Excellent irradiation fuel performance has been observed and measured on all WFAs. The fuel assembly growth, rod cluster control assembly (RCCA) drag forces, oxide thickness, total fuel rod-to-nozzle gap channel closure, and fuel assembly bow data were within the bounds of the Westinghouse experience database. Results and concluding remarks from the PIEs are provided in this paper.

In 2012, several WFAs experienced mechanical damage of the spacer grids due to high lateral loads during core loading of both SU2 and SU3. The high loads were caused by mechanical interference due to a combination of distortion and stiffness of the mixed core. However, it shall be noted that all fuel rods remained hermetically sealed and non-leaking. Moreover incremental grid damage has not been observed on any WFA in any consecutive outage.

To prevent damage of the WFA spacer grids during core loading and unloading, Westinghouse modified the WWER-1000 fuel design further to increase lateral grid strength and to minimize the risk for harmful mechanical interaction between assemblies. The design includes a thicker spacer grid outer strap with an enhanced profile, an all Alloy 718 grid structure for improved stability, and improvements to the top and bottom nozzles.

1. Introduction

Westinghouse has completed manufacturing and delivery of five full regions of the Westinghouse WWER-1000 Fuel Assembly (WFA) design to the South Ukraine NPP (SUNPP). In addition one region of the upgraded Robust Westinghouse WWER-1000 Fuel Assembly (RWFA) design was delivered to South Ukraine Unit 3 (SU3) in the autumn of 2014.

Within the Ukraine Nuclear Fuel Qualification Program (UNFQP) Westinghouse and the United States Department of Energy, through the Pacific Northwest National Laboratory (PNNL), supplied one full reload batch of 42 WFAs to SU3. In 2015, 26 of these assemblies completed their planned four cycles of safe operation reaching an average assembly burnup above 42 MWd/kgU with satisfactory performance on all counts. The reload batch was preceded by the delivery of 6 Lead Test Assemblies (LTAs), which were introduced in SU3 in 2005. The LTAs have completed their planned four cycles of operation and reached an average assembly burnup in excess of 43 MWd/kgU.

Post Irradiation Examinations (PIEs) for all WFAs have been completed after each cycle of operation and six WFAs have been subject to a more extensive inspection program at each outage. In 2012, 2013 and 2015 the Westinghouse Fuel Inspection and Repair Equipment (FIRE) workstation were used for the SU3 inspections. Three WFAs have been inspected in the FIRE in all three outages and three have been inspected in two outages.

Excellent irradiation fuel performance has been observed and measured on all WFAs. All WFAs have also been subject to the standard leak testing process with all fuel rods found to be hermetically sealed and non-leaking.

In 2012, several WFAs experienced mechanical damage of the spacer grids during loading of both South Ukraine Unit 2 (SU2) and SU3. The grids were damaged due to high lateral loads exceeding their strength limit. To prevent recurrence of these damages, Westinghouse upgraded the WWER-1000 fuel design to increase lateral grid strength and to minimize the risk for harmful mechanical interaction between assemblies. The upgraded design, Robust Westinghouse WWER-1000 Fuel Assembly (RWFA) includes a thicker spacer grid outer strap with an enhanced profile, an all Alloy 718 grid structure for improved stability and improvements to the top and bottom nozzles.

In December, 2014 Energoatom and Westinghouse signed a contract for increased deliveries, to SUNPP and Zaporizhzhya Nuclear Power Plant (ZNPP).

2. Westinghouse WWER-1000 Fuel Assembly Design Development History

In this section, a brief overview of the development of the WFA as well as of the enhanced design RWFA, is provided. The development of the WFA LTA- and Region designs have earlier been presented in the 7th and 9th International Conferences on WWER Fuel Performance, Modelling and Experimental Support in 2009 and 2011, respectively, see References 1 and 2. A separate paper for the Enhanced Westinghouse WWER-1000 Fuel Design for Ukraine Reactors, the RWFA, is provided for the 11th International Conferences on WWER Fuel Performance, Modelling and Experimental Support, 2015, see Reference 3.

Significantly different from the Westinghouse VV6 Temelin fuel assembly design, the WFA and later the RWFA, were designed to not only be 100% compatible with the WWER-1000 reactors, but also, very importantly, to perform safely in mixed core transitions and to excel reliably and economically in equilibrium core operations.

2.1. LTA development and manufacturing

The original development on the WFA design started in early 2001 and resulted in 6 LTAs being shipped in 2005. This design fulfilled all design objectives with good margins. The testing performance was also excellent and all completed tests showed significant margin to the design limits.

Manufacturing of LTAs was carried out at the fuel fabrication facility in Columbia, South Carolina, USA, and went very well. The fuel was shipped in April 2005 and loaded in SU3 during the 2005 outage.

2.2. WFA Development and Manufacturing

With the opportunity for continuous improvements and additional margins envisioned for cycle extensions beyond the traditional 4 cycles of operation in WWER 1000 units, the double bulge grid attachment feature was embodied in the WFA Region design. The double bulge at each grid location vs. a single bulge is shown schematically in Figures 2.1 for the LTA design and in Figure 2.2 for WFA design.

The effect of this design feature is a significantly improved skeleton structural stiffness equivalent to the successfully operating Westinghouse square lattice designs.

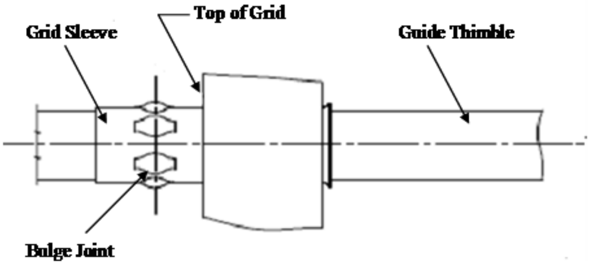

Figure 2.1. LTA Design

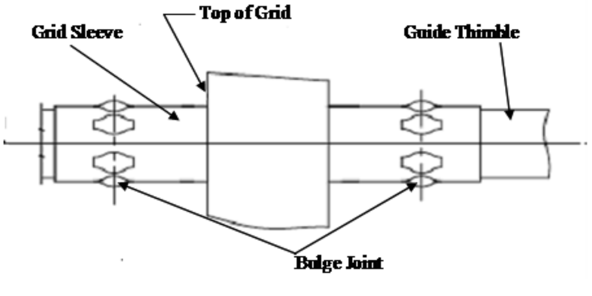

Figure 2.2. WFA Design

In addition to the double bulge feature, it was also decided to change the material in the major part of the grids from Alloy 718 to Zr-1%Nb material. In the WFA Region design, Zr-1%Nb material is used in 13 of the WFA grids to further improve fuel cycle economics. In the LTA design, only 2 grids were of Zr-1%Nb material. With the Region design the Fuel Assembly (FA) stiffness remains well within the variability which has been shown to have a negligible effect on fuel assembly dynamic performance, while simultaneously improving the fuel cycle cost by approximately 1 %. The remaining 3 grids (Top, Bottom, and 1-st from the Bottom Grid) continue to be of Alloy 718 material.

This first full 42 fuel assembly reload batch of the WFA Region design was manufactured at the fuel fabrication facility at Westinghouse Sweden and loaded in SU3 in February 2010.

2.3. RWFA Development and Manufacturing

In 2012, several WFAs experienced mechanical damage of the spacer grids during core loading of both SU2 and SU3. The grids were damaged by mechanical interference due to high lateral loads exceeding their strength limit. The mechanical interference was caused by a combination of distortion and stiffness of the mixed core. However, it shall be noted that all fuel rods remained hermetically sealed and non-leaking. It shall also be pointed out that as a result of measures taken to optimize the loading sequence, no grid damage has been observed in any of the consecutive outages.

To prevent damage of the WFA spacer grids during core loading and unloading, Westinghouse developed an enhanced WWER-1000 fuel design, the RWFA design, to increase lateral grid strength and to minimize the risk for harmful mechanical interaction between fuel assemblies.

Incorporated design enhancements include a thicker spacer grid outer strap, an enhanced spacer grid outer strap profile to mitigate core loading and unloading risks, an all Alloy 718 grid structure for improved stability, and improvements to the top and bottom nozzles. Capable of meeting increased lateral loads generated from using a higher axial trip limit for the refueling machine crane, the design was verified by extensive mechanical and thermal-hydraulic testing, which included a newly developed fuel assembly-to-fuel assembly handling test rig to assess performance during bounding core loading and unloading conditions. Through these extensive design enhancements and comprehensive testing program, the enhanced WWER-1000 design provides additional performance, handling, and reliability margins for safe reactor operation.

For more details on the RWFA design, please see the paper “Enhanced Westinghouse WWER-1000 Fuel Design for Ukraine Reactors” in the material for this 11th International Conferences on WWER Fuel Performance, Modelling and Experimental Support, 2015.

Manufacturing of the first RWFA reload batch was carried out at the fuel fabrication facility at Westinghouse Sweden in 2014 and loaded in SU3 in March 2015.

3. Operational Experience and Post Irradiation Examination (PIE) results

The 6 LTAs were introduced in SU3 in 2005 and were discharged in 2010 after completing four cycles of operation as planned. The average assembly burnup for the 6 LTAs is more than 43 MWd/kgU.

In December, 2014, 26 WFAs of the Region design completed their planned four cycles of operation reaching an average assembly burnup in excess of 42 MWd/kgU. Another 36 WFAs are currently operating their fourth cycle in SU3. Also, SU2 has been loaded with WFAs and 27 of these assemblies have completed two cycles of operation and reached an average assembly burnup of more than 24 MWd/kgU.

PIEs for the WFAs have been completed after each cycle of operation. All assemblies have been examined for visible damage or non-standard position of fuel assembly components during unloading and reloading. All WFAs have also been subject to the standard leak testing process with all fuel rods found to be hermetically sealed and non-leaking.

In each outage, six WFAs have been subject to a more extensive inspection program. In 2012, 2013, and 2015, the Westinghouse FIRE workstation was used for the SU3 inspections. Three WFAs have been inspected in the FIRE in each of the three outages and three have been inspected in two outages.

The FIRE workstation supports full scope fuel visual inspections as well as measurements of oxide, bow, twist, FA length, grid width and RCCA drag forces. In addition an in-mast sipping system as well as equipment for fuel reconstitution is included.

Excellent irradiation fuel performance has been observed and measured on all WFAs. The fuel assembly growth, rod cluster control assembly (RCCA) drag forces, oxide thickness, total fuel rod-to-nozzle gap channel closure, and fuel assembly bow data were within the bounds of the Westinghouse experience database. Results and concluding remarks from the PIEs are provided below.

3.1. LTA Operational Experience and PIE Results

The LTAs performed well in the SU3 core during Cycles 17-20, 2005-2010, demonstrating results well in agreement with all predicted calculations and in all of the PIEs that were performed after completion of each of the four cycles. The LTAs have now been discharged after completing the planned four cycles of operation.

The LTAs were operated in different core locations during each operating cycle. Each LTA was even operated in a rod cluster control assembly (RCCA) core location during Cycle 19.

Results from the third PIE were presented in detail at the 8th International Conference on WWER Fuel Performance, Modelling and Experimental Support. Upon completion of the planned 4 cycles of operation, the final PIE was performed.

The final PIE results at the end of SU3 Cycle 20, in 2010 were presented at the 9th International Conference on WWER Fuel Performance, Modelling and Experimental Support. This final PIE continued to yield satisfactory results on all counts, and it was concluded that the 6 Westinghouse LTAs performed as expected during their operational regimes. Specific conclusions are:

- All FAs looked good visually with no evidence of abnormalities in any part of the fuel assemblies.
- All grids remained in their designated axial positions, were intact, and had no indication of excessive corrosion.
- The fuel rods all looked good. They were crud free, straight, and corrosion was well within expected levels. No fretting or any other type of wear scars on the cladding of periphery rods was present. The fuel rod growth was as predicted and even more growth could have been accommodated by the FAs.
- RCCA drag forces were all acceptable, and this was no surprise as all 6 LTAs in control rod locations during their 3rd cycle of operation had passed the control rod drop times tests satisfactory.

Very good performance was demonstrated in the WWER-1000 reactor water chemistry environment for the Zr-1%Nb as grid material, and the ZIRLO®[1]fuel cladding and structural components.

Drag forces during the final unloading of the LTAs from the core did not exceed the design values and requirements, indicating absence of any excessive LTA bow or twist.

3.2. WFA Region Design Operational Experience and PIE Results in SU3

Within the UNFQP, Westinghouse and the United States Department of Energy, through the PNNL, supplied the first reload batch of 42 WFA Region design to SU3 in 2010. Core follow of the 42 WFAs in transition cores has been carried out during 2010-2014, Cycles 21-24, and detailed examination of selected WFAs has been conducted after completion of each cycle.

In addition, full-face visual inspections have been performed during the core offload of all operating WFAs, on each of the six faces using a diagonal view. Video examinations have been made available to Westinghouse personnel for assessment. These assessments were used to make a judgment about the extent of a condition and to make a determination of potential impact that the condition could have on the operational performance of the assembly.

All WFAs in Cycles 21-24 have also been subject to the standard leak testing process with all fuel rods found to be hermetically sealed and non-leaking.

In the outage of 2012, several WFAs showed damage that apparently occurred as a result of the reloading process. High interaction forces between fuel assemblies during the reload process caused damage to the grids. The fuel assemblies were visually inspected and subsequently assessed to determine whether they could be operated safely during subsequent cycles.

As a consequence of these inspections, 16 WFAs of the first reload batch and 2 WFAs of the second reload batch are held in the spent fuel pool (SFP). Of these 18 WFAs, 14 can be used as-is and 4 must be repaired.

In 2012 also several fresh WFAs were damaged during loading. This resulted in the State Nuclear Regulatory Inspectorate of Ukraine prohibiting loading of fresh WFAs. As a consequence no fresh WFAs have been loaded in the consecutive outages. However, the loading forces have been reduced by implementation of an improved core loading sequence for use with both WFA and RWFA designs. With this enhanced loading sequencing, reloading of irradiated WFAs have been successful. The risk for damage during loading has been significantly reduced with this approach.

Twenty-six (26) WFAs have now completed their full four cycles of operation, 18 irradiated WFAs are held in the SFP as described above, and 36 WFAs continue to operate their fourth cycle in the SU3 Cycle 25 core.

Excellent irradiation fuel performance has been observed on all WFAs in Cycles 21-24 with all results within the bounds of the Westinghouse experience database. No fuel assembly damage has been observed on any fuel assembly after the 2012 outage. Details on the final SU3 PIE after completion of Cycle 24 is provided below.

3.2.1. EOC24 PIE in SU3

During the period of 22-28 December, 2014, 26 Westinghouse WWER-1000 Fuel Assemblies (WFA) were inspected during offload. Thereafter, full scale PIE was performed on 6 selected WFAs using the Westinghouse FIRE stand. These inspections were carried out in February, 2015. Also all 66 WFAs that had operated in the Cycle 24 core were visually inspected during core unloading and SFP loading.

Twenty-six (26) of the 66 WFAs which had operated in Cycle 24 belong to the UNFQP reload batch. A UNFQP Commission with representatives from the Ukrainian Center for Reactor Core Design (CRCD), SUNPP, PNNL and Westinghouse approved all of the 26 UNFQP WFAs without reservations.

Specifically the following can be noted:

- Fuel assembly or fuel rod damage was not observed on any WFA.
- The maximum RCCA drop time at Cycle 24 was 2.34 sec at BOC and 2.34 sec at end of cycle (EOC), which is significantly below the design value of 4.0 sec. None of the 26 WFAs operated under RCCA in Cycle 24.
- The highest WFA drag force during core unloading equaled ~ 70 kgf which is significantly lower than the design limit of 150 kgf. The minimum WFA drag force during core unloading was below 5 kgf.

Full scale PIE on the six selected WFAs included half-face fuel assembly visual inspections, fuel assembly length measurements, RCCA drag force measurements, grid growth measurements, fuel rod elongation measurements, peripheral rod oxide measurements, and fuel assembly bow and twist measurements.

Selected WFA for Full Scale PIE

One 3x-burnt WFA and five 4x-burnt WFAs (UNFQP WFAs) were selected for the full scale PIE using the Westinghouse FIRE stand. The average burnup of the inspected WFAs covers a range from 35.5 to 45.6 MWd/kgU, while the fuel rod burnup is in the range from 30.6 to 48.4 MWd/kgU.

The five 4x-burnt UNFQP WFAs were selected for inspections because they have been operating in different core sectors with one group of fuel assemblies (with similar burnup) on the core periphery, and the other group in the core center. Furthermore, all these FAs have a database of PIEs obtained during the outage of 2013 and three FAs have PIE results from the outage of 2012. See the WFA inspections history core map in Figure 3.1. Thus, the results of measurements for 5 WFAs after the 4th operation cycle, combined with the database on the FAs after their 2nd and 3rd operation cycles, provide a sufficient scope of operational data on FA elongation and bow, fuel rod and zirconium grid radiation growth, and closure of fuel rod gaps with FA burnup in the range of 20.5 – 45.6 MWd/kgU.

The 3x-burnt WFA was selected for inspection because there are operational data obtained for it during the PIE in the outage of 2013. Therefore, the results of measurements obtained during 2014 inspections will allow:

(1) to increase the operational database for confirmation of WFA design parameters with increasing burnup and

(2) to evaluate repeatability of measured radiation-induced parameters of the WFA design elements after 3 operation cycles performed during the outage of 2013.

Also, the location in the core for this 3x-burnt WFA and the results of shape and bow measurements, combined with similar data obtained for the 4th cycle WFAs, will allow evaluation of how burnup and local surrounding impact WFA deformation in the mixed core.

Actual fuel rod corrosion measurements were carried out for the first time for ZIRLO claddings operated in the WWER-1000 coolant chemistry. To provide statistical data on the thickness and nature of oxide distribution on the fuel rod cladding, two (2) peripheral fuel rods with similar burnup were inspected for the 4th cycle WFAs.

For the 3x-burnt WFA 3 groups of peripheral fuel rods were selected for measurements to provide additional information about oxide thickness on the cladding and thickness variations over the fuel stack active part. These measurements supplement the data of similar measurements obtained for the 4th cycle WFA fuel rods, and expand the database on ZIRLO oxidation in the burnup range of 30.6 – 48.4 MWd/kgU.

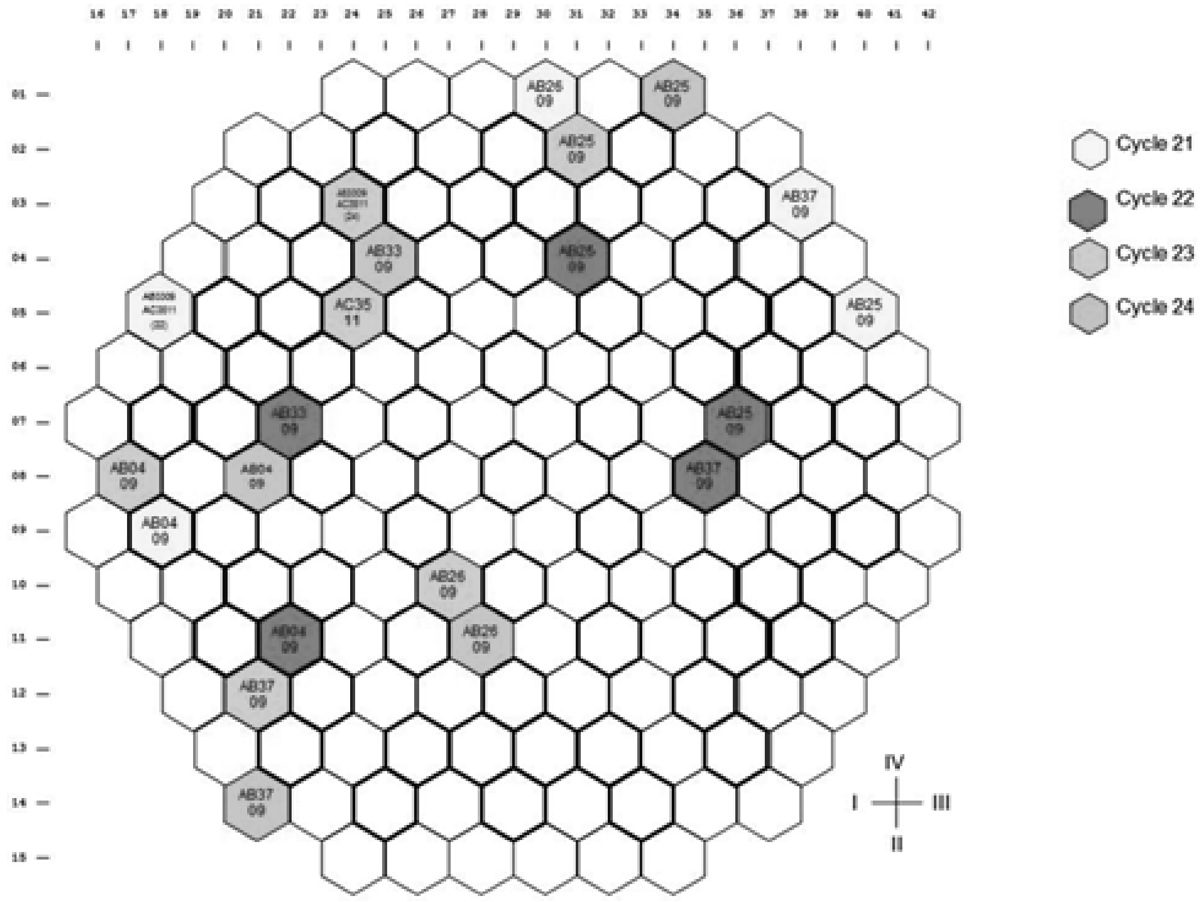

Figure 3.1. WFA Inspections History Core Map

Half Face Visuals

The Westinghouse camera system was used to perform half face visual inspections on fuel assemblies. These visuals were used to obtain rod-to-nozzle gap and channel gap data.

Half face (5 to 6 rods) visuals were used to determine fuel rod growth. The fuel assemblies were scanned using the camera system mounted on the XYZ inspection fixture. Axial gaps between each peripheral rod and the assembly nozzles were measured from the videos to determine the fuel rod growth data.

The minimum total rod-to-nozzle gap was 30.1 mm which is greater than the minimum allowable value of 22 mm and the calculated fuel rod growth data is consistent with the Westinghouse ZIRLO clad fuel rod growth database and the previous SUNPP PIE results.

Half face visuals were used to obtain fuel rod bow data. The fuel assemblies were scanned using the camera system mounted on the XYZ inspection fixture. The channel spacing between each peripheral rod in Spans 1 through 15 was measured from the videos to determine the fuel rod bow data.

The maximum percent channel closure for each fuel assembly is less than the maximum allowable limit of 50% closure. The SU3 EOC-24 data are consistent with previous SUNPP results.

Fuel Assembly Length

Fuel assembly length and growth were determined by measuring the height difference between a known reference standard. The lengths were measured using the stainless steel instrument tube probe. A stainless steel length standard was used to calibrate the system. The probe was inserted into the fuel assembly instrument tube. The length was determined by calculating the difference between the measured standard and the measured fuel assembly data.

The measured fuel assembly growth for each inspected fuel assembly is significantly less than the maximum allowable value of 6.48 mm. The maximum average calculated FA growth is 1.97 mm. The SU3 EOC-24 fuel assembly growth data are fully consistent with the Westinghouse database and the previous SUNPP results.

RCCA Drag Force

RCCA drag was measured in the SFP with a special tool that was used to grip the RCCA hub. A load cell and a signal conditioner were used to measure the drag, and the data were recorded on the data logger.

The RCCA drag forces were less than the maximum allowable value of 8 kgf for the fuel assemblies that were in the Cycle 24 core, with a maximum of 5.3 kgf.

Studies have been carried out, using the Westinghouse RCCA drag force database, to determine the risk for Incomplete RCCA Insertion (IRI) in connection with a certain drag force. These studies indicated that the overall drag work, which is the drag through a distance, could be used as an indicator for the incomplete RCCA insertion condition. It was determined that the risk for IRI could become potential when the drag work exceeds 240 Nm. The drag work for all measured fuel assemblies in SU3 is significantly less than 240 Nm. The maximum is 106 Nm. The maximum RCCA drag force measurements are fully consistent with the Westinghouse RCCA drag force database with ZIRLO guide thimbles and with previous SUNPP results.

Fuel Assembly Bow and Twist

Half face visuals were used to determine the fuel assembly bow. The distance to the face of the grid edge was measured while the camera that was mounted on the XYZ inspection fixture was moved in the Z direction. In the measurement process the Corner 5-6 (the corner between Faces 5 and 6) was positioned closest to the XYZ inspection fixture to measure the bow on Face 4. The fuel assembly twist was determined from the rotation of the bottom turntable with respect to the top nozzle, while inserting the fuel assembly into the workstation.

The measured fuel assembly bow was less than 10 mm with a maximum of 9.2 mm.

The measured twist was less than 3 degrees for all assemblies.

The SU3 EOC-24 bow and twist results are consistent with the Westinghouse database with ZIRLO guide thimbles.

Grid Growth

Grid growth data was obtained while the measurement fixture was on top of the workstation. The system used the ultrasonic transducers to obtain data. In the measurement technique, the data is obtained while either inserting or withdrawing the fuel assembly from the workstation. The fixture clamp was used to hold the fuel assembly in place during the measurement process.

The grid growth is 0.22% and all grid growth results are consistent with the database for zirconium grids.

Peripheral Fuel Rod Oxide

The eddy current (EC) lift-off technique was used to measure corrosion films on fuel rod cladding. The technique measured the distance from the bare zirconium alloy metal surface to the EC probe (separated by the oxide thickness) as a voltage, and converts the voltage into the distance (oxide thickness) using a calibration curve established based on the reference. If heavy crud is observed on the fuel rod, an attempt must be made to brush off crud so the EC data corresponds to the true oxide layer since the EC lift-off technique cannot differentiate between oxide and crud.

The peripheral fuel rod oxide measurement technique was used to collect oxide data without removing fuel rods from an assembly, therefore, oxide thickness values were measured only at one azimuthal orientation of a fuel rod. In comparison, between two and eight azimuthal orientation measurements are taken when using the single fuel rod oxide measurement technique.

The reported oxide values were averaged. Averaging over 22.5 mm axial length sections is an accepted industry practice since these average values eliminate local oxide variations and they are more representative when compared to the models.

The maximum measured value was 24 μm in WFA AB-2605, which is significantly less than the maximum allowable values of 50 μm. The SU3 EOC-24 results are on the low side of Westinghouse WWER oxide database, but it shall be noted that this database also contain oxide measurements on rods with Zr-4 cladding. ZIRLO fuel rods do tend to accumulate less oxide thickness in comparison to Zr-4 fuel rods.

3.3. WFA Region Design Operational Experience and PIE Results in SU2

The first region of 42 WFA was loaded in the SU2 core in Cycle 24, 2011. During the EOC-24 outage in 2012 several WFAs were noted to have bent grid corners. These conditions were observed while performing visual inspections during the core offload. Rub marks on the bottom nozzle, top nozzle, and multiple faces of spacer grids were also observed. Debris was also noted on some of these fuel assemblies and a rod contact mark was noted on one fuel assembly.

Twenty-seven (27) 1x burnt WFAs were reloaded into the Cycle 25 core. Of the 15 fuel assemblies not loaded into the core; 3 had no damage and are acceptable to use-as-is. Twelve (12) WFAs will need to be repaired. As a consequence of Ukrainian Regulator decision, no fresh WFAs were loaded in SU2 Cycle 25.

Due to the FA damages observed at EOC-24 it was required to carry out core offload and outage inspections at EOC-25 to evaluate the condition of the WFAs reloaded in the Cycle 25 core. All 27 WFAs in the C25 core were twice-burned.

SU2 EOC 25 Core Offload Results

1. No additional fuel assembly damage was observed on any of the irradiated fuel assemblies.
2. All twenty-seven (27) fuel assemblies were acceptable for re-use. Debris removal was recommended for 7 of the 27 fuel assemblies. One (1) fuel assembly requires a detailed inspection or should be used in a location with the damaged face facing the core baffle.

Despite the conclusion that all 27 irradiated WFAs were in good condition, no WFA was reloaded into SU2.

SU2 EOC-25 Outage Results

Excellent irradiation fuel performance was observed on the measured fuel assemblies. The total rod-to-nozzle gap, channel closure, fuel assembly growth, RCCA drag, and fuel assembly bow data were within the bounds of the Westinghouse experience database.

- The minimum total rod-to-nozzle gap is greater than the minimum allowable value of 22 mm. The calculated assembly-wise average percent fuel rod growth from the EOC-25 at SU2 is consistent with the Westinghouse ZIRLO clad fuel rod growth database, and the EOC-22 SU3 results.
- The maximum percent channel closure is less than the maximum allowable limit of 50% closure. The SU2 data from the EOC-25 is consistent with the data from WWER-1000 plant A, and the EOC-22 SU3 results.
- The measured fuel assembly growth is significantly less than the maximum allowable value for a twice-burned fuel assembly of 6.48 mm.
- The growth percentages calculated are consistent with the Westinghouse database of fuel assemblies with ZIRLO guide thimbles and the EOC-22 SU3 results.
- The RCCA drag forces for the 4 inspected WFAs were less than the maximum allowable value of 78 N (8 kgf). The SU2 EOC-22 RCCA Drag data are consistent with the Westinghouse database for fuel assemblies with ZIRLO guide thimbles.

4. Conclusions

- The UNFQP supplied LTAs as well as the supplied reload batches of WFAs, have successfully demonstrated safe mixed-core operation. Twenty-six (26) UNFQP WFAs have completed their planned four cycles of operation. Thirty-six (36) WFAs continue to operate their fourth cycle in the SU3 Cycle 25 core.
- The spacer grids mechanical damages experienced during core loading of SU2 and SU3 in 2012 is not an operational issue. The high lateral loads were caused by a combination of distortion and stiffness of the mixed core. No incremental grid damage has been observed on any WFA in any consecutive outage.
- To prevent further mechanical damages, Westinghouse has enhanced the WWER-1000 design to increase lateral grid strength and to minimize the risk for harmful interaction between assemblies. The first reload of the enhanced Robust Westinghouse WWER-1000 Fuel Assembly has been loaded into SU3 in March-, 2015.
- All WFAs operated in the SU2 and SU3 cores have been subject to the standard leak testing process with all fuel rods found to be hermetically sealed and non-leaking.
- PIE for the WFAs has been completed after each cycle of operation. All assemblies have been examined for visible damage or non-standard position of fuel assembly components. In addition at each outage, six (6) WFAs have been subject to a more extensive inspection program.
- Excellent irradiation fuel performance has been observed and measured on all WFA. The fuel assembly growth, RCCA drag forces, oxide thickness, total fuel rod-to-nozzle gap channel closure, and fuel assembly bow data were all within the bounds of the Westinghouse experience database.

References

[1] Enhanced VVER-1000 Fuel Technology and Performance
7th International Conferences on WWER Fuel Performance, Modelling and Experimental Support in 2009, H Shah et. al

[2] Performance of the Westinghouse WWER-1000 fuel design
9th International Conferences on WWER Fuel Performance, Modelling and Experimental Support in 2011, J Höglund et. al.

[3] Enhanced Westinghouse WWER-1000 Fuel Design for Ukraine Reactors
11th International Conferences on WWER Fuel Performance, Modelling and Experimental Support in 2015, M Dye et. al.