Performance of the Westinghouse WWER-1000 fuel design

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ABSTRACT
In 2005 six (6) Westinghouse WWER-1000 Lead Test Assemblies (LTAs) were loaded in the South Ukraine Unit 3. This design has demonstrated full compatibility with resident fuel designs and all associated fuel handling and reactor components. Operations have further demonstrated adequacy of performance margins and the reliability requirements for multiple cycles of operation. The LTA’s have now been discharged after completing the planned four cycles of operation and having reached an average assembly burnup in excess of 43 MWd/kgU.

Post Irradiation Examinations were performed after completion of each cycle. The final LTA inspection program at end of Cycle 20 in 2010 yielded satisfactory results on all counts, and it was concluded that the 6 Westinghouse LTA’s performed as expected during their operational regimes. Very good performance was demonstrated in the WWER-1000 reactor environment for the Zr-1%Nb as grid material, and ZIRLO® fuel cladding and structural components. Control Rod Assemblies drop times and drag forces were all within the accepted values.

The LTA program demonstrated that this fuel design is suitable for full core applications. However, the topic of fuel assembly distortion resistance was re-visited and Westinghouse therefore considered operational experience and design features from multiple development programs to enhance the basic Westinghouse WWER-1000 fuel design for Ukrainian reactors. The design now includes features that further mitigate assembly bow while at the same time improving the fuel cycle economy. This paper describes briefly the development of the Westinghouse WWER-1000 fuel design and how test results and operational experiences from multiple sources have been utilized to produce a most suitable fuel design.

Early in 2011 a full region of the Westinghouse WWER-1000 design completed another full cycle of operation at South Ukraine Unit 3, all with excellent results. All 42 fuel assemblies were examined for visible damage or non-standard position of fuel assembly components during unloading from the core. In addition all 42 assemblies were subject to the standard leak testing process with all found to be hermetically sealed. Six fuel assemblies of this Westinghouse reload batch were then subjected to a more extensive inspection program similar to what was done during the LTA program. Detailed results and concluding remarks from the post irradiation examination is provided in this paper.

Westinghouse has now completed manufacturing and delivery of three regions of the Westinghouse WWER-1000 design to the South Ukraine NPP. Manufacturing of these fuel campaigns has gone very well without major issues, and the production of the WWER-1000 design has been integrated successfully with the other product lines in Sweden. In the second half of 2012 the first region of fuel to the Zaporizhzhya NPP will be delivered.
1. Introduction

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 Westinghouse WWER-1000 Fuel Assemblies (WFA) to Ukraine. This first full reload batch of 42 WFA was manufactured at the fuel fabrication facility at Westinghouse Sweden and loaded in the South Ukraine Nuclear Power Plant Unit 3 (SU3) in February 2010. This WFA reload batch has since accumulated another cycle of safe operation 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, and in conjunction with the transfer of Westinghouse nuclear analyses technology to Ukraine. The LTAs have now been discharged after completing the planned four cycles of operation in total compliance with the regulatory requirements, and having demonstrated very good results in all of the Post Irradiation Examinations (PIE’s) performed after completion of each of the four cycles.

A follow-on contract for deliveries of 3 reloads of WFA annually for 5 years was agreed to in 2008 between the National Nuclear Energy Generating Company Energoatom (NNEGC) and Westinghouse Sweden. The contract establishes deliveries to South Ukraine Nuclear Power Plant Units 2 and 3 and to Zaporizhzhya Unit 5. The contract also contains engineering support and thermal-hydraulic testing in the new test loop “ODEN” in Västerås, Sweden.

Westinghouse has now completed manufacturing and delivery of three full regions of the WFA to the South Ukraine NPP. In the second half of 2012 the first region of fuel to the Zaporizhzhya NPP will be delivered.

2. LTA Design Development History

Significantly different from the Westinghouse VV6 Temelin fuel assembly design, the WFA has been designed to not only be 100% compatible with the WWER-1000 reactors, but designed to specifically perform safely in mixed core transitions with existing Russian fuel assemblies and to excel reliably and economically in equilibrium core operations.

2.1 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 was considered a good design as it met all of the design objectives and with good margin. The testing performance was also excellent. All completed tests showed significant margin to the design limits and in certain tests the LTA design out-performed many other Westinghouse PWR fuel designs that have performed very well by themselves in the field for many years.

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 LTA Operational Experience and final PIE results

The LTAs performed well in the SU3 core during Cycles 17-20, demonstrating very good results 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 of their operating cycles. Each LTA was even operated in an rod cluster control assembly (RCCA) core location during Cycle 19. The LTA locations in the core during Cycles 17-20 is presented in Figure 2.1.

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 at the end of SU3 Cycle 20 in 2010 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 assemblies (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, even on the Zr1%Nb grids inner and outer strap welds.
- 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 cladding of periphery rods was present. The fuel rod growth was as predicted and could have accommodate even more growth.
- Dummy 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 with no problems.

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

There was an indication of a possible small fuel rod leak in one of the LTAs at the end of cycle 20 based on statistical analysis ($^{131}$I activity was $7.5 \times 10^{-6}$ Ci/kg; $^{133}$Xe activity was $2.6 \times 10^{-6}$ Ci/kg; however, no activity of solid fission products, such as $^{141,143}$Ce and $^{103,106}$Ru was found in the test sample). Furthermore, according to the plant procedures, the suspect LTA was still suitable for further operation. Nevertheless, plans are underway for the installation of testing equipment at SU3 to increase such inspection capabilities.
Figure 2.1 Westinghouse LTA locations within the core, Cycles 17-20
Very good performance was demonstrated in the WWER-1000 reactor water chemistry environment for the Zr-1%Nb as grid material, and the ZIRLO® fuel cladding and structural components. Appearance of the Zr1%Nb grid and Zr1%Nb inner strap intersect welds after 4 cycles of operation are shown in Figures 2.2 and 2.3 respectively.

A light coloring along the outer strap vertical welds of Zr1%Nb mid grids indicates that some corrosion is present. Visible "rippling" effect of the laser welder (see Figure 2.3) indicates that the corrosion thickness is minimal.

![Figure 2.2 Condition of Zr1%Nb Mid Grid](image)

The inner strap thickness of Zr1%Nb grids appears to be uniform within the resolution allowed by the inspection equipment, indicating that the level of corrosion is low, as expected. The picture below shows an example of intersects welds appearance of Zr1%Nb grids.

![Figure 2.3 Condition of Zr1%Nb Mid Grid inner strap intersect welds](image)

Based on the fuel rod surface appearance after four cycles of operation, it is confirmed that the expected corrosion performance of ZIRLO cladding in WWER-1000 coolant chemistry is normal and well within acceptable limits for the operational time experienced by LTAs. As an example, Figure 2.4 shows the appearance of peripheral rod clad surfaces on Face #6 of LTA AA01-03 along the entire fuel assembly length.

Visual inspection of the fuel rod top and bottom end plugs weld joints did not indicate any visible mechanical damage or discontinuities at the fuel rod ends after 4 cycles of operation (see examples in Figures 2.5 and 2.6).

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Figure 2.4 LTA AA01-03, Face #6 Fuel Rod Surface after 4 Cycles of operation
3 WFA Design Margin

The LTA program clearly demonstrated that the WFA fuel design is suitable for full core applications. However, since all of the major fuel manufacturers for PWR and WWER reactors have at one time or another experienced unintended FA distortions that can interfere with plant operational requirements, and because this situation becomes more challenging when making plans to implement extended fuel cycles, fuel designers continue to be preoccupied with this FA distortion phenomenon. Westinghouse has not been immune to this sobering experience and actively evaluated and implemented a number of measures to specifically add design margins with respect to FA distortion resistance to many of its fuel designs.

3.1 Distortion Resistance Experience

FA distortion resistance is the ability of a FA structure to resist bow and twist during operation under in-core loading conditions and Incomplete Rod Insertion (IRI) means that a control rod assembly does not insert fully into the assembly in which it resides. The type and magnitude of FA distortion is influenced by a combination of internal FA design features and external reactor interface conditions. While IRI is primarily related to FA bow there is also a contribution from items like the RCCA and drive line design.
It should be noted that the original VV6 fuel assembly delivered to Temelin is very different to the WFA designed for Ukrainian NPP’s. The key differences with impact on the IRI performance for each of these two fuel designs can be described as follows:

- **Guide Tube Geometry.** The guide tube design for the WFA uses uniform geometry, while the VV6 used un-strengthened variable geometry. Fuel assemblies with un-strengthened variable geometry are now known to be more susceptible to IRI because even for small lateral deflections in the reduced guide tube diameter regions a significant amount of drag can be developed due to the smaller gap between the control rod and the guide tube.

- **Guide Tube Material.** ZIRLO guide tube material is used for the WFA, while VV6 used Zircaloy-4. It is a known fact that irradiation growth and creep levels are less with ZIRLO guide tubes, which results in lower fuel assembly bow.

- **Skeleton Architecture.** The WFA design incorporates 16 spacer grids, while the VV6 only used 9. An increased number of grids means that the spacing between grids is smaller which has the effect of stiffening the guide tubes and reducing the magnitude of bow and resultant RCCA drag force. The grid height and guide thimble to spacer grid joint type can also have an impact.

The VV6 FA design was upgraded to include a Tube-In-Tube dashpot to eliminate the un-strengthened variable geometric design shortcomings and to use ZIRLO guide thimbles. In addition the spacer grid attachment method was enhanced from a single bulge to a double bulge to increase the lateral stiffness margin of the skeleton. The upgrades made to the VV6 assembly design eliminated the Temelin IRI performance concerns.

### 3.2 Implemented design features

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 that was found to be successful was also embodied in the WFA design used in the reload batches of fuel for Ukrainian reactors. The double bulge at each grid location vs. a single bulge is shown schematically in Figures 3.1 for the LTA design and in Figure 3.2 for WFA design.

![Figure 3.1 LTA Design](Grid Sleeve Top of Grid Guide Thimble Bulge Joint.png)
![Figure 3.2 WFA Design](Grid Sleeve Top of Grid Guide Thimble Bulge Joint.png)

The effect of this design feature is shown in Figure 3.3 in terms of lateral stiffness margin improvements and shows a relative comparison to the lateral stiffness of the VV6 fuel design. Out of pile mechanical tests also demonstrate that the skeleton structural stiffness is equivalent to the successfully operating Westinghouse square lattice designs.
As the database of successful operating experience with the utilization of Zirconium alloy spacer grids continues to accumulate worldwide, it has been technically possible to increase the use of this material in the WFA design. Zr-1%Nb material is used in 13 of the WFA grids to further improve fuel cycle economics. With this design the 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.

Figure 3.4 summarizes the design evolution from the Westinghouse LTA design to the WFA. The WFA design features are:

- **Westinghouse Removable Top Nozzle.** The spring package is designed to provide an optimal spring constant, deflection range and hold-down force. The design enables individual fuel rod inspections and repair. It also eliminates any potential risk for loose parts.

- **Inconel Top Grid.** The top grid has springs with an optimized force to minimize fuel rod bow.

- **Inconel Bottom Grids.** The bottom grids have a high spring force that provides sufficient rod retention force throughout life, to eliminate grid-rod fretting.

- **Zr-1%Nb Mid Grids with double bulge.** For increased lateral stiffness and distortion resistance with improved fuel cycle economy.

- **ZIRLO Guide Thimble Tubes.** For low growth and resistance to assembly bow.

- **ZIRLO Fuel Rod Cladding.** The ZIRLO alloy is characterized by a superior combination of mechanical properties and corrosion resistance, including robustness against coolant chemistry variants.

- **Gd₂O₃ as Burnable Absorber material.** Plant specific 3-D distributions provide for custom configurations to lower fuel cycle costs and to accommodate special high burnup requests.
The ZIRLO alloy has been used extensively by Westinghouse for PWR cladding, grids and guide tubes, with a very good track record. It is characterized by low growth and creep, low corrosion rate, robustness against coolant chemistry variability, and a mechanical strength similar to Zry-4. Currently 83 plants including SU3 worldwide have utilized the ZIRLO alloy. The Westinghouse operating experience with ZIRLO clad nuclear fuel from 1991 through March, 2010 includes 467 regions totaling 32,685 fuel assemblies and representing over 8.11 million irradiated fuel rods. Discharge burnups in excess of 52 MWd/kgU have been achieved in more than 3,700 assemblies with over 900,000 fuel rods.

Figure 3.4 Westinghouse LTA design and WFA design
3.3 WFA Performance
Under stage 2 of the UNFQP a reload batch of 42 assemblies of the WFA design was manufactured at Westinghouse plant in Västerås, Sweden and loaded into the SU3 core in 2010. Standard neutronic core follow of the 42 WFA in the transition core environment is being performed during Cycles 21-24 as well as a detailed examination program.

During March 2011, after the end of cycle 21 the batch of 42 WFAs was subjected to an examination program that included:

- visual inspections;
- RCCA drag force measurements;
- fuel assembly drag force measurements;
- fuel assembly relative length measurements;
- sipping tests.

The inspection program in 2011 was completed satisfactory and in full accordance with the established requirements. A commission composed of Westinghouse, South Ukraine Nuclear Power Plant, Center for Reactor Core Design, and PNNL was able to conclude that the 42 WFAs performed as expected during their first cycle of operation. Inspection results demonstrated:

- Integrity of all spacer grids and absence of any axial displacement.
- Absence of defects or damages in weld joints in the visible sections of the spacer grid straps; only minor burnishes in some areas on the outer surface of some spacer grids due to sliding contact during FA shuffling operations.
- Absence of defects or damages near any fuel rod end cap joint.
- Absence of any abnormal fuel rod displacement towards top or bottom nozzle.
- Absence of damages in peripheral or second row of fuel rods visible by the video camera.
- Absence of visible faulty attachments of the fuel rods into the spacer grids.

Furthermore:

- The visual inspection did not reveal any visible damage or relocation of WFA individual components that could lead to engagement with other FAs, core components, equipment or devices used for handling FAs.
- None of the 42 WFAs was observed to have damages, deformations, or other defects that would prevent them from further operation.
- The drag forces during WFA removal from the core and during visual inspection and during their removal/installation from/into storage pool rack cells did not exceed the design values. A maximum WFA drag force of ~ 80 kgf was recorded. In general, WFA drag forces during core unloading did not exceed 50 kgf. This indicates that all 42 WFA adequately resisted deformations.
- The RCCA drag force on the 42 WFAs and the drop times of the RCCA (with drive lines) in WFAs met the requirements of the SU3 Technical Specifications. Measured drop times were approximately two times less than allowable limits.
- The maximum axial difference of once burnt WFAs in the core was 2 mm.
- Sipping tests were conducted on all 42 WFA. All results were negative.
4.0 Westinghouse WFA Manufacturing

Westinghouse’s Västerås facility has now completed manufacturing and delivery of three regions of the WFA to the South Ukraine NPP. Manufacturing of these fuel campaigns has gone very well without major issues, and the production of the WFA design has been integrated successfully with the other product lines in Sweden. Customer quality audits and several manufacturing follow up campaigns have been carried out, all with satisfactory results. In the second half of 2012 the first region of fuel to the Zaporizhzhya NPP will be delivered.

5.0 Conclusions

- WFAs at the SU3 have met all operational and regulatory requirements since 2005.
- The ultimate customer, NNEGC Energoatom, has been quite satisfied with the performance of the WFAs.
- The UNFQP supplied LTAs successfully demonstrated safe mixed-core operations.
- The UNFQP supplied reload batch of WFAs is successfully demonstrating safe mixed-core operation capabilities in greater than test quantities of FAs.
- Operational performance of the LTAs and WFA has positively confirmed the performance calculations and predictions.