BOW EVALUATIONS TO SUPPORT FUEL ASSEMBLY DESIGN IMPROVEMENTS

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ABSTRACT

Fuel assembly bow during operation adversely affects fuel performance. A systematic methodology has been applied to predict in-core bow during a selected operational cycle. Unique bow measurement campaigns were performed at Ringhals 3 and 4 NPP at the beginning and at the end of the selected cycle to provide input and basis for the simulation. The predicted fuel assembly bow magnitudes and shapes have then been compared with the out-of-core bow measurements at the end of the selected cycle. It has been concluded that the fuel assembly bow prediction is reasonable. The simulation results were then used to determine the necessary fuel assembly design improvements, to mitigate the increasing assembly bow trend observed at Ringhals 3 and 4, and quantitatively assess their benefits.

Keywords: Fuel Assembly, Bow, RFA-2, MRFA-2, Ringhals 3 and 4

1. Introduction

Westinghouse Electric Company LLC (Westinghouse) introduced the 17x17 Robust Fuel Assembly (RFA) design in the United States in 1997, with insertion in European pressurized water reactors (PWR's) occurring shortly thereafter. The RFA design and its successor, RFA-2, have operated in 60+ reactors around the world with excellent overall fuel performance. For the purposes of this discussion, it is relevant to note that the RFA-2 design was introduced at Ringhals 3 in fall 2010, with Ringhals 4 following in fall 2012.

Vattenfall AB (Vattenfall), the owner of the Ringhals 3 and 4 units, established a rigorous fuel assembly bow measurement program in the mid-1990's to actively manage any adverse trends that could potentially lead to incomplete rod insertion (IRI) or peaking factor penalties (e.g., FdH for radial power and FQ for local power).

Until recently the measurement program consisted of inspecting approximately 20 selected fuel assemblies at the end of each Ringhals 3 or 4 cycle. In the last two outages in Ringhals 3 and the latest outage in Ringhals 4 this program has been expanded to encompass measurements of all fuel assemblies that operated in the core. These measurements provide a good database for evaluating assembly bow evolution trends across the two cores, so as to understand the impacts of the various fuel designs in operation and core management practices used and their resultant impact on the bow measured. Ultimately, bow magnitude and shapes provide a good baseline for evaluating potential impact on core design parameters (e.g., peaking factors) due to increased gaps between adjacent fuel assemblies during operation.

The collected bow measurements revealed an adverse upward trend in assembly bow at Ringhals 3 and 4, which needed to be addressed by Vattenfall and Westinghouse. Detailed analyses and a fuel development program were put in place to mitigate the issue before it could lead to plant operational restrictions.

The overall evaluation consequently led to RFA-2 design modifications. The Modified RFA-2 (MRFA-2) design was developed by Westinghouse to support the fuel management and operational conditions at Ringhals 3 and 4. The design's fuel assembly distortion resistance has been increased by the introduction of several operationally-proven design features to increase the skeleton's lateral stiffness and reduce the axial fuel assembly holddown loads, while meeting the pre-defined acceptance criteria for homogeneous and transition cores.

As discussed below, extensive simulation, development and testing has been completed to ensure that the design changes provide the necessary improvements in fuel assembly distortion resistance and thereby will address the upward trend in the Ringhals 3 and 4 assembly bow evolution.

2. Fuel Assembly Bow Trend Observations

The Ringhals 3 and 4 units have been performing fuel assembly bow measurements at the end of each cycle since 1995. The data have been tracked by Vattenfall for each cycle in an effort to establish trending for assembly average and maximum bow over time [1]. Note that since Ringhals 3 and 4 operate with mixed cores of Westinghouse and competitor fuel, only Westinghouse RFA-2 bow data is discussed in this paper.

Figures 1 (Ringhals 3) and 2 (Ringhals 4) provide an overview of the maximum and average one-sided (in x- or y-direction) bow trends measured out-of-core in an upright condition.

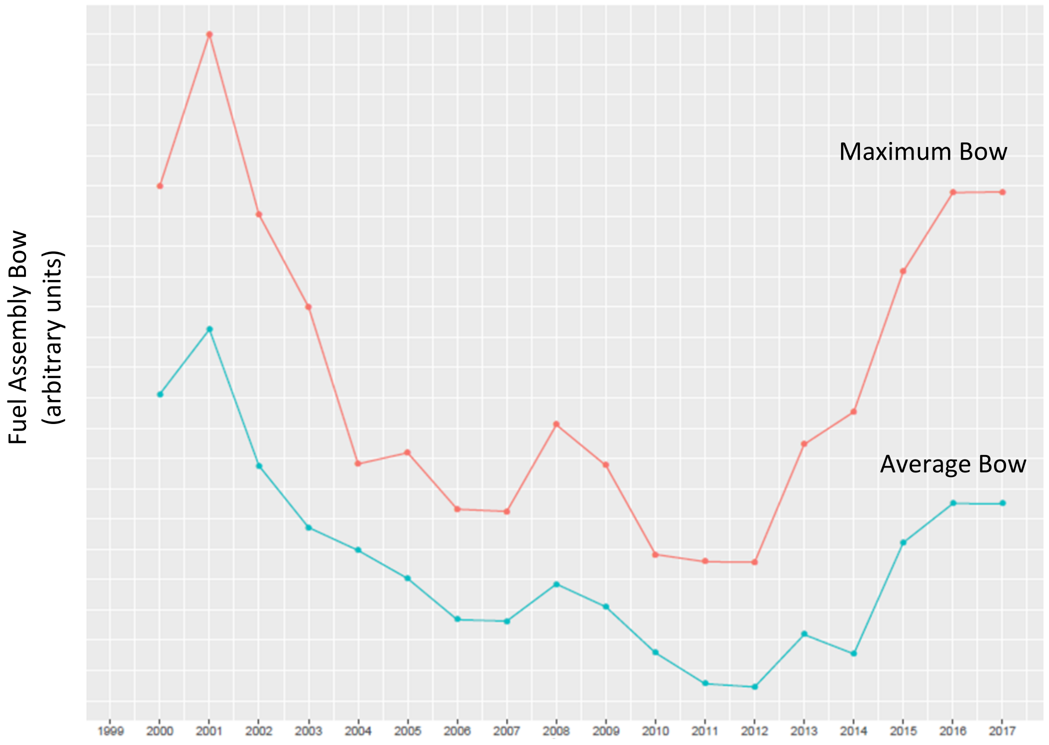


Figure 1: Ringhals 3 Fuel Assembly Bow Trend
(no dimensional values are provided above; only trend shown)

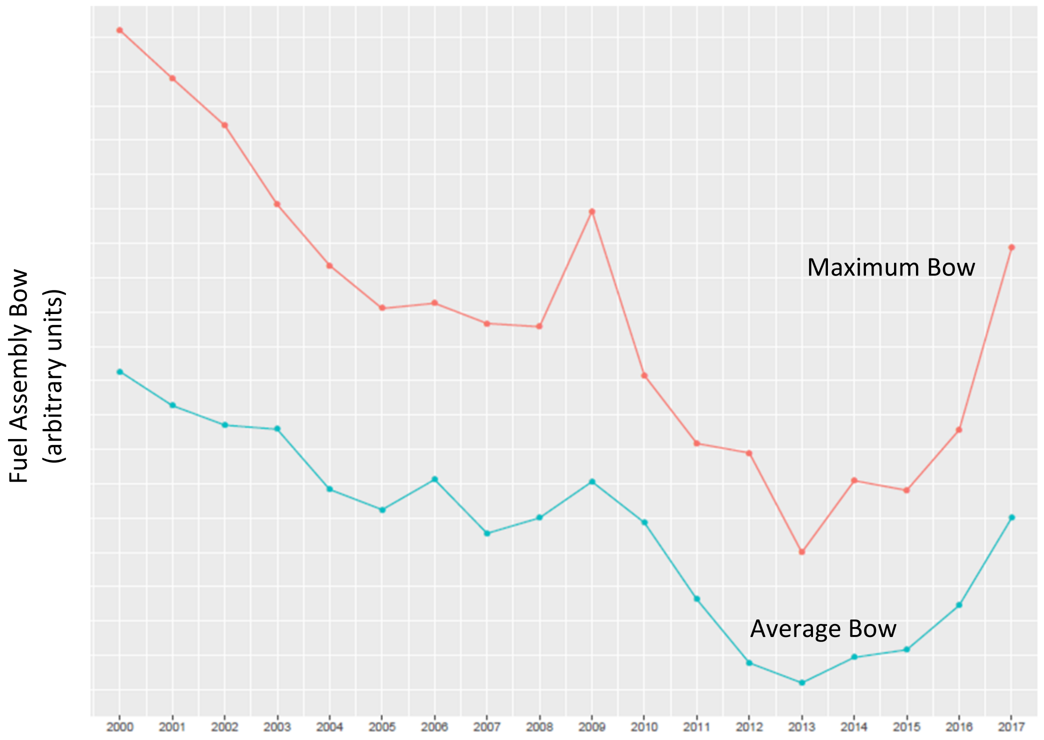


Figure 2: Ringhals 4 Fuel Assembly Bow Trend
(no dimensional values are provided above; only trend shown)

As can be seen in both Figures 1 and 2, the maximum and average assembly bow trends have increased with time since the introduction of the RFA-2 fuel design at Ringhals 3 (in 2010) and 4 (in 2012). It should also be noted that significant changes have been introduced to the units' operational conditions (uprate) and fuel management (significant changes in cycle lengths and corresponding numbers of feed assemblies) in the same time frame (2010+).

While the maximum assembly bow values were less than those seen in other RFA/RFA-2 fuel exams within the Westinghouse fleet, this adverse assembly bow trend is of concern to Vattenfall and Westinghouse, and an active program was put in place to mitigate the bow trend before it could evolve into a significant plant operational issue.

3. In-Core Fuel Assembly Bow Simulation

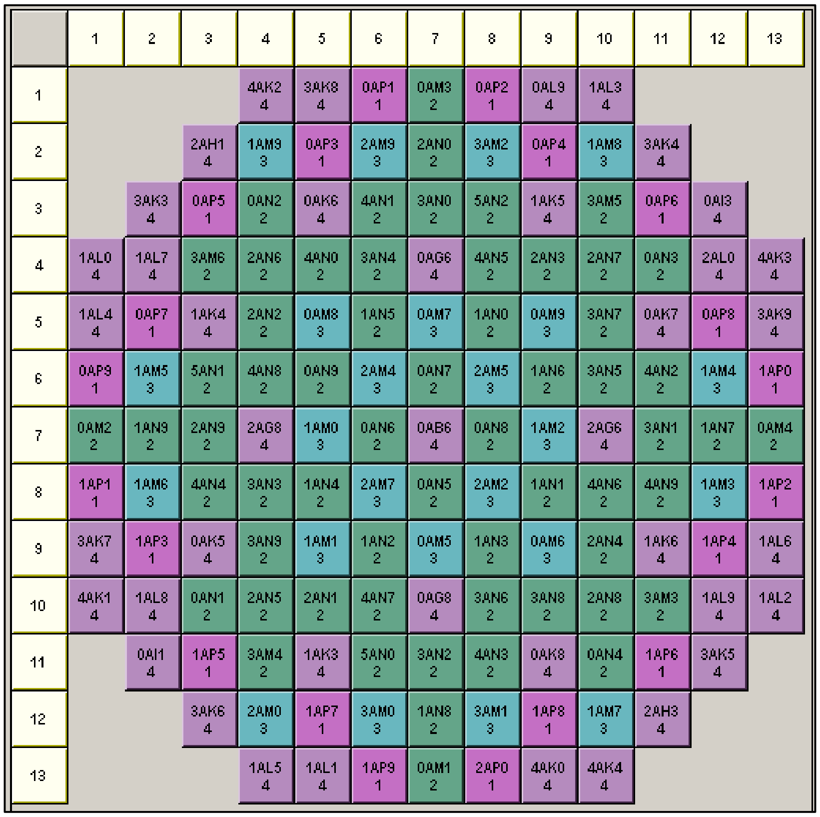
An in-core fuel assembly bow simulation was performed by Westinghouse to support recommendations to address the observed upwards bow trend at Ringhals 3 and 4.

Fuel assembly distortion is a difficult phenomenon to understand and effectively predict, given all the variables associated with the fuel's performance. Parameters such as core internals' as-built dimensions, fuel assembly characteristics, fuel management strategies, fuel and RCCA handling, etc., could potentially determine the in-core bow evolution.

Westinghouse has developed a methodology [2] and a corresponding modeling tool [3] to determine in-core bow distributions based on out-of-core bow measurements. This in-core bow distribution is then used to determine the corresponding assembly-to-assembly water gap distributions, while taking into account the representative fuel loading and core thermal-hydraulic boundary conditions. This information and other fuel design inputs then allow the fuel designer to assess the variables associated with fuel assembly bow.

For Ringhals 3, simulations were performed by Westinghouse using a model representative of the RFA-2 fuel design, with two sets of core design inputs prepared by Westinghouse and Vattenfall.

The simulation input was constructed using the Ringhals 3 end of "Cycle N-1" out-of-core assembly bow measurements provided by Vattenfall to Westinghouse. For the limited number of uninspected burned fuel assemblies then used in subsequent "Cycle N", but not in the core during the previous Cycle N-1, distorted assembly shapes were assumed for these fuel assemblies based on the previous bow measurements from assemblies at those core locations. The Ringhals 3 Cycle N core map, showing the various sub-regions, used in this simulation is presented in Figure 3.



	1	2	3	4	5	6	7	8	9	10	11	12	13
1				4AK2 4	3AK8 4	0AP1 1	0AM3 2	0AP2 1	0AL9 4	1AL3 4			
2			2AH1 4	1AM9 3	0AP3 1	2AM9 3	2AN0 2	3AM2 3	0AP4 1	1AM8 3	3AK4 4		
3		3AK3 4	0AP5 1	0AN2 2	0AK6 4	4AN1 2	3AN0 2	5AN2 2	1AK5 4	3AM5 2	0AP6 1	0AI3 4	
4	1AL0 4	1AL7 4	3AM6 2	2AN6 2	4AN0 2	3AN4 2	0AG6 4	4AN5 2	2AN3 2	2AN7 2	0AN3 2	2AL0 4	4AK3 4
5	1AL4 4	0AP7 1	1AK4 4	2AN2 2	0AM8 3	1AN5 2	0AM7 3	1AN0 2	0AM9 3	3AN7 2	0AK7 4	0AP8 1	3AK9 4
6	0AP9 1	1AM5 3	5AN1 2	4AN8 2	0AN9 2	2AM4 3	0AN7 2	2AM5 3	1AN6 2	3AN5 2	4AN2 2	1AM4 3	1AP0 1
7	0AM2 2	1AN9 2	2AN9 2	2AG8 4	1AM0 3	0AN6 2	0AB6 4	0AN8 2	1AM2 3	2AG6 4	3AN1 2	1AN7 2	0AM4 2
8	1AP1 1	1AM6 3	4AN4 2	3AN3 2	1AN4 2	2AM7 3	0AN5 2	2AM2 3	1AN1 2	4AN6 2	4AN9 2	1AM3 3	1AP2 1
9	3AK7 4	1AP3 1	0AK5 4	3AN9 2	1AM1 3	1AN2 2	0AM5 3	1AN3 2	0AM6 3	2AN4 2	1AK6 4	1AP4 1	1AL6 4
10	4AK1 4	1AL8 4	0AN1 2	2AN5 2	2AN1 2	4AN7 2	0AG8 4	3AN6 2	3AN8 2	2AN8 2	3AM3 2	1AL9 4	1AL2 4
11		0AI1 4	1AP5 1	3AM4 2	1AK3 4	5AN0 2	3AN2 2	4AN3 2	0AK8 4	0AN4 2	1AP6 1	3AK5 4	
12			3AK6 4	2AM0 3	1AP7 1	3AM0 3	1AN8 2	3AM1 3	1AP8 1	1AM7 3	2AH3 4		
13				1AL5 4	1AL1 4	1AP9 1	0AM1 2	2AP0 1	4AK0 4	4AK4 4			

Figure 3: Ringhals 3 Cycle N Core Layout
(with different sub-regions of fuel)

The simulation results of the bow evolution were then compared with the out-of-core bow measurements conducted by Vattenfall at the end of "Cycle N". The maximum out-of-core bow magnitude was conservatively predicted as presented in Table 1. A reasonable agreement between measured and predicted maximum assembly bow dimesions and shapes was observed as presented in Figure 4. Note, however, that the core location of the fuel assembly with the maximum radial bow was not well predicted. This is likely due to the use of an incomplete set of the initial bow distributions/data and the corresponding loading forces. Also, hydraulic lateral forces were not included in this simulation. The example of measured and predicted in-plane bow at a selected grid elevation is presented in Figure 5.

Out-of-Core Maximum Bow	**X-Direction**	**Y-Direction**
Predicted / Measured Ratio	1.1	1.1

Table 1: Ringhals 3 End of "Cycle N" Predicted vs. Measured Bow

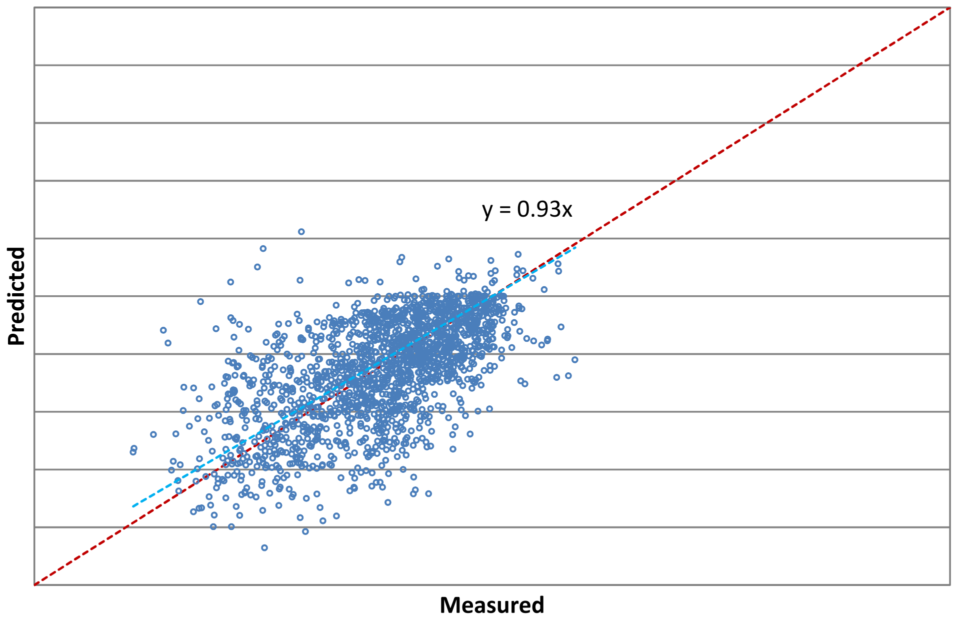


Figure 4: Ringhals 3 End of “Cycle N” Out-of-Core Predicted vs. Measured Bow

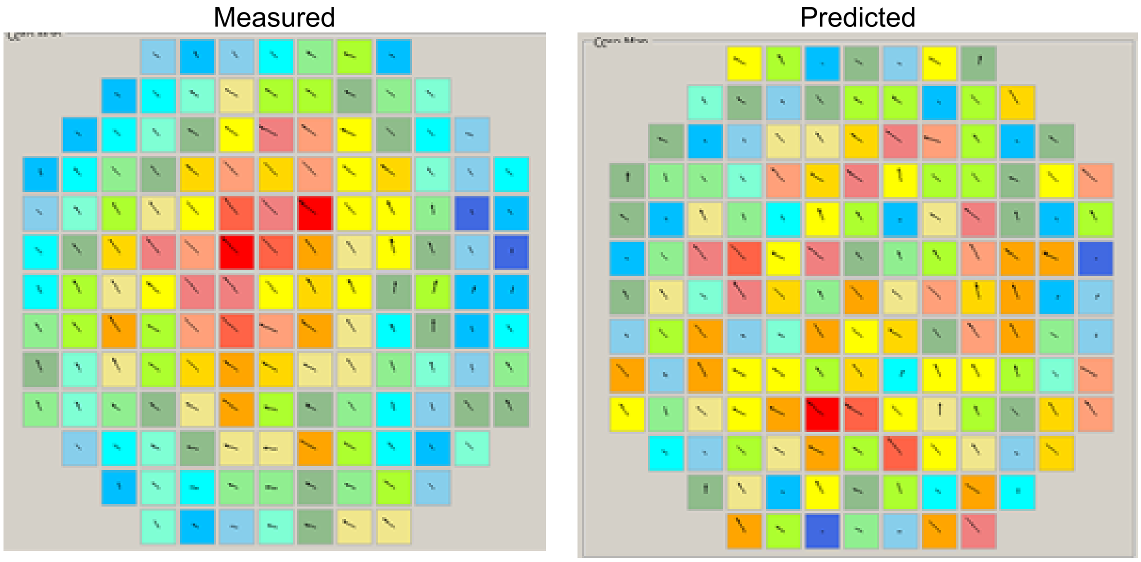


Figure 5: Ringhals 3 In-Plane Bow Distribution at a Selected Grid Elevation for an RFA-2 Core Inventory

(Arrows/vectors used in this figure reflect the relative magnitude of bow within the individual assemblies, while the various colors show locations of bowed assemblies of similar magnitude. Note that no bow prediction was made for a core with the new MRFA-2 fuel design added.)

Using the simulation results, for bow mitigation purposes, early efforts were then made to evaluate the bow direction in the core, bow shape (C, S or W shapes), values of average and maximum bow magnitudes, number of fresh feed assemblies that would tend to “straighten” the core, locations of the variously burnt fuel, etc. This work included the review of preliminary Ringhals 3 and 4 core loading plans to identify options for fuel assembly loading that may have stemmed the upward bow trend. This involved taking the bow shapes and magnitudes of planned re-insert fuel and orienting them in the core so as to minimize bow, without adversely impacting core design criteria or energy requirements for the upcoming cycle. For example, based on its bow shape, moving once-burnt fuel slated from one core location symmetrically to another location to help straighten surrounding assemblies was considered as a core design strategy.

The study of different core loading plans indicated that, with the present peaking factor restrictions and energy requirements, the loading pattern changes proposed were insufficient to significantly affect the assembly bow development in the core. The simulation results instead suggested that fuel design improvements were needed to increase the RFA-2's distortion resistance to address the observed upward bow trend.

4. Modified RFA-2 Development

As part of a multi-pronged approach to mitigating the increasing assembly bow trend, Westinghouse developed in concert with Vattenfall, a new fuel design, 17x17 Modified RFA-2 (MRFA-2), for specific application at Ringhals 3 and 4. The MRFA-2 design's development built upon the previously noted overall good performance history of the RFA/RFA-2 product (60+ plants having used 27,000+ assemblies since the design's introduction through 2017). The specific objective of the now completed MRFA-2 design project was to enhance fuel assembly distortion resistance via increasing skeleton stiffness and reducing holddown forces acting on the fuel during operation.

The MRFA-2 design incorporates an added bulge at the top of each mid grid to stiffen the assembly (confirmed by MRFA-2 test results and operational experience from other Westinghouse and Combustion Engineering designs with similar design features), plus optimizes the top nozzle holddown forces acting upon the assembly. Figure 6 shows the location of the added bulge, while Figure 7 reflects the final design for the top nozzle (Westinghouse Integrated Nozzle (WIN) with Recess). The MRFA-2 WIN utilizes the "Recess" feature to lower the top nozzle leaf springs by a small distance on the fuel assembly, resulting in a reduction in holddown forces that act upon the assembly in-core.

The 17x17 MRFA-2 design for Ringhals 3 and 4 includes the following key features:

- ZIRLO®[1] Guide Thimble with Tube-in-Tube dashpot
- ZIRLO Instrument Tube
- Westinghouse Integral Nozzle (WIN) with Recess
- Alloy 718 Top Grid
- ZIRLO Mid Grids with double bulge feature
- ZIRLO Intermediate Flow Mixing (IFM) Grids
- Alloy 718 High Force Bottom Grid
- Alloy 718 Robust Protective Grid (RPG)
- Standardized Debris Filter Bottom Nozzle (SDFBN)
- Debris Mitigating Long Fuel Rod Bottom End Plugs
- Optimized ZIRLO™ Clad Fuel Rods with rod bottom zirconium dioxide protective coating
- Mixed Gd_2O_3 Burnable Absorber Rods

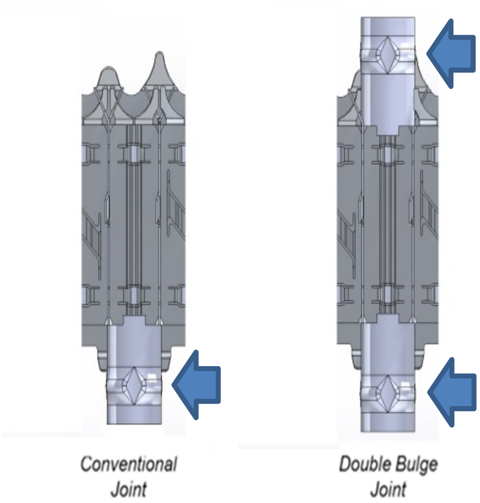


Figure 6: Comparison of Conventional Joint (RFA-2) vs.
Double Bulge Joint (MRFA-2) Mid Grid Bulge Configurations

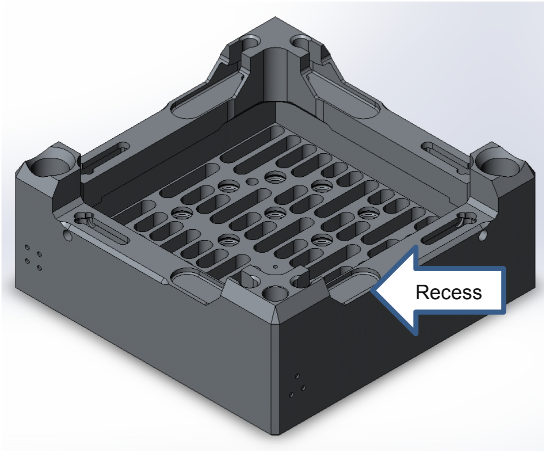


Figure 7: 17x17 WIN Top Nozzle with Recess (MRFA-2)

The comprehensive fuel development program described here utilized numerous tests and simulations to confirm that the MRFA-2 design has enhanced distortion resistance, while meeting all requirements for Ringhals 3 and 4 homogeneous and transition cores.

In particular, MRFA-2 skeleton and fuel assembly tests have been conducted to confirm that the lateral stiffness of the MRFA-2 design increased relative to the Ringhals 3 and 4 RFA-2 design. The typical assembly load-versus-deflection test results are presented in Figure 8. The MRFA-2 skeleton lateral stiffness increases by ~30% relative to the current RFA-2 design, while the fuel assembly lateral stiffness increases by 8 to 20%, depending on the bow amplitude.

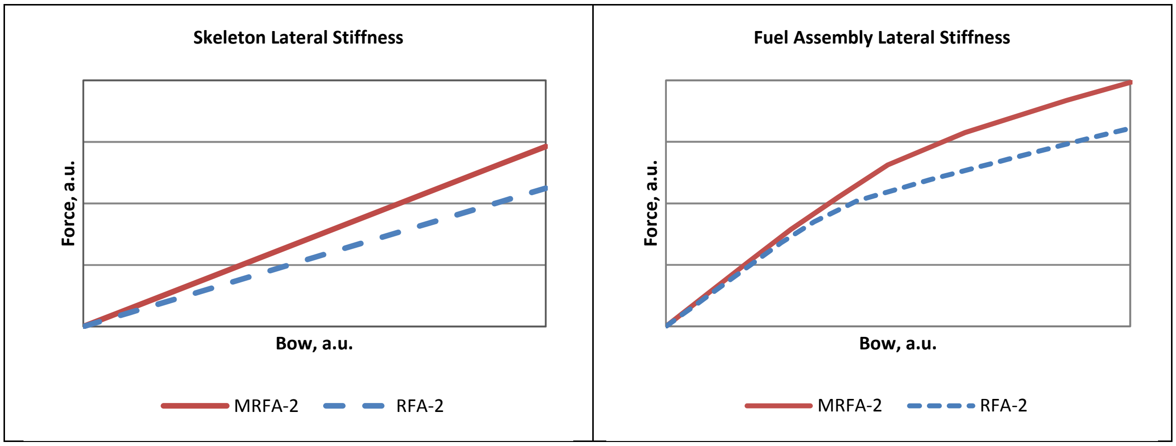


Figure 8: MRFA-2 and RFA-2 Skeleton and Fuel Assembly Lateral Stiffness

In addition, top nozzle holddown force was reduced by 20% relative to the current RFA-2 design by the introduction of the “Recess” feature in the WIN nozzle.

Additional simulations on a comparative basis were performed to assess the expected reduction in fuel assembly bow for the MRFA-2 design. While the actual operation conditions for MRFA-2 are not yet known for future Ringhals cycles, the bow evolution of a single fuel assembly of the new design at representative Ringhals 3 and 4 operating conditions suggests that the MRFA-2 design has the potential to reduce bow relative to the RFA-2 design (Figure 9).

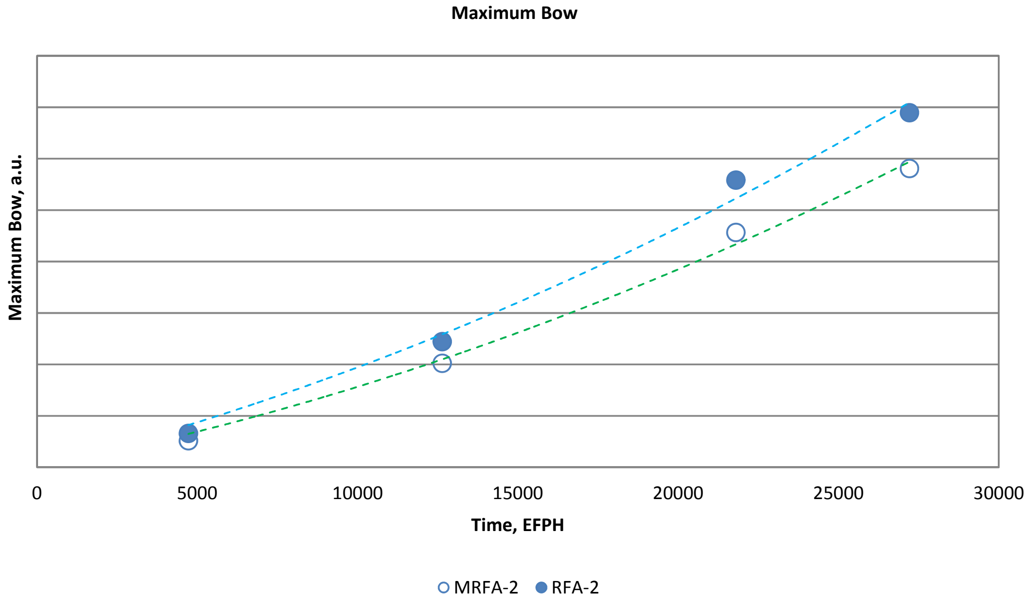


Figure 9: MRFA-2 vs. RFA-2 Estimated Bow Evolution on a Comparative Basis

The MRFA-2 design utilizes all of Westinghouse's proven fuel design features to increase fuel assembly distortion resistance (Table 2).

Feature	RFA-2			MRFA-2
	US Customer	European Customer	Vattenfall	
ZIRLO Skeleton	X	X	X	X
Thick-Walled Guide Thimble	X	X	X	X
IFM Grid	X		X	X
Tube-in-Tube Dashpot		X	X	X
Reduced Top Nozzle Holddown Force (with Recess)				X
Double Bulge Skeleton				X

Table 2: Features that Increase Fuel Assembly Distortion Resistance

Development of this new fuel design (MRFA-2) was just completed and delivered to Ringhals 3 in region reload quantities as part of the mid-2018 outage. The same fuel design will be used for Ringhals 4 in future cycles. Vattenfall plans to operate the new design through its three-cycle operational life, while taking out-of-core bow measurements at the end of each cycle for all fuel assemblies in the core. This bow data will then be compared to the historical bow data to confirm the new design is working to effectively halt the upward assembly bow trend.

5. Conclusion

The efforts discussed above indicate that, with a good measurement program in place to collect assembly bow data, the necessary analytical tool exists to properly model the subject cores. The understanding of the variables associated with fuel assembly bow then allow for predictions of future bow based on the various core management scenarios as defined by the core loading plan. The analytical tool also provides the necessary information to conservatively compare the existing fuel design (RFA-2) with the new assembly bow mitigating design (MRFA-2). With the now completed MRFA-2 development program's analyses and testing, the new MRFA-2 design clearly shows added assembly bow margin relative to the RFA-2 design. Planned bow measurements in the future at Ringhals 3 and 4 will provide final confirmation of the MRFA-2's success.

6. References

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