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Ex-core neutron exposure monitoring and reactor internals aging management at Ringhals

Greg Fischer[1,*], *Jenny* Roudén[2], *Johan* Blomström[2], and *Sylena* Smith[1]

[1]Westinghouse Electric Company LLC, Cranberry Township, PA 16066, USA
[2]Ringhals AB, SE-430 22 Väröbacka, Sweden

Abstract. This paper discusses the management of plant aging at the Ringhals Units 3 and 4 nuclear power plants and provides a summary of its extensive database of reactor dosimetry comparisons. Key exposure quantities of interest for reactor internals component aging evaluations are described compared to a similar plant with more typical fuel management practices. Finally, the incorporation of Ringhals exposure results into downstream thermal-mechanical calculations for Units 3 and 4 is described, as well as the relationship of these results to the reactor internals component inspection regime at Ringhals.

1 Introduction

Ringhals is a four-reactor commercial nuclear power plant located on Sweden's Western coast. Unit 1 at Ringhals is an ASEA-designed boiling water reactor, while Units 2 through 4 are Westinghouse-designed 3-Loop pressurized water reactors (PWRs). Units 1 and 2 were permanently retired at the end of 2020 and 2019, respectively, while Units 3 and 4 are expected to operate into the mid-2040s.

The radiation-induced degradation of the critical primary system components is being carefully managed to ensure safe and efficient operation throughout the projected service lifetime of the plant. As part of this program, Ringhals has instituted aggressive changes to its fuel designs and core loading patterns [1] to minimize the neutron exposure to sensitive regions on the reactor vessels of Units 3 and 4. Ex-vessel neutron dosimetry (EVND) measurement comparisons have been used to provide confirmation that the core loading pattern changes are achieving the intended reduction in neutron exposure. Ringhals Units 3 and 4 are now crossing the 40-year operation milestone with plans for continued operation far into the future. Recent work performed by Westinghouse and Ringhals has examined the neutron exposure and mechanical aging of the reactor internals components that hold and constrain the active core.

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[*] Corresponding author: fischega@westinghouse.com

2 Vessel and Internals Materials Issues at Ringhals

As previously reported [4] the Reactor Pressure Vessels (RPV's) of Ringhals Unit 3 and 4 have a beltline weldment that has proven to have a larger than usual shift in transition temperature, thus limiting the maximum fluence that the vessels may achieve during their lifetime. The reason for this higher embrittlement rate is high Nickel and Manganese content in the beltline weld, ~1.5 wt% for each of the two elements.

Due to different start-of-life conditions for the two RPV's there are different approaches to the remaining lifetime. Unit 3, which has a higher start-of-life transition temperature, has to use Shielding Fuel Assemblies in the periphery on the main axis of the core. The current version reduces the flux from the main axes of the core by a factor 7-8 times the original configuration with low-leakage patterns. With this shielding factor the irradiation embrittlement and current deterministic analysis of the Pressurized Temperature Shock (PTS) will limit the RPV on unit 3 to about 60 years of operation. Unit 4 will reach the limiting value also after about 60 years of operation but without Shielding Fuel Assemblies.

There are international efforts on-going that might change the pre-requisite in the analyses. For example, changing the input data to directly measured fracture toughness instead of conversion of results from impact testing; see [5]. This change in the input material properties in the structural integrity analyses reduces the transition temperature with remaining margin and thus adds allowable operating time for the RPV.

Beyond 40 years of operation the power plants are in so-called Long-Term Operation and the dose to internal components reaches levels that effect the material properties to an extent that could induce flaws in the structure due to irradiation. For instance, baffle bolts have shown such degradation mode internationally. Ringhals have not seen such failures in the inspection program. There are also some international experiences with cracks in circumferential weld and axial welds on the Core Barrel. These are also followed by the inspection program. Especially on Unit 3, where the axial weld in high flux region are placed behind the neutron pads. There are also other components that reach fairly high dose levels that need to be monitored both by analyses of the irradiation level as well as through inspection programs.

3 Institution of EVND and SFAs

Since 2008, Ringhals Units 3 and 4 have had an ex-vessel neutron dosimetry measurement program. At the axial elevation of the circumferential RPV welds nearest to the core midplane, aluminum capsules are positioned at four azimuthal locations in the reactor cavity as shown in Fig. 1. In addition, at the location of maximum flux (Location "A" in Fig. 1), two additional capsules are positioned at the elevations of the bottom and top of the active fuel. The dosimetry capsules contain copper, titanium, iron, nickel, niobium and cobalt-aluminum sensor materials. The capsules are supported and positioned by stainless steel chains that can be segmented and analysed for additional dosimetry data. At present, EVND measurements are collected at five-fuel cycle intervals. Both Ringhals units operate on 12-month fuel cycles.

Starting in 2009, twelve specially-designed shielding fuel assemblies (SFAs) were loaded into the periphery of the core along the cardinal axis locations to achieve a reduction in RPV neutron exposure. The fuel changes have been instituted in two "generations" of SFA designs. The first generation SFA design was axially-uniform, and employed three rows of stainless steel pins, followed by five rows of depleted uranium pins, followed by nine rows of low-enriched uranium pins for peripheral fuel assemblies on the core cardinal axes. A figure and core map for the first generation SFA design are provided in [1].

At Ringhals Unit 3, a second generation SFA design was instituted, providing stronger and more targeted reactor vessel neutron exposure reduction. The second generation SFA design is radially uniform, and features low-enriched uranium fuel pins in the top half of the assembly and stainless steel pins on the bottom half of the fuel assembly. See Fig. 2.

Ringhals Unit 4 used the first generation of SFA until the 2017 when the technical lifetime of the first generation of SFA were reached. Given its better initial material properties, Ringhals chose to re-load conventional fuel assemblies into peripheral positions at Unit 4. This strategy is expected maintain RPV neutron exposure within critical limits while still achieving the operational goals of the plant.

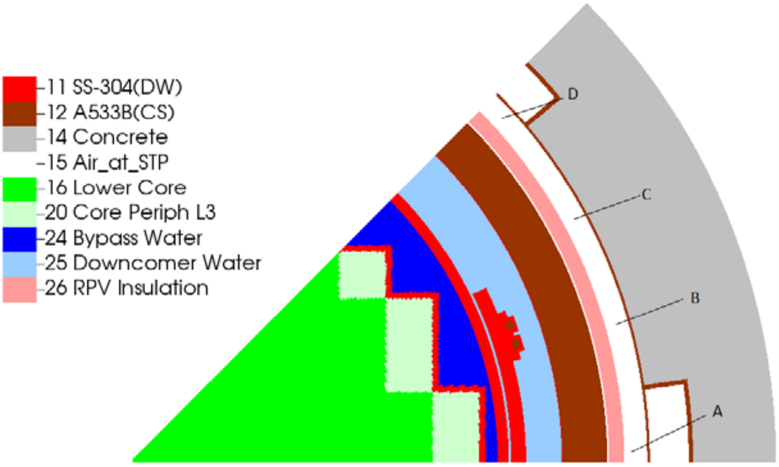

Fig. 1. Ex-Vessel Dosimetry Measurement Locations (A, B, C, and D) Ringhals.

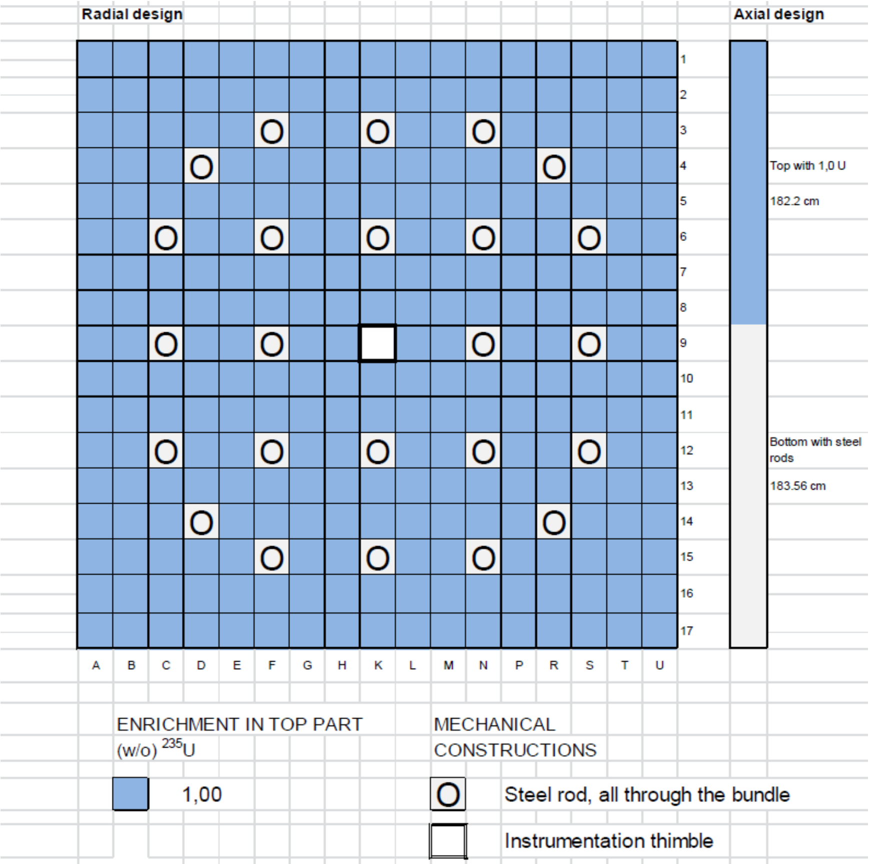

Fig. 2. Configuration of Second Generation Shielding Fuel Assemblies at Ringhals.

4 Ringhals Dosimetry Database

At Ringhals Unit 3, the dosimetry database consists of 88 in-vessel and ex-vessel high-energy threshold dosimetry sensor comparisons retrieved from the beltline elevations of the RPV. Similarly, At Ringhals Unit 4, the dosimetry database contains 93 beltline-region in-vessel and ex-vessel high-energy threshold dosimetry sensor comparisons. These data have been evaluated with the latest Westinghouse methodology [2], which applies three-dimensional discrete ordinates radiation transport calculations with ENDF/B-VI-based cross-section data in 47-neutron and 20-photon energy groups, and the comparisons are summarized in Table 1.

From the comparisons shown in Table 1, it may be observed that very few of the fission monitors (U-238 and Np-237) contained in the surveillance capsules are included in the comparisons. These measurements were performed by a third-party laboratory and either not reported to Westinghouse or showed large deviations from the database of Westinghouse measurements for similar plants. As a result, most of the fission monitor data were not evaluated. Note also that Table 1 only presents high-energy threshold dosimetry reactions that are most pertinent to material damage correlation parameters like fast neutron fluence (E > 1.0 MeV) and iron dpa. The cobalt-aluminum sensors included in the in-vessel and ex-vessel dosimetry capsules have been evaluated but are not reported here as they are not used as a formal benchmark of the calculational methodology.

In addition to the in-vessel and ex-vessel data, both plants underwent an extensive and innovative reactor vessel clad sampling campaign, previously described in [1]. As a result of these programs, the neutron environment inside the Ringhals Units 3 and 4 reactors is well-understood and continuously monitored.

Table 1. Summary of Beltline-Region Dosimetry Comparisons.

Sensor Type	Ringhals Unit 3			Ringhals Unit 4		
	Average	% Std Dev	# Samples	Average	% Std Dev	# Samples
Cu	0.98	11.6	18	1.05	16	22
Ti	0.97	9.5	16	1.06	7.8	16
Fe	1	8.9	19	1.05	8.1	22
Ni	0.94	9.8	19	0.98	7.3	16
Nb	0.99	9.2	16	1.07	7	16
Np	N/A	N/A	0	0.99	N/A	1
Total	**0.98**	**9.9**	**88**	**1.04**	**10.4**	**93**

5 Neutron Exposure Calculations for Reactor Internals Components

The [2] methodology generates a library of three-dimensional multi-group scalar flux data for each fuel cycle operated over the history of Ringhals Units 3 and 4. With this library of data, it is straightforward to extract neutron and/or gamma-ray exposure quantities at any location in the reactor environment and at any period of operation (past, present, or future) using tri-linear interpolation.

Ringhals and Westinghouse jointly developed a list of locations where neutron exposure data would be input to reactor vessel internals aging management evaluations. Neutron exposure were was retrieved and supplied to Ringhals for the core barrel, core barrel welds, the baffle plates, former plates, and upper and lower core plates. Exposure quantities evaluated include Fast Neutron (E > 1.0 MeV) and Iron DPA.

Plots of the projected Ringhals Unit 3 neutron exposure data after 52 effective full power years (EFPY) of operation are shown in Fig. 3, with a “binning” of fast neutron (E > 1.0 MeV) fluence according to the Region definitions set forth in MRP-191 [3]. Note the visible “shadow” imparted by continued operation with the axially-non-uniform 2nd Generation SFAs in Fig. 3.

A quantitative comparison of the volumes of material categorized into each MRP-191 region between Ringhals and a very similar (not-quite-identical) Westinghouse three-loop plant located in the USA appears in Table 2. The data in Table 2 reflect projected future exposure after 52 effective full power years (EFPY) of operation at each plant. Ringhals Unit 3, assuming continued operation with SFAs, shows reductions in the most highly-irradiated material relative to a similar 3-Loop plant. By contrast, Ringhals Unit 4, which assumes a reversion to a more typical core loading pattern, shows larger volumes of highly-irradiated material. Taken together, the variation in Table 2 reflects differences in core loading pattern designs and operating characteristics between the plants considered.

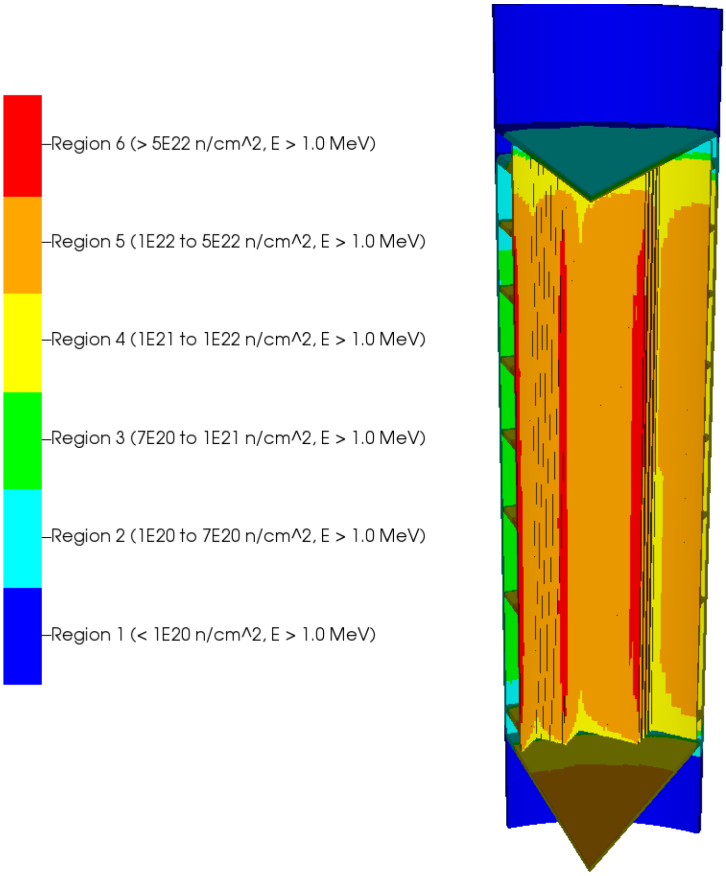

Fig. 3. MRP-191 Region Categorization at Ringhals Unit 3 After 52 EFPY.

Table 2. Comparison of Estimated MRP-191 Material Volumes Between Similar 3-Loop Plants After 52 EFPY.

Neutron Fluence Range (n/cm^2, E > 1.0 MeV)	Material Volume (cm^3)			Ratio	
	Ringhals-3	Ringhals-4	USA 3-Loop NPP	Ringhals-3 / 3-Loop	Ringhals-4 / 3-Loop
< 1E20	1.12E+06	1.08E+06	1.13E+06	0.98	0.95
1E20 to 7E20	1.03E+06	8.77E+05	1.11E+06	0.93	0.79
7E20 to 1E21	6.43E+05	6.12E+05	4.55E+05	1.41	1.35
1E21 to 1E22	2.10E+06	2.16E+06	2.13E+06	0.99	1.01
1E22 to 5E22	1.14E+06	1.27E+06	1.18E+06	0.96	1.08
> 5E22	5.32E+04	7.97E+04	6.25E+04	0.85	1.28
Total	6.08E+06	6.08E+06	6.08E+06	-	-

6 Reactor Internals Aging Management Evaluations

According to Swedish regulations, the In-Service Inspection (ISI) are determined on the basis of inspection groups. These inspection groups are classified based on damage and consequence index. Depending on the outcome there are three distinct groups: A, B and C.

The groups have different inspections intervals and portion of the components to be inspected. For example, objects put in group A are fully inspected by qualified personnel and equipment and objects in group C are inspected in-house at an extent that is determined by a periodic program. Part of the program is similar to EPRI MRP-227 [6].

Aging management of the internals consists mainly of an ISI program and one of the parameters for the grouping into different categories are the irradiation of the components. Higher dose may indirectly put a component into a more frequent ISI program. The dose impacts the material properties which is an input to the damage tolerance report which determines the detection target for the ISI method.

Two of the components are prescribed by the regulator, and these are the pressure vessel and the baffle bolts. The regulator has decided that these are to be inspected by qualified ISI every ten years.

Swedish regulations also stipulate that there should be a Periodic Safety Report (PSR) every ten years in order to prolong the operating licence for the plants. According to the latest performed PSR in 2019, the Long-Term Operation are guided by the IAEA Time Limiting Aging Analysis (TLAA) program, which is similar to the GALL report, NUREG-1801 [7].

To complement the dosimetry analysis, Ringhals has historically tested irradiated materials that have been made available after irradiation, for example the Flux Thimble Tubes have been tested for different irradiation levels. From these testing the Flux Thimble exchange criterion has been evaluated. The Flux Thimble Tubes are replaced when they reach 80 dpa or 20 years in the reactor. The material properties from the tested Flux Thimble Tubes are also used to evaluate the material properties of other internal parts where the dose can be evaluated. Other parts that may be used for evaluation of the fluence levels based on measured activity are for example the material removed from the top former during Up-flow conversion on Unit 3.

Ringhals unit 2 were permanently shut down in late 2019. Some parts of the internals are removed in order to determine the material properties and activity of the components. These materials are contributed to the bi-lateral project SMILE which is managed from the Swedish company Studsvik. Parts that are of particular interest are the baffle plates and the weld and base metal of the core barrel.

7 Conclusion

Ringhals AB intends to operate Units 3 and 4 into the mid-2040s. Integral to that plan is a program to manage and monitor neutron exposure levels to the RPV and reactor internals components through regular neutron fluence analysis and benchmarking of fluence analysis results against ex-vessel neutron dosimetry measurements. Neutron exposure quantities are inputs to determinations on required inspection level of rigor and frequency for the ISI program. In addition, irradiated material harvested from Ringhals, together with computed neutron exposure levels, are being used to improve the state of knowledge of irradiated material properties. This program helps to ensure the safe operation of the Ringhals units far into the future.

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