Intermediate Range Detectors for Control Rod Worth Measurements with Rod Insertion Method

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ABSTRACT

The possibility to use intermediate range detectors for the control rod reactivity worth measurements with the rod insertion method in typical pressurized water reactor was studied. In aim to predict ex-core neutron detector response, a detailed geometrical model of the core and ex-core structures with explicitly modelled ex-core neutron detectors were developed to be used with the state-of-the-art Monte Carlo code for neutron transport MCNP. The developed model and methods were used to predict intermediate range ex-core neutron detector response and its perturbation with the control rod movement. The axial dependant reaction rate redistribution factors were determined and used to correct the measured signal to obtain the control rod reactivity worth. Control rod reactivity worth measured with the rod insertion method was compared to the boron dilution measurements. A good agreement within 2 % was observed, which supports the possibility to use intermediate range detectors for rod insertion measurements in combination with detailed 3D Monte Carlo calculations. The use of intermediate range detectors for rod insertion measurements using newly calculated axial dependent reaction rate redistribution factors represent the way to update and improve the rod insertion measurements.

1 INTRODUCTION

For a safe operation of a nuclear power plant (NPP) it is important to accurately control the reactivity. Reactivity in a typical pressurized water reactor (i.e. Krško NPP) is controlled by boric acid dissolved in the water, the control rods, and burnable absorbers in the reactor core. The control rod reactivity worth is a safety related physical parameter and can be determined by calculations and by measurement. It can be measured by different methods, e.g. the boron dilution method, rod swap method or the rod insertion method. The rod insertion method [1] was developed at the Reactor physics department at the Jožef Stefan Institute and was world novelty at the time of publication. It is based on the analysis of the signal recorded with the ex-core neutron detectors during the continuous insertion of a control rod bank [2], [3]. The control rod reactivity worth is measured for each new core configuration before the start-up. For the rod insertion method power range detectors are currently utilized at the Krško NPP. Power range detectors cover almost the entire active core height and enable axial averaging of the signal. Their downside is relatively low neutron signal at low reactor powers compared to the background. On contrary, to the power range detectors, the intermediate range detectors utilize compensated ionization chambers, where signal due to the gamma rays can be compensated. Their upside is that their signal is well above the background signal or noise. As the control rod moves, the neutron flux profile in the reactor core also changes [4]. These redistributions can change the reading of the ex-core detectors, resulting in a non-linear power reading and influence control rod reactivity worth determination. To account for radial and axial redistributions, redistribution correction factors are introduced [4]. Due to the smaller active height intermediate range neutron detectors are more sensitive to the neutron flux redistributions caused by the control rod movement compared to the power range detectors. With accurate determination of neutron flux redistribution factors, the possibility to use intermediate range detectors instead of the power range detectors appears attractive and is analysed within this work.

2 KRŠKO NUCLEAR POWER PLANT

The research conducted within this paper focused on the Krško NPP, a representative pressurized water reactor. The Krško NPP is a Westinghouse design plant and has a two-loop pressurized water reactor that began electricity production in 1981. Currently, the thermal rating is 1994 MWt with 727 MWe gross electric production. The core is composed out of 121 fuel assemblies. Each fuel assembly has a 16×16 lattice filled with 235 fuel rods, 20 guide tubes for control rods and 1 guide for in-core instrumentation. In Krško NPP control rods are distributed in banks divided into safety (SA and SB) and operation (A, B, C and D) groups as presented in Figure 1. All control rods within the same bank are moved simultaneously.

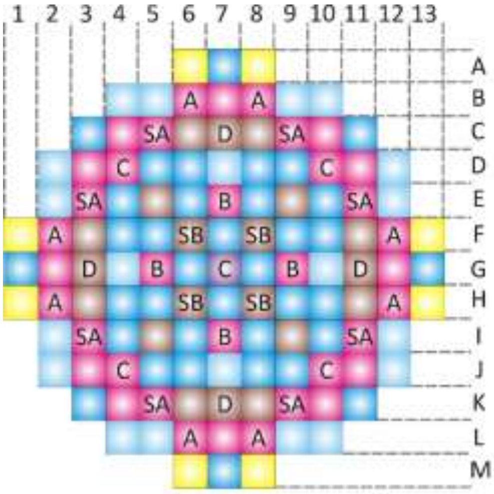

Figure 1: Krško nuclear power plant core configuration with marked control rod banks positions with letters. Different colors mark fuel assemblies with similar burnup and enrichment.

The ex-core detector system monitors neutron flux from shutdown conditions to 120 % of full power. This represents neutron flux variations from 10^{-1}-10^{11} n/(cm^{2}s) at the detector positions. To be able to cover such a wide range different types of neutron detectors are utilized. For the power reading on the source range level the Source Range Nuclear Instrumentation (SRNI) as BF_3 counters are used. The compensated ionisation chambers are used for the power reading in the intermediate-range as Intermediate Range Nuclear Instrumentation (IRNI), when the neutron flux levels begin to increase. They are sensitive enough to enable measurements at the source range, as well as at the full reactor power. In compensated ionisation chambers, the signal due to the gamma rays can be compensated. The SRNI and IRNI are positioned inside the polyethylene cover, which slows down fast neutrons escaping the reactor core to thermal energies that can be detected. During the normal power plant operation (at full power) the uncompensated ionisation chambers as Power Range Nuclear Instrumentation (PRNI) are used. The PRNI are not covered with the polyethylene cover. Both, neutrons and gamma rays contribute to the PRNI response. The ex-core neutron detectors are positioned inside the holes in the concrete wall next to the pressure vessel. The SRNI are positioned at the bottom, covering the lower part of the active core height. The IRNI are positioned on the top of the SRNI, approximately in the middle of the active core height. Schematic view of ex-core detectors positioning is presented in Figure 2. The redundancy is ensured by multiple locations, SRNI and IRNI are positioned at 90° and 270°. PRNI are positioned in four equally spaced locations around the core (locations 45°, 135°, 225° and 315°) with 2 power range detectors per channel.

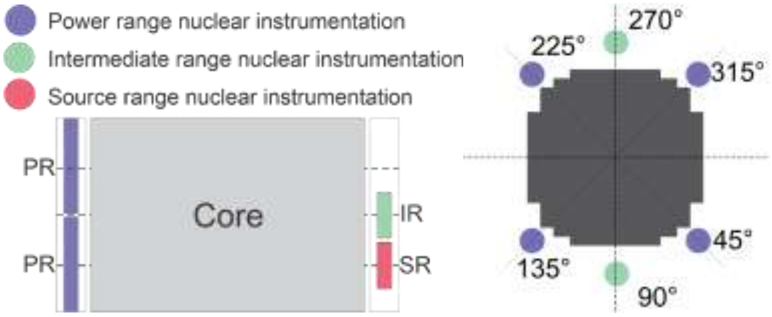

Figure 2: Axial (left) and azimuthal (right) positioning of ex-core detectors. Source range (SR) detectors are presented in red, intermediate range (IR) detectors in green and power range (PR) detectors in purple.

3 ROD INSERTION METHOD

The rod insertion method is based on the analysis of the recorded current coming from the ex-core neutron detectors during the continuous insertion of the control rod bank. Its main advantage is the high execution speed (about 15 minutes per control rod bank) in contrast to the boron dilution method, which takes about 4 hours. At the beginning of the rod insertion the nuclear reactor is critical with the control rod of interest completely withdrawn (marked with letter T in Figure 3). Then the control rod is inserted with constant insertion speed. When control rod is fully inserted (marked with letter B in Figure 3) it is waited for approximately 30 s before withdrawing the control rod bank (marked with letter I in Figure 3). The representative measured time signal from PRNI during rod insertion method is presented in Figure 3. With the insertion of the control rod bank the neutron flux and detector signal decreases for several orders of magnitude almost to the level of the background signal. When the control rod is completely inserted (marked as grey area in Figure 3) the background signal is determined (marked as black dashed line in Figure 3). The corrected signal can be obtained by subtracting the background from the measured signal. From the time course of the detector signal the reactivity is calculated using the inverse point kinetic equation [5]. To be able to use the inverse point kinetic equations the detectors signal needs to be proportional to the average neutron flux in the core. With the insertion of the control rod the spatial and temporal effects occur and the following corrections need to be applied: dynamic (evaluated in [3]) and spatial (evaluated within this paper). They can be applied during the measurement or within the post-processing of the detector signal.

For the rod insertion method power range detectors are utilized at the Krško NPP, because they allow axial averaging of the signal (two detectors at different axial positions per channel). However, their downside is relative low neutron signal compared to the background gammas at low reactor powers. The comparison of the measured detector signal from PRNI and IRNI detectors for the same control rod bank is presented in Figure 3. Because different types of neutron detectors with different signal amplitudes are compared, the normalization to the maximum signal was performed for comparison. It can be observed that in case of the PRNI applying background correction to the signal is necessary, however for the IRNI it is not needed. On contrary, to the PRNI, IRNI are compensated ionization chambers and the signal due to the gamma rays can be compensated. Due to the smaller active height IRNI are more sensitive to the neutron flux redistributions caused by the control rod movement. With accurate determination of neutron flux redistribution factors, the possibility to use intermediate range detectors instead of the power range appears attractive and is analysed within this work.

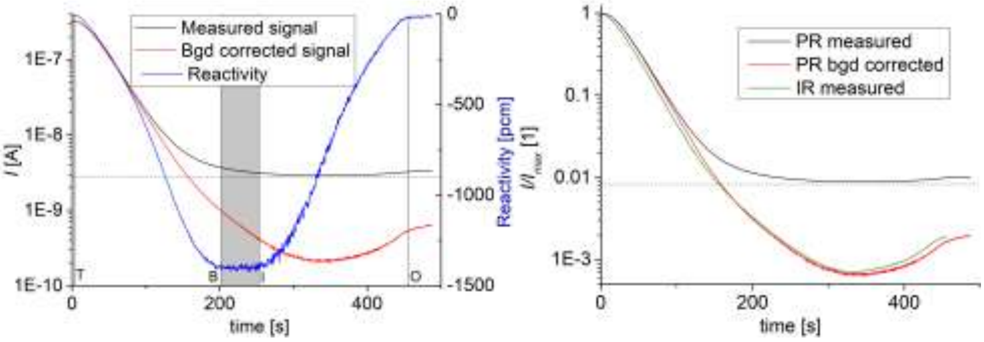

Figure 3: Absolute measured current (left) and relative measured currents normalized to the maximum value (right) during the rod insertion measurement for 28th fuel cycle SA control rod bank. Black and green colour denotes power range and intermediate range detectors, respectively. Current corrected by measured background (blacked dashed line) for power range neutron detector is in red. In blue is presented calculated reactivity.

4 CALCULATION PROCEDURE AND MODELS

This section outlines the calculation procedure employed to obtain the response of the ex-core neutron detectors. To accomplish this, two geometry models of the Krško NPP were created using the Monte Carlo code MCNP [6]. The first model provided a detailed description of the core configuration, encompassing the corresponding temperatures, densities and isotopic compositions. This model was used to study the fixed neutron source description needed to perform neutron transport outside the reactor core and determine the ex-core neutron detector response. For the results presented in this paper the fixed neutron source was generated to represent the hot zero power core state and was described on a fuel pin scale in 24 axial layers. The appropriate description of fixed neutron source for the ex-core neutron detector calculations was evaluated in previous research [4]. The second model (see Figure 4[1]) used for the calculations presented within this paper features an explicitly modelled ex-core neutron detectors, simplified representation of the reactor pressure vessel, and other important surrounding structures within the containment.

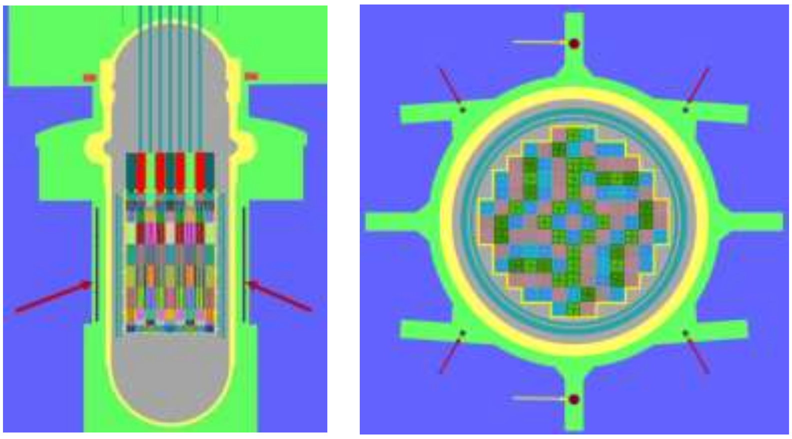

Figure 4: Side view (left) and xy view (right) of the ex-core detector positions (PRNI marked with red and IRNI with yellow arrows) inside the MCNP containment building model.

To speed up the convergence of the results outside the reactor core the hybrid code ADVANTG [7] was used to generate variance reduction parameters.

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[1] Figure is generated with Radiant utility within the ADVANTG used for rendering images of MCNP geometry models in a 3-D perspective [7].

5 RESULTS

Calculations presented in this paper were performed with Monte Carlo neutron transport code MCNP 6.1.1. [6] using ENDF/B-VIII.0 nuclear data library [8]. Variance reduction parameters generated with the ADVANTG code were generated using bplus nuclear data library with included up-scattering and FW-CADIS methodology [7]. Default values were used for other solver options. To ensure that the final results were valid and converged, all statistical tests were checked in the MCNP output file.

5.1 Neutron Flux Redistribution Factors

During the insertion of a control rod bank, the spatial distribution of the neutron population is changed [4]. Since the detector measures the local neutron flux at the ex-core location, a spatial correction should be applied to obtain a corrected response and a correct determination of the control rod reactivity worth. To account for radial and axial redistributions, neutron flux redistribution factors are introduced as a function of the axial position of the control rod bank. The neutron flux redistribution factors currently used at the Krško NPP were obtained using a single adjoint flux distribution calculation for the first operational cycle. The calculation was performed using the deterministic 2D code DOT-4.2 [9] and therefore could not accurately describe the geometry and neither predict the 3-D effects. The first operational cycle, unlike subsequent cycles, where Low Leakage Loading Pattern (LLLP) approach was applied, had fresh fuel located at the periphery of the core, resulting in about 30 % higher neutron leakage out of the core. It should be noted that these factors are about 30 years old and were determined with old Sailor nuclear data libraries [10] using rough energy discretization (47 neutron energy groups). In addition, they were determined only for PRNI. In our previous research the comparison of currently used neutron flux redistribution factors for PRNI and new factors calculated using MCNP were evaluated [4]. The important thing to note is that it is more appropriate to study the ex-core detector response (or ^{10}B(n,α) reaction rate) rather than solely neutron flux variations. This paper focuses on the determination of reaction rate redistribution factor for intermediate range detectors to be able to use them for the measurements of the control rod worth with the rod insertion method. An additional improvement is possibility to consider the impact of the reaction rate redistribution factors determined at multiple control rod axial positions.

The reaction rate redistribution factors ($f(\Phi)$) are defined by comparing the ^{10}B(n,α) reaction rate (*RR*) at the ex-core neutron detector location for the core configuration with the xth bank of interest completely inserted and all control rods completely withdrawn (marked with 0) as:

$$f\left(RR\left({}^{10}B(n,\alpha)\right)\right) = \frac{RR_x\left({}^{10}B(n,\alpha)\right)}{RR_0\left({}^{10}B(n,\alpha)\right)}. \tag{1}$$

The reaction rate redistribution factors for different control rod banks in multiple axial positions are presented in Figure 5 for the 28th fuel cycle. The step 0 denotes fully inserted control rod bank and step 225 denotes fully withdrawn control rod bank. The value of reaction rate redistribution factor is 1.0 at step 225, which corresponds to completely withdrawn control rod bank or ARO (all rods out) core configuration. It can be observed that the shape of the axial dependence of the reaction rate redistribution factors differs between different control rod banks. This can be explained by the positioning of different control rod banks within the core relative to the IRNI location (see Figure 1 and Figure 2). Observed variations further supports the idea of updating the rod insertion method with axial dependant reaction rate redistribution factors obtained by method presented in this work. It can be deduced that the axial dependence of the reaction rate redistribution factors has approximately the same shape for control rod banks B and SB. Both control rod banks (B and SB) are positioned closer to the centre of the reactor core (see Figure 1), which means that their insertion (control rod movement from step 225 to step 0) lowers the neutron flux distribution relatively more in the centre of the core compared to the core periphery. This leads to the reaction rate redistribution factor >1.0, since the neutron flux distribution within the core is tilted to the periphery compared to the ARO configuration, and the neutron detector measures a lower control rod reactivity worth, than the actual effect in the core is. The opposite can be observed for the control rod banks located at the core periphery (banks A, C and SA). The insertion of the control rod (movement from step 225 to step 0) located at the core periphery lowers the neutron flux distribution at the core periphery relatively more than at the centre of the core. This results in a reaction rate redistribution factor <1.0 when control rod is inserted (step 0), because the neutron flux distribution inside the core is tilted toward the core centre compared to the ARO configuration, and the neutron detector measures a higher control rod bank reactivity worth, than its effect in the core is. We can observe that the closest to the intermediate range detectors lies control rod bank A, which is the reason for its high reaction rate redistribution factors in comparison to other banks. The unique shape of the control rod bank D factors can be observed. This is due to its relative position inside the reactor core, as it is located approximately in the middle between the periphery and the core centre (see Figure 1).

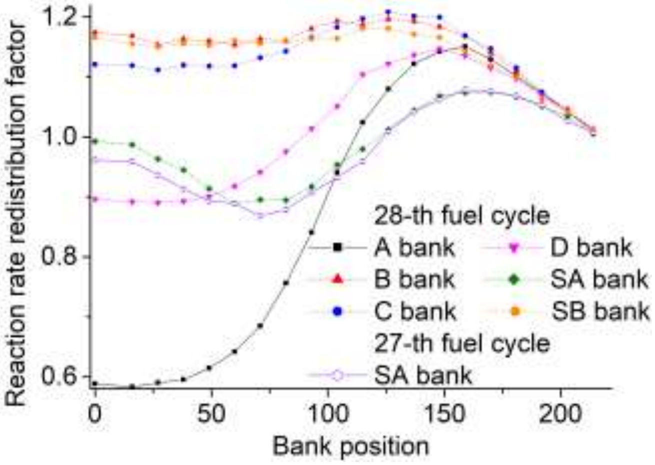

Figure 5: $^{10}B(n,\alpha)$ reaction rate redistribution factors in different axial positions for different control rod banks and fuel cycles for intermediate range detectors.

To demonstrate the difference in the reaction rate redistribution factors for different fuel cycles, the results for 27th fuel cycle for SA bank in multiple axial steps are presented in Figure 5. The SA bank was chosen for the analysis, because it enables direct comparison to the boron dilution method, which is performed only for the SA bank. It can be confirmed that amongst different cycles, reaction rate redistribution factors for the SA bank have approximately the same shape. However, differences in the values at different axial positions between the cycles are present, which additionally supports the hypothesis for the need to consider the reaction rate redistribution factors for individual bank and individual fuel cycle.

5.2 Comparison to the Boron Dilution Method

The aim of this section is the final validation of the implementation of new reaction rate redistribution factors for intermediate range detectors. During the start-up test, control rod reactivity worth for the SA bank is measured also with the *boron dilution method*. With the boron dilution method, the individual control rod bank is measured in multiple axial steps by maintaining the reactor close to criticality by compensating boric acid concentration variation effect on the reactivity with the control rod movement. This method is very accurate and needs no correction factors, which makes it an excellent choice for comparison to the other methods. Its downside is its execution time, which takes several hours per control rod bank. It should be mentioned that the control rod reactivity worth measured by the boron dilution method is a *static* control rod reactivity worth, since the distribution of the delayed and prompt neutrons are close to the equilibrium, due to the slow and small reactivity changes. As already explained, on the contrast, the rod insertion method is based on the measurement of the ex-core neutron detector signal during the continuous insertion of the control rod bank. The control rod reactivity worth measured with the rod insertion method is so called *dynamic*. This means that the core state during the rod insertion is not *static*, since the insertion of the control rods is altering the prompt and delayed neutron population differently during the measurement. Due to dynamic mode of measurement, the delayed neutron distribution is trailing behind the prompt neutron distribution. It must be pointed out that the reaction rate redistribution factors calculated in multiple axial positions within this research considered the static reactor core state for each control rod axial position. In order to compare measured control rod reactivity worth from the rod insertion method to the measurements from the boron dilution method, two main corrections must be applied: spatial and dynamic. The redistribution factor due to the spatial redistribution of the neutron flux during the insertion of the control rod are studied within this paper. The dynamic correction due to the temporal delay of the measured signal was evaluated in [2]. It was determined, that the conversion factors from dynamic to static control rod reactivity worth need to be determined for individual control rod bank and fuel cycle. Applying the dynamic-to-static control conversion factors is necessary, when comparing the boron dilution and rod insertion method.

The SA bank reactivity worth was analysed with boron dilution method and rod insertion method measured with intermediate range detectors. Results are presented in Table 1 for different fuel cycles. Those cycles were chosen for the comparison because they represent the equilibrium fuel cycle currently used at the Krško NPP. Good agreement within ~2 % between the intermediate range detector measurements with rod insertion method and boron dilution method measurements can be observed. The deviations are comparable to those observed for the PRNI [3]. The results presented for the rod insertion measurement considered the dynamic-to-static conversion factors from [2] and reaction rate redistribution factors in multiple axial positions presented within this paper. This confirms the possibility to use IRNI for rod insertion measurements in combination with detailed 3D calculations. Use of IRNI detectors seems rather better choice than the currently used PRNI, due to the discrimination of the signal due to the gamma rays and higher detector signal compared to the background (see Figure 3).

Table 1: Static control rod reactivity worth for SA control rod bank.

Cycle No.	Boron dilution (BD) [pcm]	Rod insertion (RI) [pcm]	RI/BD – 1 [%]
27	1249	1275	2.1
28	1273	1251	-1.7

6 CONCLUSION

The possibility to use intermediate range detectors for control rod reactivity worth measurements with the rod insertion method is presented. The developed detailed geometrical models of the reactor core and ex-core structures for a typical pressurized water reactor used with the state-of-the-art Monte Carlo code for neutron transport MCNP are presented. They were used to study the ex-core neutron detector response and determine neutron flux redistributions caused by the control rod movement. The reaction rate redistribution factors in multiple axial positions for intermediate range detectors were determined. It was found out that calculation of reaction rate redistribution factors is needed in multiple axial positions for individual control rod bank and for individual fuel cycle. The newly determined reaction rate redistribution factors for intermediate range detectors were used to study rod insertion measurements and to determine static control rod reactivity worth for the SA bank. Values were compared to the reference values measured with the boron dilution method where good agreement within 2 % was confirmed, which supports the idea to use the intermediate range detectors for rod insertion measurements. The use of intermediate range detectors for rod insertion measurements using newly calculated axial dependent reaction rate redistribution factors represent the way to update and improve the rod insertion measurements. This would improve the axial calibration of their reactivity worth and consequently improve the safety of the nuclear power plant.

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