Effect of Water Gap and Fuel Assembly Positioning in Passive Neutron Albedo Reactivity Measurements for Spent Fuel Encapsulation Safeguards

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Abstract

The Passive Neutron Albedo Reactivity (PNAR) Ratio is proportional to the net neutron multiplication of a spent fuel assembly. In the planned integrated non-destructive assay instrument for Finnish encapsulation safeguards, a PNAR instrument is used to confirm the presence of fissile material. In this study, the sensitivity of fuel-type-specific PNAR Ratio measurements to the size of the water channel of the instrument is determined using MCNP5 Monte Carlo simulations. Based on the study results, use of the smallest possible water channel is recommended to maximize the dynamic range of the instrument. In the Finnish fuel encapsulation context, this means using water gap sizes of 5 mm and 3 mm for measurements of boiling water reactor (BWR) and water-water energetic reactor (VVER-440) fuel, respectively. Based on the neutron emission rates of the Finnish spent fuel inventory, we recommend maximizing count rates by having detectors all around the fuel assembly, i.e., 4 detectors for BWR fuel and 6 detectors for VVER-440 fuel. With these water gap sizes, and neutron detectors all around the fuel assembly, the variation of the PNAR Ratio measurement caused by the uncertainty on the position of the fuel in the instrument is estimated to be 0.06% for BWR fuel and 0.13% for VVER-440 fuel.

Introduction

The Passive Neutron Albedo Reactivity (PNAR) concept has been developed to measure the neutron multiplication of nuclear fissile materials.[1-4, 7-9, 11, 14, 15] To meet the recommendations given to the International Atomic Energy Agency (IAEA) in the "Application of Safeguards to Geological Repositories (ASTOR) Report on Technologies Potentially Useful for Safeguarding Geological Repositories," the integrated non-destructive assay (NDA) instrument designed for repository-related safeguards measurements in Finland is expected to incorporate a PNAR system.[5] The purpose of the NDA instrument is to determine, by a set of measurements, whether a fuel assembly is compliant with its declaration. The primary metric measured by a PNAR instrument is the PNAR Ratio, which is proportional to the multiplication of the measured fuel assembly.[11] The PNAR Ratio is calculated in the context of spent fuel by taking the ratio of the neutron count rate measured when the assembly is in a high-multiplying setup to the count rate when the assembly is in a low-multiplying setup. In the high-multiplying configuration, the nuclear fuel is surrounded by hydrogen-rich material (such as polyethylene or water). This maximizes the flux of thermal neutrons back-scattered to the assembly. The measured PNAR Ratio will be compared to a simulated value. A difference between expected (i.e., simulated) and measured PNAR Ratio values can be caused by two main factors:

- deviation of the actual fissile material content from declared values due to uncertainties in the initial assembly characterization and details of reactor exploitation or due to diversion of fissile material;
- uncertainties associated with the PNAR instrument.

In the Finnish instrument design, the high-multiplying configuration is achieved by measuring the fuel while underwater in a cooling pool. In the low-multiplying configuration, the back-scattered flux of thermal neutrons is suppressed by using a material that is an efficient thermal neutron absorber. In the Finnish conceptual PNAR design, a liner made out of cadmium is positioned underwater, close to the fuel, to create the low-multiplying configuration. The fuel is in a fixed position for the measurements, while the Cd-liner moves up and down along the assembly to create the high- and low-multiplying configurations. In the absence of fissile material, the PNAR Ratio is close to 1; a PNAR Ratio above 1 is due to neutrons created by fission induced by thermal neutrons present in the high-multiplying configuration that are absorbed by the Cd-liner in the low-multiplying configuration. Thus, the PNAR concept can be thought of as interrogating the spent nuclear fuel assembly with thermal neutrons emitted at the location of the Cd-liner. In studying the design parameters of the PNAR instrument, provided the intrinsic detection efficiency is the same for both PNAR configurations, the higher the PNAR Ratio value obtained for a chosen reference assembly, the wider the dynamic range of the instrument. This in turn means that the instrument can better resolve deviations of the fissile material content from the declared content.

As the PNAR Ratio is proportional to the multiplication of a given assembly, it is necessary to calibrate the instrument. In the encapsulation/repository context, the context of interest of this publication, it is anticipated that approximately 100 assemblies will be measured as part of the instrument characterization process. The PNAR instrument will provide a comparison of the multiplication among all these assemblies. Furthermore, because the initial conditions of each assembly as well as the reactor history are known, the multiplication can be calculated for each assembly. In this manner, a connection between the measured PNAR Ratio and the calculated multiplication of each assembly is obtained.

Because the goal of reactor operators is to optimally extract the inherent nuclear potential energy in each assembly, most assemblies being measured at an encapsulation facility will have nearly the same multiplication; a multiplication value that indicates that the fissile material is still present in the assembly. For this reason, another useful application for the PNAR Ratio to regulators may be in a "threshold mode" by which the following logic is applied: if a PNAR Ratio is measured below a given value (selected based upon the measurement performed as part of the characterization process), then a notice/alarm is given the regulator.

PNAR Instrument Design

For the PNAR Ratio, the water gap between the Cd-liner and the fuel impacts how much the Cd-liner can alter the multiplication of the fuel. The position of the fuel assembly within the central measurement channel of the PNAR device is a source of uncertainty in the determination of the PNAR Ratio because this position affects the water gap. The present study characterizes these two effects via Monte Carlo simulations with MCNP5.[10]

The geometry of the PNAR instrument should be adapted to the geometry of each fuel type. Reactors currently active in Finland use either square boiling water reactor (BWR) fuel or hexagonal water-water energetic reactor (VVER-440) fuel (pressurized water reactor fuel will be used in the Olkiluoto 3 reactor). The PNAR instruments to be developed for Finland are expected to operate underwater, but spent BWR fuel is stored in fresh water while spent VVER-440 fuel is stored in boron-doped water at a concentration of 14±1 g of boric acid per kg of water.

The geometry of the conceptual BWR-specific PNAR instrument is shown in Figure 1. The key features of the geometry are introduced below.

- ^{3}He tubes: 17.4 mm in diameter and a fill pressure of 6 atm. The tubes are placed in the horizontal plane perpendicular to the fuel assembly. The maximum active length of 200 mm is divided into five segments in order to study the effect of detector length.
- Lead shielding, needed to reduce the gamma dose to the ^{3}He tubes, which is 52 mm thick at its thickest.
- Cadmium is located around the detectors and in the Cd-liner surrounding the fuel; Cd was included in the detector in order to preferentially detect high energy neutrons from the fuel as this was shown by Lee, et. al.[1] to more uniformly sample neutrons spatially from the fuel. All Cd layers are 1 mm thick; the Cd-liner is 0.74 m long.
- Four detector units, each housing one detector (D1-D4) on each side of the assembly to reduce the sensitivity to anisotropy in the assembly burnup. To accommodate the size of the detector units, the detectors are placed at two closely located vertical levels, with a 100 mm vertical offset (D1and D2 form the bottom layer while D3 and D4 form the top layer).

The VVER-440-specific PNAR instrument, shown in Figure 2, has the same features as the BWR-specific one, except that it has six ^{3}He tubes, reflecting the hexagonal geometry of the fuel. The active length of each tube is 100 mm. Detectors D2, D4, D6 form the top detector layer while detectors D1, D3, D5 make up the bottom detector layer. An additional large volume of polyethylene, 0.74 m long, surrounds the fuel assembly. This polyethylene displaces the borated water, ensuring sufficient multiplication power in the high-multiplying configuration of the PNAR instrument.

The Radiation and Nuclear Safety Authority of Finland decided that the NDA system to be used for encapsulation safeguards should have a measurement time of, at most, 5 minutes.[6]

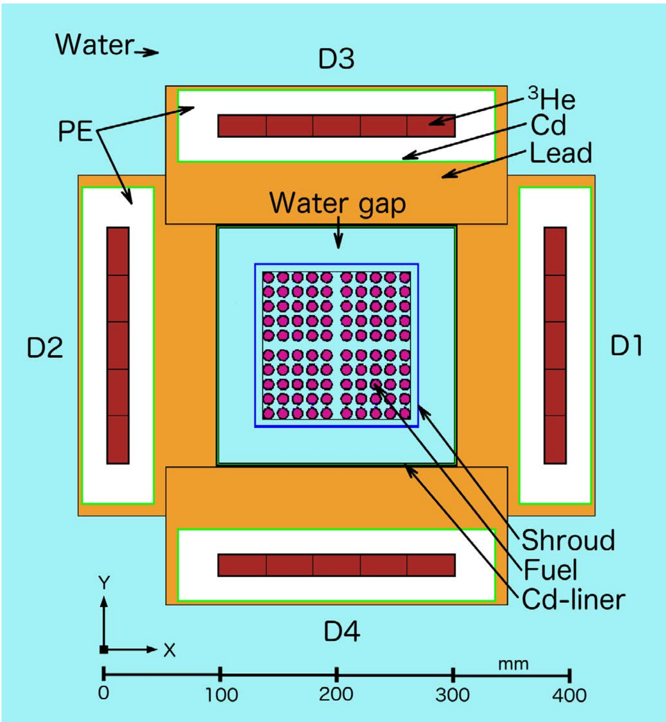

Figure 1. Top View of the BWR-Specific PNAR Instrument with a 10x10 BWR Fuel Assembly in the Measurement Channel

A water gap of 30 mm, the largest water gap used in this study, is present around the fuel. The drawing is to scale. The ^{3}He tubes surround the fuel assembly on all four sides and are located in two horizontal (X,Y) planes with a 100 mm vertical (Z) offset (D3 and D4 above D1 and D2 in this top view). The ^{3}He tubes are divided into five segments in order to study the effect of detector length.

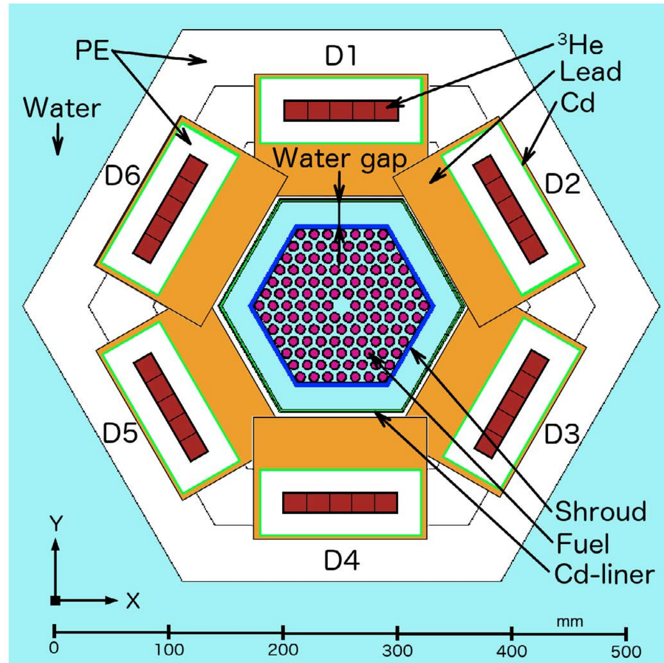

Figure 2. The Horizontal (XY Plane) Cross-Sectional View of the VVER-440-Specific PNAR Instrument with a VVER-440 Assembly in the Measurement Channel

A water gap of 20 mm, the largest water gap used in this study, is present around the fuel. The drawing is to scale. The ^{3}He tubes surround the fuel assembly on all six sides and are located at two different vertical levels with a 100 mm Z-axis offset.

Subsequently, the PNAR measurement process is planned to consist of two 2-minute measurements (with/without Cd-liner) with a 1-minute intermission to move the Cd-liner in or out of the active instrument region. The count rates for the fuel expected to be measured at the Finnish encapsulation facility with the PNAR instrument are expected to vary roughly between 800 counts/s and 200,000 counts/s for the combined count rate of the four detectors. This range was estimated between a 17 GWd/tU, 60 year cooled assembly and a 55 GWD/tU, 20 years cooled assembly, respectively.[11] For the particularly low neutron emitting assemblies, the counting duration is expected to be increased.

Monte Carlo Simulations

Measurements of the PNAR Ratio were simulated using the Monte Carlo N-Particle Code Version 5 (MCNP5 V1.40) with 0.60c cross sections libraries.[10] The isotopic mixture of the spent fuel assemblies was produced by the Monteburns code as part of the Next Generation Safeguards Initiative (NGSI).[12-14] For the same burnup, initial enrichment and cooling time, the isotopic mix will vary between PWR fuel considered in the NGSI and BWR and VVER fuel considered here. However, these differences are not expected to have a significant impact on the PNAR design characteristics of interest in this publication. Two typical isotopic compositions, available from the NGSI, were used:

- initial enrichment 3 wt.%, burnup 30 GWd/tU, cooling time 20 years (IE=3, BU=30, CT=20)
- initial enrichment 4 wt.%, burnup 45 GWd/tU, cooling time 20 years (IE=4, BU=45, CT=20)

Within the isotopic mixtures available from the NSGI, these are equivalent to near fully burnt assemblies with parameters that most closely match the typical Finnish fuel. Note that the PNAR Ratio is not very sensitive to variation in the cooling time within the range of interest for this study (20-60 years).[11] Considering neutron attenuation and scattering in the setups under study, only a 1.2 m long section of the fuel assembly is simulated, as neutrons generated outside of this section do not contribute to the PNAR signal.

As VVER-440 fuel has only a 3% greater mass per unit length compared to 10×10 BWR fuel, both fuel types are expected to have a very similar neutron emission rate.

For each PNAR Ratio, two independently-seeded simulation runs of 1×10^9 initial neutrons are performed, one with and one without the Cd-liner. Any additional neutrons produced in the simulation, such as those resulting from induced fission, are followed through until they are absorbed or leave the simulated volume. The output of a simulation run is the probability per source neutron of a neutron being absorbed in a given detector, with its associated statistical uncertainty (MCNP tally F4). The count rate is calculated by the product of the detection probability per source neutron times the number of source neutrons emitted per second by the fuel section simulated.

Simulation parameters for water gap and assembly position

To estimate the effect of the size of the water gap, the PNAR Ratio was simulated with increasing water gap size, while keeping the assembly in the center of the instrument's measurement channel. For BWR fuel, the water gap size varied from 5 mm to 30 mm while for VVER-440 fuel, the water gap size varied from 3 mm to 20 mm.

The uncertainty due to fuel positioning will depend on how well the crane positions the assembly inside the PNAR instrument's measurement channel as well as on how bent the assembly is. For a deployed system, the PNAR operator will likely want to remeasure several assemblies several times to quantify the PNAR uncertainty due to positioning. In the current study, we investigate this uncertainty by simulating the following displacement scenarios:

- center - the assembly is in the center of the instrument's measurement channel with an equal water gap on all sides
- side - the assembly is centered against one of the walls of the measurement channel
- corner - the assembly is positioned in a corner of the measurement channel

Figures 3 and 4 show how these scenarios are simulated for BWR and VVER-440 fuel, respectively.

BWR Fuel Results

Figure 5 shows the PNAR Ratio as a function of the water gap for BWR fuel in the center of the PNAR instrument. The water gap size affects the multiplication conditions for both the high- and low-multiplying configuration, and thus the neutron count rates.

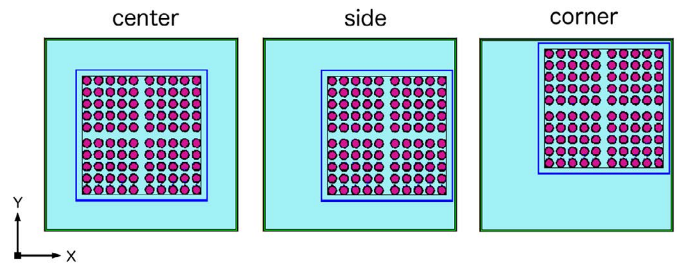

Figure 3. Horizontal (XY Plane) Cross-Sectional View of the Three Simulated Positions of the 10×10 BWR Fuel Assembly Inside the PNAR Instrument's Measurement Channel for a 30 mm Water Gap

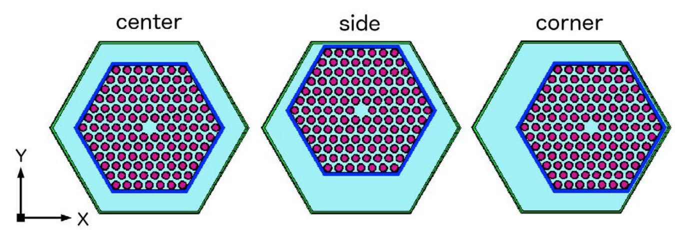

Figure 4. Horizontal (XY Plane) Cross-Sectional View of the Three Simulated Positions of the VVER-440 Fuel Assembly Inside the PNAR Instrument's Measurement Channel for a 20 mm Water Gap

With a thicker water gap, the neutrons emitted by the fuel have a higher probability to thermalize, back-scatter, and induce fission in the assembly, enhancing multiplication and increasing the neutron flux from the assembly towards the detectors. A thicker water gap reduces the ability of the Cd-liner to affect the thermal neutron flux reflecting back into the fuel in the low-multiplying configuration as more neutrons leaving the fuel reflect back into the fuel before they reach the Cd-liner. On the other hand, with a thicker water gap, the neutron flux reaching the detectors contains a larger fraction of thermalized neutrons, reducing the fraction of neutrons detected (thermal neutrons are absorbed by the Cd surrounding the detectors). Our simulations show that the combination of the above factors results in a neutron count rate which decreases with increasing water gap for both the high- and low-multiplying configurations, as illustrated in Figure 6, but the neutron count rate decreases faster in the high-multiplying configuration. As a result, the PNAR Ratio decreases with increasing water gap. The difference between the PNAR Ratio measurement with a 5 mm water gap and 1.0, the PNAR Ratio value for an idealized non-multiplying assembly, will be used as the reference value for the dynamic range of the instrument in discussing the BWR simulation results. This dynamic range will vary depending on the assembly selected. The assembly selected for the comparative analysis in this paper is approximately a fully irradiated assembly, which is similar to the vast majority of fuel being measured at an encapsulation facility.

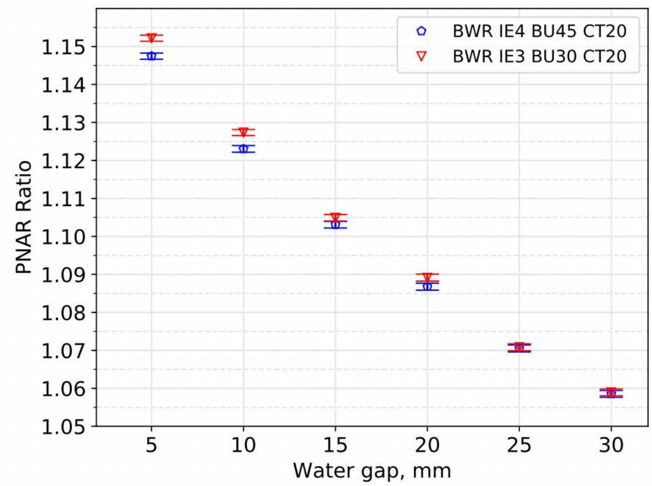

Figure 5. The PNAR Ratio for the BWR Fuel-Specific PNAR Instrument in Fresh Water as a Function of the Size of the Water Gap Around Fuel Assemblies with IE=4, BU=45, CT=20, and IE=3, BU=30, CT=20

The error bars indicate the standard deviation due to statistics in the simulations.

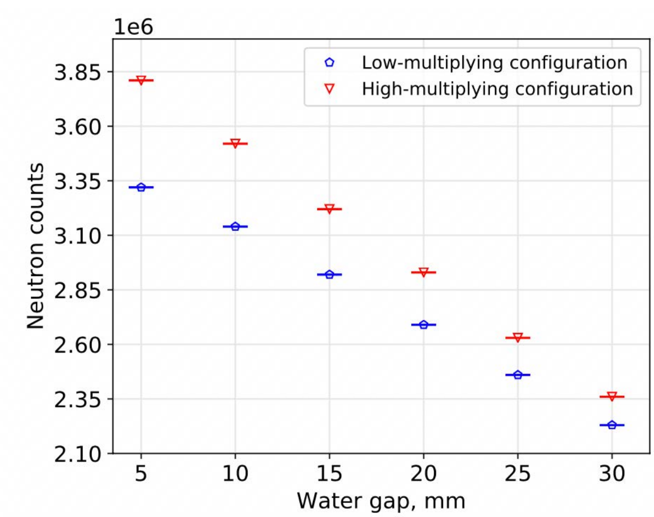

Figure 6. Simulated Neutron Counts as a Function of the Size of the Water Gap for the High- and Low-Multiplying Configurations

The simulations were done for a fuel assembly with IE=4, BU=45, CT=20. The neutron sample size is 1x10^{9}.

The PNAR Ratio with a 5-mm water gap is 1.1475±0.0008 for fuel with 4 wt.% initial enrichment and 1.1522±0.0008 for fuel with 3 wt.% initial enrichment. The uncertainties given are for MCNP statistics only. When the water gap is increased to 20 mm, the PNAR Ratio values become 1.0868±0.0009 and 1.0892±0.0009 for fuel with 4 wt.% and 3 wt.% initial enrichment, respectively. The dynamic range of the PNAR instrument decreases by ~40% in the case of a 20-mm water gap relative to the case of a 5-mm water gap. Further increase of the water gap size up to 30mm leads to a ~60% reduction of the dynamic range.

As the simulated PNAR Ratios for the two fuel assemblies are very close, and closely follow the same trend, we chose to simulate only the fuel with parameters IE=4, BU=45, CT=20 for the rest of the study. These parameters match most closely the characteristics of typical Finnish spent nuclear fuel.

Figure 7 shows the PNAR Ratio for fuel with IE=4, BU=45, CT=20 located at the three different positions shown in Figure 3. The water gap size is 5 mm. The PNAR Ratios labeled "T" are obtained by summing the signals from all four detectors into a "total" PNAR Ratio, while the values associated with the D1-D4 labels represent PNAR Ratios obtained for each individual detector. For each situation, three active detector lengths were simulated: 40, 120, and the full length of 200 mm. The active length is centered on each side of the instrument. As expected, a longer active detector length improves the statistics of the simulation. Shorter active detector lengths do not affect the PNAR Ratio value when the fuel is in the center or side position. However, in the corner position, the PNAR Ratio shows a small decreasing trend with decreasing active detector length.

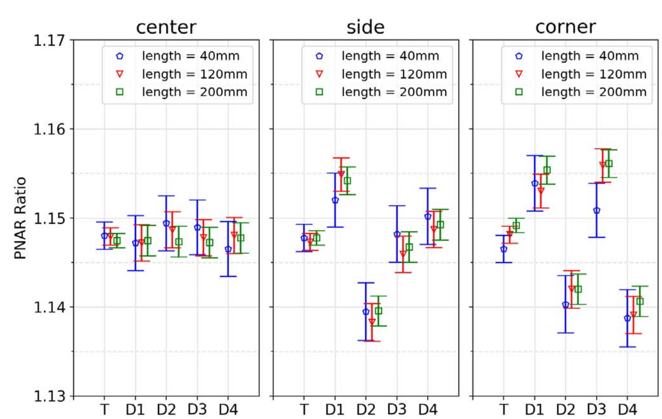

Figure 7. The BWR PNAR Ratio for a 5-mm Water Gap as a Function of the Active Detector Length and Fuel Assembly Positioning Inside the PNAR Instrument's Measurement Channel

D1-D4 refer to the individual detectors and T to the sum of all detectors. The error bars indicate the standard deviation due to statistics in the simulations.

With fuel in the center position, the PNAR Ratio values from individual detectors are within 1-sigma deviation (relative deviation of ±0.07%) of the total value. The statistical uncertainty for 120 mm and 40 mm detector sections increases up to ±0.09% and ±0.13%, respectively.

In the other two positions, individual detector measurements show large differences, consistent with the geometry of the measurement. In the side position, the detector closest to the assembly (D1) measures the largest PNAR Ratio. Detectors D3 and D4 are located in symmetric positions relative to the fuel and have comparable PNAR Ratio values. Detector D2 measures the lowest PNAR Ratio because the water gap between the fuel and the Cd-liner is widest on its side. The same logic explains the pattern of PNAR Ratio values when the fuel is in the corner position. In the central and side positions, the total PNAR Ratio values are very close (1.1475 and 1.1478, respectively, with equal absolute uncertainty of ±0.0008). In the corner fuel position, the total PNAR Ratio value is slightly higher (1.1492±0.0008). The PNAR Ratio variation due to the fuel assembly position becomes more pronounced as the water gap size increases, as can be seen in Figure 8. The difference in total PNAR Ratio values between the center and corner fuel positions for the 15-mm water gap case is 0.0206±0.0013.

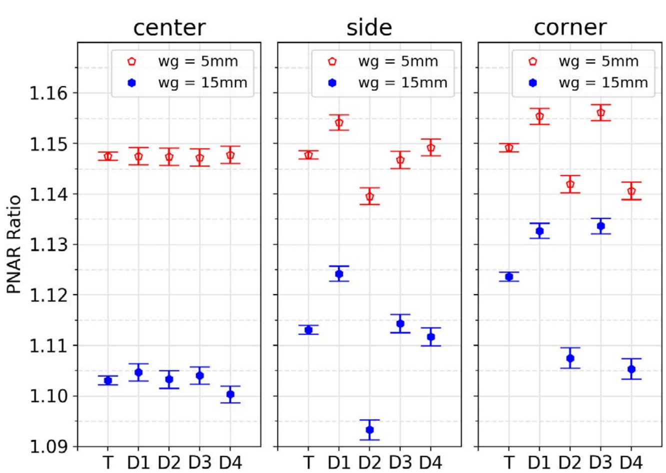

Figure 8. The BWR PNAR Ratio for 5- and 15-mm Water Gaps as a Function of Fuel Assembly Position Inside the PNAR Instrument's Measurement Channel

D1-D4 refer to the individual detectors and T to the sum of all detectors. A 200mm active detector length is used. The error bars indicate the standard deviation due to statistics in the simulations.

A summary of the PNAR Ratios obtained for the BWR fuel assembly with IE=4, BU=45, CT=20 as a function of water gap size and fuel position is shown in Table 1. The PNAR Ratios are given for full length detectors (200mm). The systematic uncertainty on the PNAR Ratio caused by the uncertainty on the fuel assembly position in the water channel is estimated as the average deviation of the PNAR Ratios of the three positions. Note that this estimation is very approximate and a conservative value as the side and corner positions are extreme situations. An accurate quantification of the uncertainty will need to be done experimentally by repeatedly remeasuring assemblies. For the 5-mm water gap case, the average PNAR Ratio is 1.1481 with an average deviation of 0.0007. For the 15-mm thick water gap case, the average PNAR Ratio is 1.1133 with a standard deviation of 0.0069. For the 5-mm water gap, the size of the systematic uncertainty estimate is approximately equal to the Monte Carlo statistical uncertainty on each simulated PNAR Ratio. For the 15-mm water gap case, the estimate of the systematic uncertainty due to fuel positioning is eight times larger than the Monte Carlo statistical uncertainty, making the estimate insensitive to our simulation statistics.

VVER fuel results

Figure 9 shows the PNAR Ratio as a function of water gap size for VVER-440 fuel with 3 wt.% and 4 wt.% initial enrichment in the center of the VVER-440-specific PNAR instrument. A water gap size from 3 mm to 20 mm is considered. The strong impact of boron-enriched water on the PNAR Ratio results in a substantial dynamic range reduction for the VVER-440-specific instrument.[15] The difference between the PNAR Ratio measurement with a 3-mm water gap and PNAR Ratio value 1.0 is used as the reference value for the dynamic range of the VVER-440-specific instrument. This dynamic range will vary depending on the assembly selected. The assembly selected for the comparative analysis in this paper is approximately a fully irradiated assembly, which is similar to the vast majority of fuel being measured at an encapsulation facility. The dynamic range is reduced by 77% for the VVER-440-specific instrument when the water gap increases from 3 mm to 20 mm. For a 5-mm water gap, the VVER PNAR Ratio shows a reduction of the dynamic range of 0.053 or 36% relative to the BWR case. As the PNAR Ratios observed for the two simulated fuel types match closely at all water gap sizes, all further results are shown only for fuel with IE=4, BU=45, and CT=20.

Table 1. The PNAR Ratios for BWR Fuel (IE=4, BU=45, CT=20) with Statistical Uncertainties for 5- and 15-mm Water Gaps as a Function of Fuel Assembly Position Inside the PNAR Instrument and Detector Selection

D1-D4 refer to the individual detectors and Total to the sum of all detectors.

Water gap (mm)	Detector	Center		Side		Corner	
		PNAR Ratio	Uncertainty absolute/relative(%)	PNAR Ratio	Uncertainty absolute/relative(%)	PNAR Ratio	Uncertainty absolute/ relative(%)
5	**Total**	**1.1475**	**0.0008/0.07**	**1.1478**	**0.0008/0.07**	**1.1492**	**0.0008/0.07**
	D1	1.1475	0.0017/0.15	1.1542	0.0016/0.13	1.1554	0.0016/0.13
	D2	1.1474	0.0017/0.15	1.1396	0.0017/0.15	1.1420	0.0017/0.15
	D3	1.1472	0.0017/0.15	1.1467	0.0017/0.15	1.1561	0.0016/0.13
	D4	1.1478	0.0017/0.15	1.1492	0.0017/0.15	1.1407	0.0017/0.15
15	**Total**	**1.1031**	**0.0009/0.08**	**1.1131**	**0.0009/0.08**	**1.1237**	**0.0009/0.08**
	D1	1.1047	0.0017/0.16	1.1242	0.0015/0.13	1.1327	0.0015/0.13
	D2	1.1033	0.0017/0.16	1.0933	0.0020/0.18	1.1075	0.0020/0.18
	D3	1.1040	0.0017/0.16	1.1143	0.0018/0.16	1.1337	0.0015/0.13
	D4	1.1003	0.0017/0.16	1.11178	0.0018/0.16	1.1053	0.0020/0.18

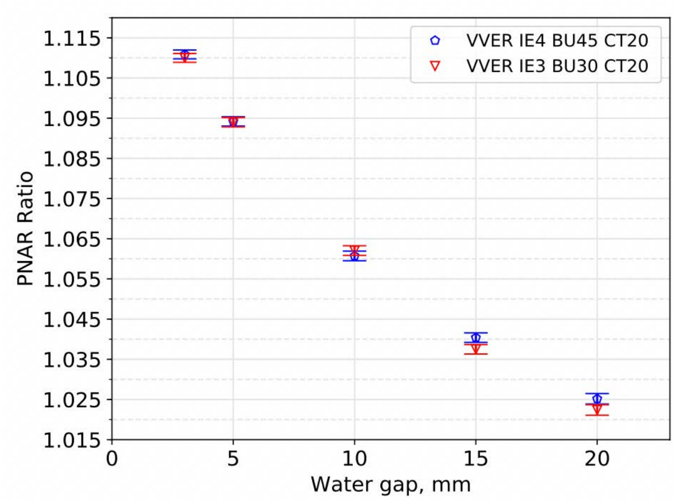

Figure 9. The PNAR Ratio for the VVER-440 Fuel-Specific Instrument in Borated Water as a Function of Water Gap Size Around Fuel Assemblies with IE=4, BU=45, CT=20 and IE=3, BU=30, CT=20

The error bars indicate the standard deviation due to statistics in the simulations.

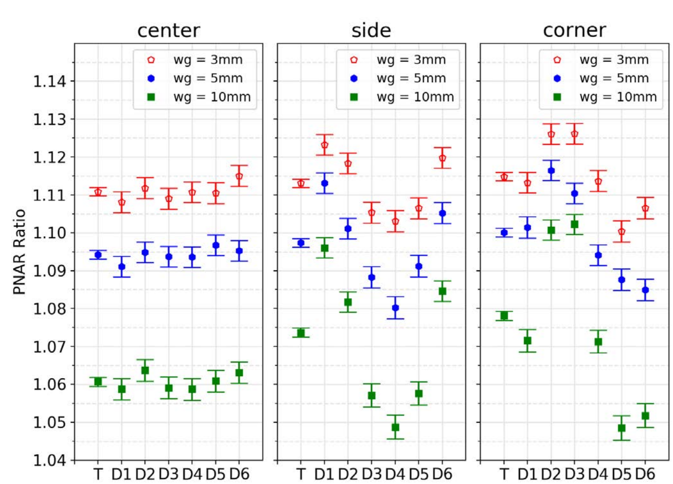

Figure 10. The VVER-440 PNAR Ratio for Water Gap sizes of 3 mm, 5 mm, and 10 mm for the Three Fuel Assembly Positions Inside the PNAR Instrument's Measurement Channel

D1-D6 refer to the individual detectors and T to the sum of all detectors. The error bars indicate the standard deviation due to statistics in the simulations.

Figure 10 shows the VVER-440 PNAR Ratio for water gap sizes of 3 mm, 5 mm, and 10 mm for the three fuel assembly positions. The PNAR Ratio from individual detectors follows the geometry of the fuel displacement scenarios as expected. The detectors closest to the fuel (D1 for the side position, D2 and D3 for the corner position) measure the highest PNAR Ratio values while the detectors farthest from the fuel (D4 for the side position, D5 and D6 for the corner position) measure the lowest PNAR Ratio values. With the fuel in the center position, the PNAR Ratios for individual detectors are identical within statistical uncertainty. The presence of borated water increases the statistical uncertainty on the PNAR Ratio determinations. The spread (difference between maximum and minimum values) of the PNAR Ratio values between detectors reaches 0.047 and 0.054 for side and corner positions, respectively, when the water gap is 10 mm.

Table 2 summarizes the PNAR Ratio values for the VVER-440-specific PNAR instrument, for a fuel assembly with IE=4, BU=45, CT=20 for varying water gap size and fuel position. The average total PNAR Ratio for the center, side and corner positions when the water gap is 3 mm, 5 mm, and 10 mm is, respectively, 1.1129, 1.0972 and 1.0708. The average deviations are, respectively, 0.0014, 0.0020 and 0.0068. Note that, as the side and corner positions are extreme situations, these average deviations are an approximate and conservative estimate of the systematic uncertainty due to the fuel assembly position. An accurate quantification of the uncertainty will need to be done experimentally by repeatedly remeasuring assemblies. As in the case of BWR, the fuel displacement effect is well-pronounced; it exceeds the 1-sigma simulation statistical uncertainty for the 10-mm water gap by a factor of 6.

Table 2. The PNAR Ratios for VVER-440 Fuel (IE=4, BU=45, CT=20) with Statistical Uncertainties for 3 mm, 5 mm, and 10 mm Water Gaps as a Function of Fuel Assembly Positioning Inside the PNAR Instrument and Detector Selection

D1-D6 refer to the individual detectors and Total to the sum of all detectors.

Water gap (mm)	Detector	Center		Side		Corner	
		PNAR Ratio	Uncertainty absolute/relative(%)	PNAR Ratio	Uncertainty absolute/relative(%)	PNAR Ratio	Uncertainty absolute/relative(%)
3	**Total**	**1.1109**	**0.0011/0.10**	**1.1131**	**0.0011/0.10**	**1.1148**	**0.0011/0.10**
	D1	1.1080	0.0027/0.25	1.1232	0.0027/0.24	1.1132	0.0028/0.25
	D2	1.1118	0.0027/0.25	1.1184	0.0027/0.24	1.1261	0.0027/0.24
	D3	1.1090	0.0027/0.25	1.1054	0.0027/0.25	1.1262	0.0027/0.24
	D4	1.1107	0.0027/0.25	1.1031	0.0028/0.25	1.1137	0.0028/0.25
	D5	1.1105	0.0027/0.25	1.1065	0.0027/0.25	1.1004	0.0028/0.26
	D6	1.1150	0.0028/0.25	1.1198	0.0027/0.24	1.1066	0.0028/0.25
5	**Total**	**1.0942**	**0.0012/0.11**	**1.0974**	**0.0012/0.11**	**1.1001**	**0.0012/0.11**
	D1	1.0911	0.0027/0.25	1.1131	0.0027/0.24	1.1014	0.0028/0.26
	D2	1.0948	0.0027/0.25	1.1012	0.0027/0.25	1.1165	0.0027/0.24
	D3	1.0937	0.0027/0.25	1.0883	0.0028/0.26	1.1104	0.0027/0.24
	D4	1.0936	0.0027/0.25	1.0803	0.0029/0.27	1.0941	0.0027/0.25
	D5	1.0967	0.0027/0.25	1.0912	0.0029/0.26	1.0877	0.0028/0.26
	D6	1.0953	0.0027/0.25	1.1052	0.0027/0.25	1.0849	0.0028/0.26
10	**Total**	**1.0607**	**0.0012/0.11**	**1.0737**	**0.0012/0.11**	**1.0781**	**0.0012/0.11**
	D1	1.0588	0.0028/0.27	1.0961	0.0026/0.24	1.0715	0.0030/0.28
	D2	1.0637	0.0029/0.27	1.0817	0.0027/0.25	1.1007	0.0026/0.24
	D3	1.0591	0.0028/0.27	1.0571	0.0031/0.29	1.1023	0.0026/0.24
	D4	1.0587	0.0028/0.27	1.0487	0.0032/0.30	1.0713	0.0030/0.28
	D5	1.0609	0.0028/0.27	1.0576	0.0031/0.29	1.0485	0.0032/0.30
	D6	1.0631	0.0029/0.27	1.0847	0.0027/0.25	1.0518	0.0032/0.30

Tobin, et al. investigate the uncertainty in the PNAR Ratio due to a variation in boron content of 14±1 g per kg of water.[15] For a fuel assembly with 4 wt% initial enrichment, 45 GWd/tU burnup and 20 years cooling time in the center of the PNAR instrument with a water gap of 3.4 mm, the 1-sigma uncertainty on the PNAR Ratio is 0.4%. This is three times larger than the 0.13% uncertainty derived from the results in Table 2 for the same fuel assembly parameters but for a water gap of 3 mm. Therefore, in the case of VVER-440 fuel in borated water, the boron content will need to be constant to better than about 0.2 g per kg of water for the uncertainty on the PNAR Ratio due to variations in boron content to be negligible in comparison with the uncertainty due to variations in positioning. An accurate measurement of the boron content will thus be needed.

Discussion and Some Practical Considerations

The purpose of this simulation study is to support design choices concerning the water gap between the spent fuel and the Cd-liner of a PNAR instrument. Increasing the water gap decreases the PNAR Ratio measured for a given assembly (Figures 5 and 9), thus reducing the dynamic range and the sensitivity to detect an anomaly in the amount of fissile material. Additionally, a larger gap leaves more room for fuel positioning variation, increasing the uncertainty related to this variation (Figures 8 and 10 and Tables 1 and 2). The safety of fuel manipulation operations for safeguards measurements determines the minimum water gap that is practically possible. The smallest water gap sizes simulated in this work (5mm for BWR fuel and 3 mm for VVER-440 fuel) correspond to the size of the spent fuel racks used in Finland. As these water gap sizes have thus proven to be practical from an operational point of view, we recommend using the same values for the PNAR instrument.

Most simulations were performed for BWR and VVER-440 fuel assemblies with 4 wt.% initial enrichment, 45 GWd/tU burnup and 20-year cooling time. The VVER and BWR had an estimated neutron emission rate of 7.9×10^{6} n/s for the 1.2 m long fuel assembly simulated, and 2×10^{7} n/s for a full-length assembly. As this source strength is in the numerator and denominator of the PNAR Ratio, it does not impact the PNAR Ratio magnitude but it does impact the counting statistics.[12] This neutron emission rate is at the high end of what is expected in the Finnish encapsulation scenario, with a ratio of neutron emission rate of 255 for the strongest to weakest fuel assemblies to be encapsulated.[11]

Having neutron detectors symmetrically all around the fuel assembly mitigates the uncertainty due to position variation, as is demonstrated by the results shown in Figures 8 and 10 and Tables 1 and 2. Having detectors all around the fuel assembly increases in importance when the water gap size increases. For the small water gap size recommended based on the present results, having detectors all around the fuel assembly may not be necessary to mitigate the variation due to fuel positioning, as this variation will not dominate the total uncertainty of the measurement.

To reduce cost and complexity, one can design PNAR instrument variants with fewer detectors. To preserve robustness against fuel positioning uncertainty, we consider that half of the detectors are symmetrically removed for both fuel-type-specific instruments. In this few-detector design, for BWR fuel, the PNAR Ratio changes by 0.0001 for fuel in the central and corner positions and 0.0003 for the side position. For VVER-440 fuel, the PNAR Ratio changes by 0.001 for the side and corner positions and 0.002 for the center position. The absolute statistical uncertainty on the total PNAR Ratio increases from 0.0008 to 0.0012 for BWR and from 0.0011 to 0.0016 for VVER-440 cases, which is consistent with the factor 2 reduction in statistics due to the removal of half of the detectors. The effect on the PNAR Ratios is smaller than the simulated sample size statistical uncertainty for BWR fuel and similar to the simulated sample size statistical uncertainty for VVER-440 fuel.

A PNAR instrument that does not have detectors on all sides is less costly and complex. However, while the performance of the few-detector PNAR instrument variants is comparable to that of the instrument designs with detectors on all sides considered in this work, they cannot be recommended for two practical reasons: they are vulnerable to detector failures and unfavorable for long-cooled fuel. If a single detector malfunctions in the few-detector design, the PNAR Ratio measurement becomes unreliable, whereas with detectors on all sides the remaining detectors provide a reliable PNAR Ratio measurement. With a factor 255 difference between the highest and lowest expected neutron count rates within the Finnish spent fuel inventory, the use of the full set of 4, resp. 6, detectors for the BWR, resp. VVER-440, in the PNAR instrument is also recommended to best maintain good measurement statistics. The statistical uncertainty on the PNAR Ratio can also be reduced by longer measurement times. However, a discussion of this is beyond the scope of the present work. Nonetheless, expected neutron count rates will need to be considered when establishing detailed measurement protocols for the range of fuel characteristics that will be encountered in practice.

Conclusions

The PNAR technique is planned to be part of the integrated NDA system for encapsulation safeguards in Finland. With it the neutron multiplication of a spent fuel assembly can be measured, and the declared fissile material content of spent nuclear fuel verified. A PNAR instrument prototype is under development. Certain design choices are made based on the results of Monte Carlo simulations. In this work, MCNP5 simulations were used to study the effect on the PNAR Ratio of the size of the water gap between the spent fuel and the Cd-liner of the PNAR instrument. They also provided an estimate of the effect of the uncertainty associated with the positioning of the fuel inside the instrument's measurement channel. BWR fuel in fresh water and VVER-440 fuel in borated water were investigated. A small water gap is recommended as it provides a larger PNAR Ratio dynamic range and a smaller uncertainty due to fuel positioning variations. We recommend using the same water gap sizes as present in the spent fuel racks used in Finland: 5 mm for BWR fuel and 3 mm for VVER-440 fuel. With these water gap sizes, and detectors all around the fuel assembly, the variation of the PNAR Ratio measurement caused by the uncertainty on the position of the fuel in the instrument is estimated to be 0.06% and 0.13%.

The statistical uncertainty of our simulations is better than will typically be the case in the Finnish context.[11, 15] It is thus recommended to maximize count rates by having detectors all around the fuel assembly as in the simulated conceptual design: 4 detectors for BWR fuel and 6 detectors for VVER-440 fuel. Such a detector configuration also minimizes the sensitivity of the PNAR Ratio to the fuel position.

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