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Measuring spent fuel assembly multiplication in borated water with a passive neutron albedo reactivity instrument

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ABSTRACT

The performance of a passive neutron albedo reactivity (PNAR) instrument to measure neutron multiplication of spent nuclear fuel in borated water is investigated as part of an integrated non-destructive assay safeguards system. To measure the PNAR Ratio, which is proportional to the neutron multiplication, the total neutron count rate is measured in high- and low-multiplying environments by the PNAR instrument. The integrated system also contains a load cell and a passive gamma emission tomograph, and as such meets all the recommendations of the IAEA's recent ASTOR Experts Group report. A virtual spent fuel library for VVER-440 fuel was used in conjunction with MCNP simulations of the PNAR instrument to estimate the measurement uncertainties from (1) variation in the water boron content, (2) assembly positioning in the detector and (3) counting statistics. The estimated aggregate measurement uncertainty on the PNAR Ratio measurement is 0.008, to put this uncertainty in context, the difference in the PNAR Ratio between a fully irradiated assembly and this same assembly when fissile isotopes only absorb neutrons, but do not emit neutrons, is 0.106, a 13-sigma effect. The 1-sigma variation of 0.008 in the PNAR Ratio is estimated to correspond to a 3.2 GWd/tU change in assembly burnup.

1. Introduction

The Finnish Radiation and Safety Authority (STUK), in order to implement the recommendation of the International Atomic Energy Agency (IAEA) assembled NDA experts outlined in the "Application of Safeguards to Geological Repositories (ASTOR) Report on Technologies Potentially Useful for Safeguarding Geological Repositories", [1] funded research to conceptually design two integrated nondestructive assay (NDA) systems; one system to measure boiling water reactor (BWR) fuel and one to measure VVER-440 fuel. The integrated instruments each have three parts, a Passive Gamma Emission Tomography (PGET) instrument [1–4], a Passive Neutron Albedo Reactivity (PNAR) instrument [1,5–7] and a load cell that will measure the assembly weight. This study will focus on the PNAR instrument, which supports several of the recommended characteristics outlined for the NDA system by the ASTOR experts. Among those characteristics, PNAR has the unique role, in the integrated system, of measuring the assembly's neutron multiplication. Although the ASTOR participants were organized by the IAEA, their recommendations are not IAEA policy; the inclusion of multiplication as a metric is novel. Multiplication was included because it is a direct indication of the presence of fissile material.

In Finland there will be two measurement locations. The BWR fuel will be measured in fresh water while the VVER-440 fuel, as with most pressurized water reactor spent fuel pools, will be measured in borated water. The task of measuring the assembly's neutron multiplication in borated water reduces the sensitivity of the instrument and increases the uncertainty. The current study quantifies both the anticipated sensitivity and uncertainty of a conceptual PNAR instrument designed to measure VVER-440 fuel in borated water.

2. Passive neutron albedo reactivity physics

The PNAR concept involves the comparison of the neutron count rate of an object when that object is measured in two different setups. One setup is designed to enhance neutron multiplication while the other setup is designed to suppress it. As implemented in Finland, the high multiplying section is produced by the assembly in water, while the low multiplying section is created by putting 1 mm of Cd as close as possible

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to the fuel while it remains in the pool. As the result of criticality safety regulations, the water in pool containing VVER-440 fuel is borated, while the pool containing BWR fuel is fresh. Cd was selected for the low multiplying section due to its extremely large absorption cross-section for all neutron energies below ~0.5 eV. The PNAR signature, the PNAR Ratio, is calculated by dividing the count rate measured in the high multiplying section by the count rate measured in the low multiplying section.

The PNAR implementation in Finland, an implementation that combines (a) a ^{3}He detector tube and polyethylene (PE) surrounded by Cd and (b) a low multiplying section produced with a Cd-liner, lends itself to a conceptual discussion of the PNAR physics. The only significant difference in the measured count rate for a section of fuel measured in both the high and low multiplying sections, is the counts resulting from the multiplication caused by the neutrons that are absorbed in the Cd-liner. The contribution from neutrons not absorbed in the Cd-liner, are in both the numerator and denominator of the PNAR Ratio. In isolation, these high-energy neutrons that are unaffected by the Cd-liner create a PNAR Ratio of 1.0; any deviation from 1.0 is due to counts produced by chain reactions initiated by neutrons that are absorbed by the Cd-liner. Because the PNAR signal is produced by the neutrons returning into the fuel with an energy below the Cd-cutoff energy of ~0.5 eV, the PNAR technique is sometimes described as interrogating the fuel with low energy neutrons from the location of the Cd-liner.

3. Passive neutron albedo reactivity VVER-440 hardware

The PNAR conceptual design is part of an integrated NDA system that needs to meet the safeguards and safety needs of Finland in the context of VVER-440 spent fuel encapsulation and geological disposal. In Fig. 1, a vertical cross-cut of the VVER-440 PNAR detector module is illustrated. In Fig. 2 a horizontal cross-cut illustrates that there are three detectors around the assembly at one axial location. Below the three detector modules illustrated at one axial level are three more detectors which are rotated around the fuel assembly by 60°. The two levels are separated by ~0.1 m. In Fig. 3, the full 74 cm vertical extent of the detector is evident as well as the vertical separation between the two detector layers as one detector from each layer is shown. This number of detectors was selected to improve simulation statistics as well as to enable research into how the number of detectors impacts the sensitivity of the instrument to assembly location in the detector. The final deployment is expected to have three detectors unless there is some need for redundant instruments.

Several aspects of the PNAR design are listed here:

- The ^{3}He in the neutron detector has a 0.1 m active length, 17.4 mm or 3/4th inch diameter, 6 atm pressure, and is surrounded by a cylinder of PE that has a diameter of 58 mm.
- The ^{3}He tube and cylindrical PE are surrounded by a layer of cadmium so that, as a unit, the detector module detects primarily epithermal and fast neutrons incident upon it.
- The layer of lead is 46 mm thick at the thickest point in Fig. 1.

The Cd-liner located close to the fuel, the full 0.74 m length of which is indicated in Fig. 3, is the core hardware part needed to implement the PNAR concept. This Cd-liner, in the Finnish implementation of PNAR, will be mobile. For the low multiplication part of the PNAR measurement, it will be located as illustrated and for the high multiplying part it will be moved below the PE slab.

The PE slab located outside the detector modules is there for two primary reasons: (a) to raise the neutron multiplication of an assembly inside the detector when the Cd-liner is not present and (b) to reduce the uncertainty in the neutron count rate resulting from the variation in the boron content of the water

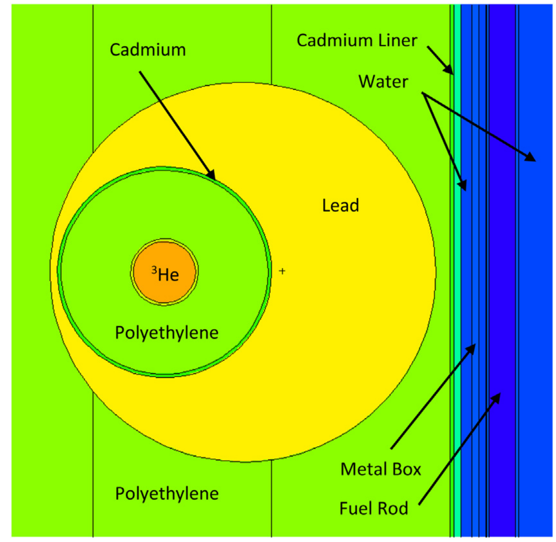

Fig. 1. Vertical (XZ plane) cross-sectional view of the VVER-440 PNAR detector along one side of a VVER-440 fuel assembly. Proportions are accurate.

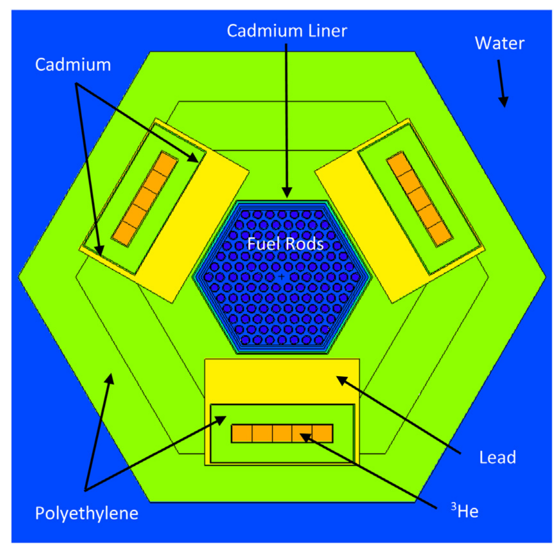

Fig. 2. Horizontal (XY plane) cross-sectional view of the VVER-440 PNAR detector along one side of a VVER-440 fuel assembly. Proportions are accurate.

4. Simulated passive neutron albedo reactivity signal

To assess the capability of the PNAR detector customized for VVER-440 fuel, the PNAR Ratio was simulated and calculated using 12 assemblies that span a range of initial enrichment (3, 4 and 5 wt%) and burnup (15, 30, 45 and 60 GWd/tU) for a cooling time of 20-years. The cooling time of 20 years was selected because the Finnish repository expects to accept fuel that cooled between 20 and 60 years; additionally, as noted on page 48 of [1], the multiplication of typical assemblies is expected to change by less than 10% over this time range. Each assembly was chosen to have a uniform isotopic content that matches the average content for an assembly of the given characteristics. The Monte Carlo N-Particle Code Version 6 (MCNP6™) [8] with 0.80c cross sections [9] was used for the PNAR simulations. The isotopic mixture of the various assemblies was produced by the Monteburns code [10] as part of the Next Generation Safeguards Initiative [11,12]. As many irradiation codes accurately simulate the neutron transport relevant isotopic content of an irradiated assembly, several different codes could