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DEVELOPMENT OF A MODELING APPROACH TO ESTIMATE RADIATION FROM A SPENT FUEL ROD QUIVER

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ABSTRACT

Before encapsulation of spent nuclear fuel in a geological repository, the fuels need to be verified for safeguards purposes. This requirement applies to all spent fuel assemblies, including those with properties or designs that are especially challenging to verify. One such example are quivers, a new type of containers used to hold damaged spent fuel rods. After placing damaged rods inside the quivers, they are sealed with a thick lid and the water is removed. The lid is thick enough to significantly reduce the amount of the gamma radiation penetrating through it, which can make safeguards verification from the top using gamma techniques difficult. Considering that the number of quivers at storage facilities is foreseen to increase in near future, studying the feasibility of verification is timely.

In this paper we make a feasibility study related to safeguards verification of quivers, aimed at investigating the gamma and neutron radiation field around a quiver designed by Westinghouse AB and filled with PWR fuel rods irradiated at the Swedish Ringhals site. A simplified geometry of the quiver and the detailed operational history of each rod are provided by Westinghouse and the reactor operator, respectively.

The nuclide inventory of the rods placed in the quiver and the emission source terms are calculated with ORIGEN-ARP. The radiation transport is modeled with the Serpent2 Monte Carlo code. The first objective is to assess the capability of the spent fuel attribute tester (SFAT) to verify the content for nuclear safeguards purposes. The results show that the thick quiver lid attenuates the gamma radiation, thereby making gamma radiation based verification from above the quiver difficult.

KEYWORDS: nuclear safeguards, simulation, spent fuel, quivers, inspection

1. INTRODUCTION

Spent nuclear fuel assemblies from Swedish light water reactors (LWR) are currently stored at the nuclear power plant for up to a few years, before being shipped to the Central Interim Storage for

Spent Nuclear Fuel (Clab). Fuel assemblies containing damaged or leaking fuel rods need special attention. The damaged rods need to be removed from the assemblies, which can only be done at the plant sites. Recently, Westinghouse has presented a new storage solution for damaged fuel rods called quivers. A quiver is a container with outer dimensions that allow it to be handled as any other LWR assembly. Quivers are made of stainless steel, and can store 14-28 boiling water reactor (BWR) fuel rods or 30-60 pressurized water reactor (PWR) fuel rods [1]. Quivers are still relatively rare objects, in Sweden around a dozen of them are in use today. However, their number is expected to increase worldwide as operators prepare for a more long-term storage alternative for damaged fuel rods.

There are several instruments and measurement techniques developed and under development for the safeguards verification of spent nuclear fuel. The majority of these instruments rely on the detection of gamma and/or neutron radiation emitted from the fuel object. Quivers may however be challenging to verify since its design attenuates, and therefore reduces the radiation to be measured. The most recent research plan published by the Swedish Radioactive Waste Management Company (SKB) also brings attention to the verification of quivers [2]. Ideally, quivers should be verified with the same instruments as regular fuel assemblies. Fuel inspections at NPP sites may include a measurement of the gamma radiation from the top of the fuel with the SFAT (Spent Fuel Attribute Tester [3]). Since verification from the top does not require fuel movements, this is the first type of measurement to be assessed.

The objective of this work is to present the methodology for modeling the quiver objects and to present preliminary results from the simulations. The simulations presented here serve as the first step of a comprehensive study. In this work, one particular PWR quiver from Ringhals NPP is being studied. The authors are permitted to disclose only limited information on the actual content and the geometry of the quiver. The geometry in the simulations is based on a simplified model provided by Westinghouse AB. The operational histories of the rods placed in the quiver were provided by the operator.

2. QUIVER GEOMETRY AND CONTENT

This study focuses on a PWR quiver. The outer dimensions of the quiver are the same as that of a PWR 17x17 assembly (21.4x21.4 cm). The quiver contains 35 steel tubes, all except one filled with moderately damaged fuel rods. The central tube is left empty. The tubes are made of stainless steel with a thickness of a couple of mm. There is one tube which has a slightly larger diameter than the others, however that tube is also filled with a single rod in this particular quiver. The tubes are arranged into a circular cluster array as shown in the left side of Fig. 1. The tubes end in a few cm thick grid spacer which is followed by a cavity. This cavity allows for retrievability, should that be necessary. The cavity is temporarily sealed with a short-term storage lid, before replacing it with a long-term storage lid as the quiver fills up. Once the long-term storage lid is placed, the water is evacuated through the central empty tube and the quiver is filled with helium. For the modeled quiver the long-term steel storage lid is already in place and has an axial height of almost 10 cm. An illustration of the structure of the lid is shown in right side of Fig. 1. The quiver is supported by four steel corner beams. For the results presented in this article, the boundaries of the geometry ended at the boundaries of the quiver's sides (as shown on Fig. 1).

The fuel rods were modeled having a length of 400 cm, with 15 cm plenum, and a 5 cm zirconium

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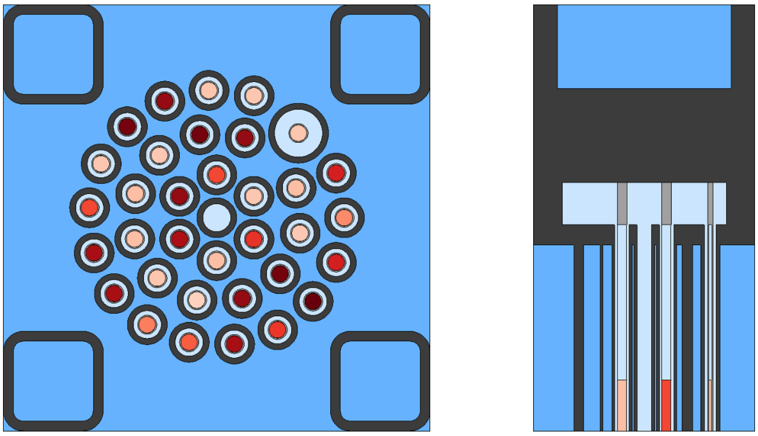

Figure 1: Left: radial cut of quiver. The rods are color coded according to burnup (darker red denotes higher burnup) Right: axial cut of the top of the quiver. (colors: dark gray - steel, light gray - zirconium, light blue - helium, blue - water, reds - fuel)

head on the top. However, in the actual simulations only the upper 50 cm of the fuel emitted particles, because it was found that the contribution from lower regions to the flux around the lid is negligible.

The 34 fuel rods in the studied quiver originate from 20 fuel assemblies and have varying burnup between 5 and 36 MWd/kgU. The burnup variation is indicated with coloring on Fig. 1. Most of the rods left the reactor in the 1980s, and the shortest cooled rods were removed in 1991. Their initial enrichment varies between 2.5 and 3.5 w%.

3. MODELED DETECTOR: SFAT

In practice, there are variations in the design of SFAT instruments. For this study the total gamma reaction rate was evaluated in a simplified SFAT detector based on the geometry details in [3]. The schematic view of the detector is shown in Fig. 2 (Z-X view). The instrument faces the center of the quiver, and the lower end of it is a couple of centimeters far from the top of the quiver. There is a 1.25 m long, 3mm thick steel tube with an inner diameter of 2.8 cm and with a 2 mm thick steel end window placed in front of the detector, which is followed by a 20 cm long collimator with a slit having a diameter of 1.0 cm. The detector itself is made of NaI and is incorporated in a lead housing.

Figure 2: Simplified SFAT model

4. COMPUTATIONAL METHODOLOGY

The nuclide inventory and the emission gamma and neutron spectra were computed with the ORIGEN-ARP software [4]. The operating history and the cooling time was set according to the information provided by the operator. No information about the placement of the individual rods in their respective original fuel assemblies was provided by the operators hence that is not considered in the simulations. In the calculations gamma data were regenerated from the Evaluated Nuclear Structure Data File (ENSDF). Additional data for 52 nuclides without ENSDF data were adopted from ENDF/B-VI data. Decay data came from ENDF/B-VII.0. For neutron emission spectra, the SOURCES code package was used, and the neutron cross-sections came from JEFF-3.0/A.

The gamma emission spectra was evaluated in a 47 energy bins, whereas the neutron spectra was evaluated in a 200-group structure, both group structures can be selected in ORIGEN-ARP. The calculated gamma and neutron emission spectra for the 20 assemblies are shown in Fig. 3. In both the left and the right panel, the darker red the curve is the higher the gamma activity is.

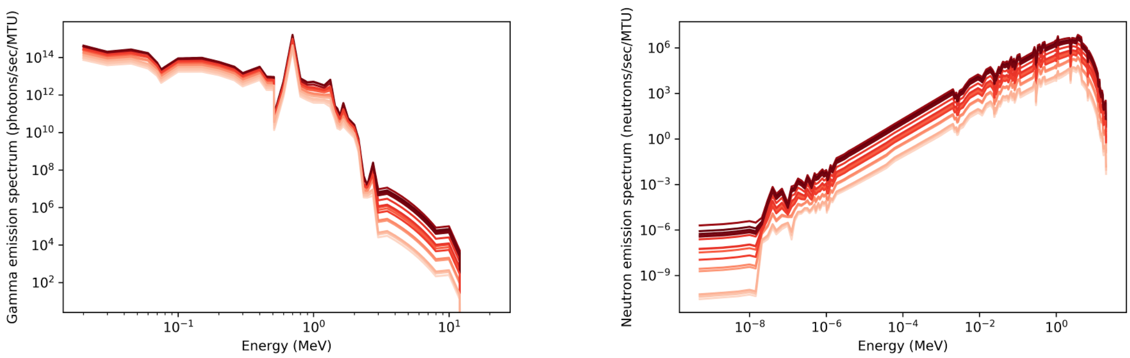

Figure 3: Calculated emission spectra of the twenty assemblies. Left: Gamma emission spectra (the darker red means higher gamma activity). Right: Neutron emission spectra (the coloring is the same as in Left side, thus darker red means higher gamma activity; MTU: metric ton of uranium)

The quiver design was modeled in Serpent2 [5] as shown in Fig. 1. From the ORIGEN-ARP output files the nuclide inventory and the emission spectra were extracted and used in the subsequent Serpent2 particle transport calculations as material definitions and source terms, respectively. The neutron cross-sections were taken from JEFF 3.1, and the provided photon libraries were used for gamma transport. Most of the simulations were run with Serpent 2.1.28, however for the SFAT studies the version 2.1.31 was used since variance reduction techniques were applied.

4.1. Variance Reduction

Some simplifications of the geometry and of the source term and also the use of variance reduction techniques were required to obtain any scores in the SFAT detector. Currently, weight windows are the only available variance reduction technique in Serpent2. Nevertheless, the capabilities have been extended lately with the implementation of an iterative global variance reduction scheme to generate weight window meshes with the purpose of uniformly distributing particles over the geometry [6].

In the SFAT calculations only the upper 50 cm of the rods were included in the geometry, because we have found that gamma photons originating from deeper regions have a negligible contribution to the flux above the lid. Another simplification in the SFAT calculations was that the source energy distribution was omitted and replaced by a monoenergetic 662 keV photon source with the emission rate calculated by ORIGEN-ARP in the 600-700 keV bin. This choice is motivated by the fact that in SFAT measurements the peak around the 662 keV line is of main interest.

In order to get scores in the SFAT detector, a weight window mesh was generated in 19 steps. First, 16 global variance reduction iterations were performed, in order to uniformly populate gamma photons over the geometry. Then, one additional iteration step optimized the mesh to propagate particles into the steel tube in front of the detector, another step optimized the mesh to propagate particles into the collimator slit in front of the detector and the final step optimized the mesh to propagate particles into the detector. In each step two million source particles were simulated. Fig. 4 is plotting scores that contribute to the overall flux in the geometry in each iteration. The figure does not serve any quantitative purpose (thus colorbars are omitted). Each slice in the figure has the same orientation as Fig. 2. One can observe that in the first 16 steps the particles are propagated further from the source, however the particles do not reach the detector yet (there is an observable shadow behind the tube in step #16). Then, in the last three steps particles are forced to travel towards the detector. In the last step, particles reach the detector volume located at the right end of the figure. However, even with the final weight window mesh relatively high errors are obtained in the detector tally. Due to memory issues we could not launch calculations with sufficient amount of source particles to reduce the error, instead we have repeatedly run the same input with a different random seed.

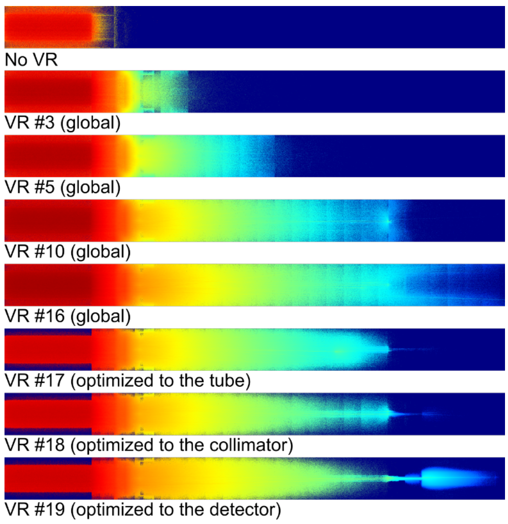

Figure 4: Scores contributing to the overall flux during variance reduction (VR) iteration steps. Serves only as a qualitative illustration.

It has to be noted, that although weight windows (and especially the global variance reduction scheme) is an excellent choice in shielding problems, such as when particles need to be propagated through the thick steel lid of the quiver, it might not be the most appropriate choice for variance reduction in heavily collimated systems, such as when the response of an SFAT detector is simulated. Another drawback of weight windows, as highlighted in the Serpent input syntax manual [7], is that weight window generators „*may not work if the source distribution is biased with weight*", which is the case in the current simulation, in which all pins have different weights due to the different emission rate. That said, the results achieved here with the applied weight window scheme have to be looked at with care. Indeed, it was found that the random error on the detector tally has a large fluctuation when the same input is run several times, which implies that high weight particles accidentally hitting the detector might bias the results.

5. RESULTS

The gamma and neutron fluxes as a function of energy were calculated in a 20 cm high water volume above the quiver lid, and can be seen in Fig. 5. The base of this volume corresponds to the top of the quiver lid. Thus, the spectra represent the observable spectra just above the quiver. The gamma spectrum is shown using the default 47-bin structure from ORIGEN-ARP, and the neutron spectrum using the 200-bin structure. Each value gives the flux integrated over space and energy (of the given bin) divided by the volume. The corresponding random errors are few percent for most of the bins, thus the errorbars are hardly visible in the plots.

The gamma spectrum in the left side of Fig. 5 resembles the shape of the gamma emission spectrum, as expected. The dominance of the 662 keV peak is visible, although the bin structure obscures it. Compared to a similar spectrum above a PWR 17x17 fuel assembly, the flux level is 3-4 order of magnitude lower due to both the lid and the relatively low burnup of pins.

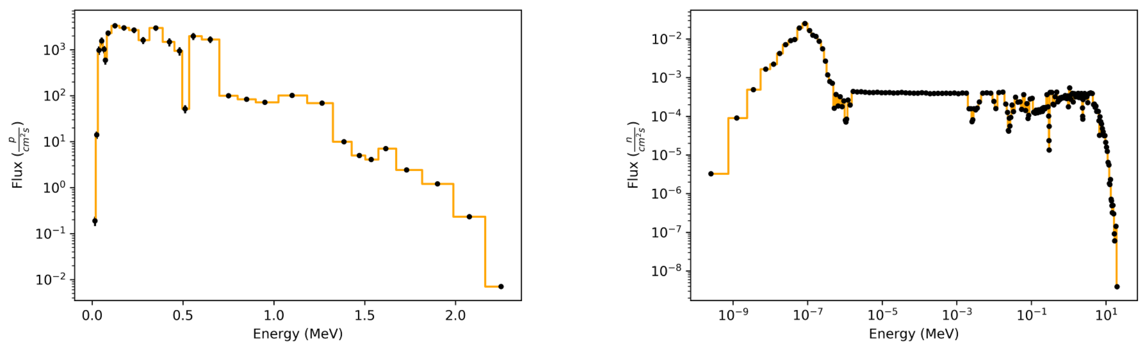

Figure 5: Left: gamma flux in the water volume above the lid. Right: neutron flux in the water volume above the lid.

The mesh-integrated gamma and neutron flux around the quiver lid is shown in Fig. 6. The contour plots are averaged over the Y-axis. The simulation of the gamma field is more challenging due to the strong attenuation of the lid, thus some fluctuation is visible in the results (left panel of Fig. 6) even though 8 billion source particles were simulated. Nevertheless, the figure allows to conclude, that the flux drops 4-5 orders of magnitude from the top of the fuel to the top of the lid, and the lid is responsible for reducing the flux by 2-3 orders of magnitude. Note that the lid mid plane refers to the top of the solid steel structure of the lid (as shown in Fig. 1), which is followed by a steel handle frame filled with water. The neutron flux (right panel of Fig. 6) is attenuated only with 2-3 orders of magnitude from the top of the fuel to the top of the lid, however due to the very low neutron source strength, in absolute values the flux is almost zero at the top of the lid.

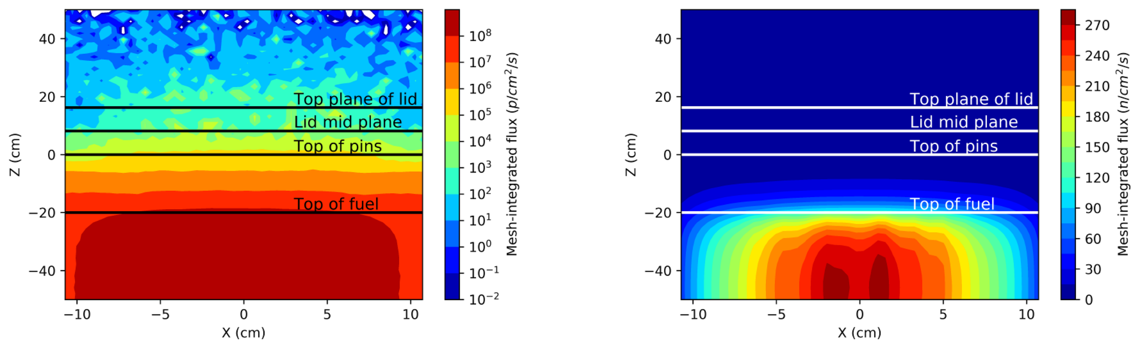

Figure 6: Left: Mesh-integrated gamma flux (for energies 600-800 keV). Right: Mesh-integrated neutron flux (for energies 0-14 MeV). Averaged over the Y-axis

The total gamma reaction rate in the modeled SFAT detector was also estimated as described in Sec. 4.1. With the variance reduction scheme presented in Sec. 4.1 the total gamma reaction rate in the 600-700 keV bin due to 662 keV photons was estimated to be 0.01 $\frac{1}{s}$. Due to memory limits, we could not run calculations long enough to obtain a random error less then 30 %. In order to obtain this reaction rate estimate, the same calculation was run a hundred times with different random seed, and finally only the results which had a lower than 50 % error were kept and averaged over. In these runs the reaction rate estimates seemed to be consistent. But in several runs, in which random errors exceeded 50 %, the estimated reaction rates had a different order of magnitude (which may be caused by high weight particles accidentally hitting the detector and resulting in a bias). As highlighted before, the reliability of the weight window scheme to predict this value is questionable, and further investigations are needed. This value nevertheless implies that the SFAT instrument is probably not capable to verify quivers even on the gross defect level, since during a five minutes long measurement less than three counts can be observed.

6. CONCLUSIONS

This paper summarizes the preliminary steps in simulating the gamma and neutron radiation field around spent fuel rod quivers. A Serpent2 model was created based on information obtained from the manufacturer and from the operator. The results show that the verification of the content of a quiver from the top is difficult, once the long-term storage lid is in place. The neutron flux is almost zero above the quiver. The gamma flux is non-zero, however it was found that with an SFAT instrument only a negligible amount of counts can be collected over several minutes. In the future we intend to investigate whether a modified SFAT (without a long steel tube) is capable of verifying gross defects of the content. It has to be noted that in the current work the boundaries of the model were set to the quiver's side, however, currently we are investigating the case when the quiver is placed in a pool to assess whether the contribution of particles scattered around the lid to the flux above the lid is relevant. This would however be reasonable to consider only in a measurement situation when the quiver is not surrounded by other fuel objects which may impact the measurements.

Currently, we are still working on verifying whether the calculated SFAT response is reliable, and it is likely that we have to change our methodology either by simulating the SFAT contribution made by each pin separately (thus omitting the emission weights, which might cause problems), or by the simulation of the SFAT signal with another Monte Carlo transport code which allows for using point detectors which is a more appropriate variance reduction technique for the problem.

The results show that on the side of the quivers the neutron flux is two orders of magnitude and the gamma flux is four orders of magnitude higher than above the lid, thus instrumentation placed close to the side may be a better alternative to verify the quiver. In the continuation of this work we intend to evaluate the response of the FORK detector and we expect to perform measurements of the Swedish quivers.

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