Estimating gamma and neutron radiation fluxes around BWR quivers for nuclear safeguards verification purposes

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ABSTRACT: Non-destructive assay (NDA) methods are at the core of nuclear safeguards verification of spent nuclear fuel (SNF). In Sweden, the spent nuclear fuel from all the reactor sites is moved to the Swedish central interim storage facility for spent nuclear fuel (for which the Swedish acronym is Clab). A new facility, Clink, is planned at the site where the SNF will undergo a safeguards verification prior to encapsulation for long-term storage. The fuel to be encapsulated includes both regular fuel assemblies as well as “non-regular” fuel assemblies including fuel objects called quivers, which are specially designed containers to house damaged or failed and leaking spent fuel rods in a way to isolate the rods from the environment and prevent contamination.

The quiver concept was recently introduced in the Swedish nuclear market by Westinghouse Electric Sweden AB and it has led to some unique challenges from a safeguards verification standpoint which stem from their construction. Their overall stainless steel build, while providing robustness to the structure, also greatly diminishes the possibility of detecting gamma or neutron radiation using traditional safeguards measurement devices. The current investigation looks into the practicalities of safeguards verification of boiling water reactor (BWR) quiver objects in the spent fuel pool from above, and also assesses the possibility of their verification from the side using the widely used Fork detector. The Fork instrument has been routinely employed by both operators and inspectors around the world to verify spent fuel for routine safeguards inspections.

In the present work, we model the BWR quiver and the Fork instrument in the Monte Carlo particle transport code, Serpent2 to estimate the radiation flux around the quiver objects. We have shown that the gamma and neutron radiation from the BWR quiver were heavily attenuated by the stainless steel lid and could not be relied on to make a safeguards verification from above. Furthermore, it was established that while gamma radiation from the quiver remains measurable on...
the sides of the quiver by the Fork instrument, the neutron counts were low compared to a typical BWR fuel assembly of similar fuel content albeit within the limits of detectability of the Fork.

Keywords: Detector modelling and simulations I (interaction of radiation with matter, interaction of photons with matter, interaction of hadrons with matter, etc); Search for radioactive and fissile materials; Gamma detectors (scintillators, CZT, HPGe, HgI etc); Neutron detectors (cold, thermal, fast neutrons)
1 Introduction

While Sweden is among the nations that are at the forefront of researching options for permanent long-term storage of spent nuclear fuel, the government has not yet approved the KBS-3 [1] method for future fuel management and eventual disposal. The spent fuel is planned to be transported from Clab to the future encapsulation facility Clink [2] and upon its arrival, it will be encapsulated in copper canisters and shipped to the future permanent geological repository planned near the Forsmark nuclear power plant (NPP). Prior to encapsulation, spent nuclear fuel needs to be verified [3] to the best possible precision from a safeguards standpoint [4, 5] since its re-verification is impossible once the fuel is placed in the geological repository. The majority of the fuel to be encapsulated is classified as regular fuel, but a minority constitutes so-called non-regular fuel [4] for which a custom-made verification approach may be needed. One example of non-regular fuels is the so-called quivers, and their safeguards verification is the main focus in this study. Quivers are
stainless steel containers which are designed with the sole purpose to house damaged or failed fuel rods in a safe manner to prevent contamination of the environment after they have been removed from the parent assembly.

Presently, there are only a few quivers in Sweden, however their numbers are expected to increase over the coming years since quivers have now been adopted by the Swedish nuclear industry as the preferred storage solution for damaged and failed spent fuel rods. All such fuel rods which have accumulated over the years are now being moved to these quivers before they are shipped from the reactor sites to Clab. Adoption of quivers as the storage solution for failed and damaged fuel has also led to some concern about their safeguards verification prior to final disposal. What makes quivers particularly challenging to verify from a nuclear safeguards standpoint is their design, which includes a thick long-term storage lid. Each quiver is filled to capacity and then a stainless steel long-term storage lid is placed onto it. As the NDA of spent nuclear fuel typically relies on the detection of gamma rays, neutrons or Cherenkov light emanating from the fuel, the presence of a thick lid is expected to cause attenuation of gamma and neutron radiation passing through it, thereby making it challenging to verify its content from above using existing instruments such as the Spent Fuel Attribute Tester (SFAT) or the Digital Cerenkov Viewing Device (DCVD) [6].

A study by [7] has looked into pressurized water reactor (PWR) quivers wherein a model of the PWR quiver was built and the gamma and neutron radiation fields around its lid were mapped to obtain an estimate of flux rates using an SFAT detector. In the present work we build a model of a BWR quiver in the Monte Carlo particle transport code Serpent2 [8] with realistic fuel content based on fuel data obtained from Forsmark NPP in Sweden, in order to estimate gamma and neutron fluxes above and around it. We will also assess if the flux values from one such quiver are within the limits of detectability of the modeled Fork instrument. The results from the current study are applicable to the specific quiver being analyzed and are not expected to be a bounding scenario for other BWR quivers in Sweden. However, the assessment will provide insight on the gamma and neutron flux values to be expected from a BWR quiver, which could prove useful during future verification of such quiver objects.

The following sections describe the details of the BWR quiver design, the development of the BWR quiver model in Serpent2 and its key features, specifications and development of the Fork detector instrument model and its response towards gamma and neutron radiation, the computational methodology employed, results and the final conclusions drawn.

2 BWR quiver design

The quivers in use in Sweden are broadly classified into two main types, PWR and BWR quivers, and are manufactured and supplied by Westinghouse Electric Sweden AB [9]. The two quiver types differ significantly in design with the major difference being the much larger capacity of the PWR quiver, which was designed to hold up to 34 damaged and/or failed fuel rods as compared to 14 such fuel rods for the BWR quiver. On the whole, overall outer dimensions of both light water reactor (LWR) quivers are identical to respective fuel assemblies.
The current evaluation focuses on the BWR quiver. The outer dimensions of the quiver are identical to that of a BWR 8 × 8 assembly (an ABB 8 × 8 in this case with a cross-section of 13.86 × 13.86 cm²). Attached to the long-term storage lid, as can be seen in figure 1, each BWR quiver is provided with a lifting handle which facilitates its maneuvering in the pool using existing fuel handling machinery without the need for any new specialized equipment. The BWR quiver is designed to accommodate up to 14 damaged and/or failed fuel rods inside rod storage tubes of two different sizes. The narrower tubes with an inner diameter of 1.4 cm are used to house fuel with minor cracks and damage, while the wider tubes with an inner diameter of 2.4 cm house fuel rods with a greater degree of damage i.e. fragmentation. The wall thickness for both tube types is 3 mm. The tubes are arranged in a roughly circular array and the cluster of tubes is flanked by stainless steel circular support beams in the four corners which run along the full length of the quiver from the bottom of the lid all the way to the fuel rod ends as can be seen in figure 1. Once the quiver is loaded to capacity and the lid is put in place, the water inside the quiver is evacuated through the central tube and it is back-filled with helium.

3 Computational methodology

This section describes details of the computational methodology employed in this study while also describing the details of fuel, quiver, and detection system models. The steps followed in the analysis are summarized as follows. Firstly, the BWR fuel rods were modeled and depleted using ORIGEN-ARP [10] to obtain the irradiated fuel material composition, gamma and the neutron source emission spectra. Once the depletion step in ORIGEN-ARP was complete, material definitions of the burned fuel rods along with the emission spectra were used to create both the gamma and the neutron source term definitions as well as irradiated fuel material definitions for all fuel rods in the quiver. Thereafter, these source terms were used in the Serpent2 model of the quiver to perform the particle transport step to obtain gamma and neutron flux values in different regions around the quiver. Since each fuel rod inside the quiver had a unique burnup history (except rods in two locations, since they came from the same original fragmented fuel rod and had identical irradiation and cooling history), the neutron and gamma source terms for each of the rods were unique.

The first objective of the current study was to map the gamma and neutron flux from the BWR quiver above and around the lid with Serpent2 and compare gamma and neutron radiation intensities with those obtained by [7]. Thereafter, in order to assess the feasibility of a safeguards verification from the sides, a Fork instrument was modeled (as described in section 3.3) according to specifications. Once the Fork prongs were modeled, the model was benchmarked against previous
studies [11, 12] to compare the detector response with a BWR assembly. Finally, the Fork was used alongside the BWR quiver model and gamma and neutron flux from fuel rods in the quiver were estimated at the Fork. Details of the modeling steps for the fuel, quiver and the Fork instrument are included in the following subsections and a flowchart depicting the methodology has been shown in figure 2.

Figure 2. Flowchart showing details of adopted computational methodology. *TRITON module has been used for preparation of cross-section libraries for the fuel designated as BWR19 in SKB-50 [13].

3.1 Fuel model specifications

The burnup calculation of the fuel was performed in accordance with information obtained from Forsmark NPP on parent fuel assemblies that the fuel rods originally came from. Irradiation histories including average power per cycle, cycle down-times, and cooling times were modelled in ORIGEN-ARP based on information received from the reactor operator. All fuel rods were assumed to have come from parent assemblies of ABB 8 × 8 [14] type with an initial enrichment of 3.0 wt.% $^{235}$U (henceforth quoted as simply in %) as an assumption, since the actual enrichment values were unknown. However, the fuel rods in a real quiver are expected to come from parent assemblies with different initial enrichments and sometimes, there may be varying enrichment between rods within a single fuel assembly. Figure 3 shows the distribution of fuel rods in a burnup-cooling time space inside the quiver. The quiver contains a total of 14 rods with burnup values ranging from 10 to 40 MWd/kgU and cooling times between 7 and 38 years. Figure 3 indicates that all but
one rod have mid-range burnup (15 ≤ BU ≤ 25 MWd/kgU), and 12 out of 14 were long-cooled (> 15 years) fuel. There was only one very high burnup rod (> 35 MWd/kgU) with a significantly shorter cooling time than most other rods.

Figure 3. Histogram of fuel rod properties in the BWR quiver.

The source definitions obtained from ORIGEN-ARP and used thereafter in Serpent2 for estimation of the gamma and neutron fluxes above the quiver lid, were defined in the top 50 cm of the active fuel after proper normalization of emission rates in accordance with reduced source length. This was done since in [15], it was found that fuel material below the top 50 cm of the active fuel does not contribute to the gamma and neutron flux above the quiver lid in any significant way. However, when estimating the flux at the prongs of the Fork detector in later sections of this study, the gamma and neutron sources were defined over the entire length of the active fuel. Additionally, the fuel rods used in the quiver analysis used the rod average burnup and therefore, presence of axial burnup zones in the fuel remains uninvestigated in the scope of the present analysis. Lastly, during the depletion step in ORIGEN-ARP, a constant specific power based on fuel burnup and cycle length was used as a simplifying assumption since in the case of a real nuclear reactor, power often fluctuates as in the case of a BWR reactor where a combination of core coolant flow rates and control blade movement is used to manage the power plant’s electricity output.

3.2 Quiver model specifications

As far as the 3D BWR quiver model in Serpent2 was concerned, the model was prepared using the technical specifications and the CAD model provided by Westinghouse Electric Sweden AB as shown in figure 1. The CAD model, though realistic, did not include structural elements such as plugs and perforations. The presence of perforations in the quiver’s lid may have a measurable impact on the gamma and neutron flux in regions above and around the lid, however this effect was not investigated as design information pertaining to such structural elements was not available from the manufacturer and therefore, all such elements were excluded from the Serpent2 model of the BWR quiver. The model of the quiver had a size of 13.86 × 13.86 cm² (identical to that of
an ABB 8 x 8 fuel assembly). The quiver lid as well as the lid lifting handle were also modeled in accordance with the technical specifications. Tubes that house the fuel rods were modeled with dimensions identical to that of an ABB 8 x 8 fuel rod [14] so that they are just long enough to fully accommodate the fuel rods while keeping their width identical to technical specifications. All the structural materials were modeled as stainless steel and the space below the long-term storage lid was modeled as filled with helium. The Serpent2 model of the BWR quiver with the fuel rods inside is depicted in figure 4 with the left panel showing a cross-section of the quiver’s long-term storage lid, and the right panel showing the arrangement of fuel rods and support beams inside the quiver.

Figure 4. Left: side view in section of the BWR quiver head. Right: top view in section showing the fuel rod array inside the quiver. Colors: gray — steel, silver — zirconium, pink — helium, blue — water, green in the left pane — plenum (air composition), shades of blue inside quiver tubes in the right pane — active fuel.

For the particle transport calculations performed in Serpent2, the modelled active fuel rod length was 371.2 cm, the height of the plenum was 26.9 cm and the pellet and cladding radii were 5.25 mm and 6.15 mm respectively, identical to that of standard ABB 8 x 8 fuel. All fuel rods were modeled as full-length rods as a simplifying assumption, notwithstanding the fact that the data received from Forsmark NPP indicated two locations inside the quiver containing partial-length rods of unknown length coming from a single original fuel rod that underwent disintegration. In reality, the fragmented rods are placed in the quiver atop partial-length leading dummy rods. This ensures that the fuel rod fragment does not fall to the bottom of the quiver tube, thereby ensuring retrievability in the future, if needed.

3.3 Fork detection instrument model specifications

The Fork instrument is available in a multitude of designs and is capable of making simultaneous measurements of gamma and neutron intensities from the spent fuel using ionization and fission chambers, respectively. It has been used by both the International Atomic Energy Agency (IAEA) and Euratom inspectors for routine spent fuel verification for many years [6, 19]. The two prongs of the Fork instrument are connected by a third side that houses associated detector electronics.
and cables. Two most well-known variants of the Fork, currently in use for inspection, are the Euratom Fork (used in the present study) and the IAEA Fork. These two variants are slightly different in terms of their design and type of sensors. Besides these two variants of Fork design, there are other widely used adaptations depending on the fuel design. In fact, the Fork is available with variations according to the dimensions of PWR (in future suited also for EPR), BWR (used also for VVER-440) or specific for less common spent fuel types, i.e. VVER-1000 [17] etc. The main difference in design for these variants is the spacing between the Fork prongs since the fuel assemblies vary in size.

For the current evaluation, the Euratom BWR Fork was modelled using design and dimensions similar to those used in [12, 18]. The two arms (or prongs) of the Fork were positioned alongside the quiver (as shown in figure 5) and the third side, connecting the two detection prongs, was excluded from the Serpent2 model. The impact of the presence of the third Fork side has not been a subject of investigation in the current work and remains to be studied in future evaluations. Each of the two prongs of the Fork housed one ionization chamber to detect gamma photons and two fission chambers for detection of thermal and epi-thermal neutrons. Furthermore, one of the two fission chambers and the ionization chamber were enclosed in a cadmium (natural) lining (of thickness 0.5 mm) while the second fission chamber was left bare. The cadmium-lined fission chamber was thus sensitive to fast and epithermal neutrons, while the bare one was sensitive to those thermalized in the pool water. Additionally, both prongs were rotated with respect to each other by 180 degrees thereby reversing the axial positions of the bare and cadmium-lined fission chambers in each prong.

**Figure 5. Left:** top view in section of the BWR Fork and the BWR quiver as modeled in Serpent2. **Right:** side view in section showing the quiver and a section of the prong of the Fork instrument. Colors: gray — steel, silver — zirconium, pink - helium, gold — cadmium, blue — water, green — HDPE, brown — brass, black — void, shades of blue — active fuel (brighter blue colour for fuel pins denotes a higher burnup).

Inside both prongs, each of the fission chambers were assumed to contain 131.8 mg of $^{235}$U as the fissile material for detection of neutrons. Since measurements using the Fork are performed under water by positioning the prongs of the system around the fuel assembly to be verified, unborated water was included around the quiver and in the Fork setup in the Serpent2 model on all sides (as shown in figure 5). The additional salient features of the Fork model include a prong separation of

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26 cm, prong radius of 4.6 cm, and ionization chambers and fission chambers with an outer radius of 1.3 cm. One of the key differences between the modeled fission and ionization chambers was the inclusion of a brass tube of 2 mm thickness thereby reducing the effective diameter of the ionization chamber to 1.1 cm. Smaller differences between fill gases in the ionization chambers and the fission chambers existed wherein the ionization chamber was filled with xenon while the fission chambers with a mixture of argon and nitrogen (exact composition unknown). For simplicity, all chambers were modeled with helium as the fill gas. Another key difference in the operation of the fission chambers and the ionization chamber is the fact that the fission chambers are operated in count rate mode i.e. the detector readout is in counts/second while the ionization chambers are operated in current mode wherein the gamma photons interacting with the detector material lead to a detector current or a signal which is measured in Amperes. Inside each prong, a shell composed of HDPE, about 4 mm thick surrounded all three chambers in the Fork prong. These dimensions were kept similar to evaluations performed in [16]. The detectors ran along the entire width of the BWR quiver in the model and prongs of the Fork instrument were positioned around the quiver about the axial center of the length of the active fuel. The centers of the ionization chambers within each prong were approximately 10 cm away from the centerline of the nearest fuel rod, while the fission chambers were about 6 cm from the centerline of the nearest fuel rod in the quiver.

3.4 BWR assembly model specifications

In order to benchmark the model of the Fork used in the present study, an evaluation was carried out to estimate the gamma and neutron detector response in the respective ionization and fission chambers in the Fork prongs. For this purpose, gamma and neutron detector responses were computed with a fuel assembly belonging to the SKB-50 [13], a set of 50 well-characterized Swedish spent fuel assemblies, previously evaluated in [11]. The assembly designated as BWR19 from the SKB-50 set was chosen due to the availability of its irradiation data from the Swedish electric corporation, Vattenfall [20] as well as due to its burnup and cooling time being roughly similar to the average burnup and cooling time of the contents of the BWR quiver being evaluated in the present study. The BWR19 assembly was modeled as an ABB 8 × 8 type with an enrichment 1.27% and it was subsequently irradiated and cooled with ORIGEN-ARP according to data from Vattenfall. ORIGEN-ARP sets the lower limit on usable enrichment at 1.5%. Hence, new cross-section libraries were generated to extend this range down to 1.0% with the help of the TRITON [21] module of the SCALE [22] code system. Thereafter, the material compositions as well as the gamma and neutron emission spectra were obtained and as before, this data was used in Serpent2 in a gamma and neutron transport calculation to obtain the detector response. Furthermore, during the particle transport step in Serpent2, each fuel rod was divided into 25 axial zones of varying source strengths. This was done by weighting the total source strength with axial burnup correction factors for each zone where the correction factors were obtained from [23]. All other model specifications such as axial and radial positioning of the Fork prongs around the assembly were kept identical to [11]. In-depth details of the methodology used to compute the detector response will be discussed in the sections that follow. Figure 6 shows the details of the fuel assembly model and the Fork instrument placed around it. The results for this benchmark evaluation are discussed in section 4.2.1.
3.5 Modeling of ionization and fission chamber response

This subsection describes the methodology followed to estimate the neutron and gamma response of the Fork instrument. After the material composition of the spent fuel rods as well as the gamma and neutron source definitions obtained previously from ORIGEN-ARP were incorporated in the Serpent2 model, the detector response from the neutron and gamma radiation of the fuel was simulated. As far as the neutron response from the fission chambers was concerned, the analysis made use of the reaction type 18 (or MT\(_{18}\)) from the ENDF (Evaluated Nuclear Data File) [24] list of reaction types. Use of MT\(_{18}\) in a neutron transport calculation with Serpent2 gave an estimate of total fission rate (thermal, fast, prompt and delayed) in a fissile material. Each fission chamber was modeled with 131.8 mg of \(^{235}\)U since [11] and [25] quote the same fissile material content for the chambers. With MT\(_{18}\) invoked, the neutron transport calculation provided estimates of fission rates inside the \(^{235}\)U present in the individual fission chambers of the Fork instrument. The fission rates were thereafter weighted with the neutron flux and fissile content to obtain the neutron count rates for each chamber. It is important to note that since each prong of the Fork housed both bare and cadmium-lined chambers, the two signals from each type of detector were summed to obtain signals from the two channels i.e. Channel A for bare chambers and Channel B for cadmium-lined chambers.

As far as the detector response towards gamma radiation was concerned, the ENDF MT = 100 reaction type was utilized to obtain an estimate for the total absorbed dose rate in Serpent2 along with a user-defined response function corresponding to ANSI/ANS-6.1.1-1977 [26] or the ICRP-21 [27] flux to dose rate conversion factors. This option provides the user with a photon dose rate in a local material (in rem/hr/p/cm\(^2\)-s) which can be converted to a detector current with a suitable conversion factor dependent on the electronics of the detection system. It must be noted that the dose-to-detector current conversion factor is strongly dependent on the detection system.

\[\text{Figure 6. Left: top view in section of the BWR Fork and the BWR19 fuel assembly (from SKB-50). Right: side view showing sections of the assembly and of the prong of the Fork instrument. Colors: gray — zirconium, yellow — active fuel, blue — water, green — HDPE, pink — helium, brown — brass, black — void, gold — cadmium.}\]
and associated electronics in use and a suitable value is decided based on several measurements and cannot be estimated using simulations alone. Lastly, just like in the case of the fission chamber channels, since each prong of the Fork instrument housed one ionization chamber for detecting gamma radiation, the total output signal was obtained by summing the signals from each prong.

4 Results

This section gives details on the results of different analyses carried out in the present study. Section 4.1 describes the results from estimation of the gamma and neutron flux from the fuel rods above the quiver lid in order to draw a comparison with past studies [7]. Section 4.2 will delve into the details of the Monte Carlo transport calculations performed to estimate flux values at the Fork instrument in different detection instrument-fuel/quiver configurations.

4.1 Gamma and neutron fluxes above the BWR quiver lid

4.1.1 Computational benchmark of the BWR quiver model with past studies

The gamma and neutron emission spectra obtained from ORIGEN-ARP for all the 14 fuel rods are shown in figure 7 wherein for both the sub-figures, a brighter red shade of the plot line indicates higher activities (or burnups) while deeper blue shades indicate low activities. The figure for the gamma emission spectrum shows some key features such as a prominent bump in the 662 keV region which contains contribution from, among other nuclides, $^{137}$Cs with an emission intensity reaching $10^{12}$ photons/sec/MTU. It was also worth noting that nearly all fuel rods had roughly similar emission spectra at lower energies while at higher energies, fuel rods with higher burnups tend to emit more gamma photons. As far as the neutron emission spectrum was concerned, there was a clear distinction in magnitude between low burnup and high burnup fuel rods at both low energies and high energies, with the highest emission intensity reaching $10^6$ neutrons/sec/MTU for fuel rods with the highest burnup. The shape of the neutron spectrum for all 14 rods however remains similar.

![Figure 7. Left: computed gamma emission spectrum from ORIGEN-ARP. Right: neutron emission spectrum obtained from ORIGEN-ARP for all 14 fuel rods.](image)

The variation of gamma and neutron flux as one moves away from the active fuel and towards the BWR quiver lid was also estimated with Serpent2 and has been depicted in figure 8. Both plots in figure 8 show the average of the gamma/neutron flux tallies along the depth of the quiver and
suggest a drop in the gamma flux by a factor of roughly $10^5$ from approximately $10^{10}$ photons/cm²/s near the ends of the active fuel to approximately $10^5$ photons/cm²/s towards the top of the quiver lid, while the neutron flux readily drops to zero even before reaching the end of the fuel plenum. The right pane in figure 8 also shows a higher neutron flux in one region of the quiver, due to presence of a high burnup rod (> 35 MWd/kgU) in one of the locations. In this region, the flux was nearly twice as high (reaching 56 neutrons/cm²/s) compared to most other regions within the quiver. In order to keep overall statistical uncertainties below 3%, a total of 1 billion particle histories were simulated and averaged for several Monte Carlo simulations. All individual Monte Carlo cases include statistical uncertainties of < 10% for both gamma and neutron flux estimations and upon averaging across several runs, they were further reduced to < 2–3%. The serpentTools [28] package was used to read in the detector tallies in the output files from the particle transport calculations carried out in Serpent2 to create the plots shown in figure 8.

![Figure 8. Left: mesh integrated gamma flux above and around the BWR quiver lid (0–20 MeV). Right: mesh integrated neutron flux above and around the BWR quiver lid (0–14 MeV).](image)

The results from the first part of this study were found to be in line with those from [7] where the total gamma and neutron flux from the quiver were seen to be of roughly the same order of magnitude as the PWR quiver. The flux values for both gammas and neutrons were roughly of the same order, taking into account the number of fuel rods in the BWR quiver when compared to the PWR quiver from [7] which holds more than twice as many rods. Moreover, it was observed that the drop in gamma and neutron flux across the quiver lid was also comparable, where the gamma flux was reduced by a factor of $10^6$ and the neutron flux dropped to zero in both PWR and BWR quivers. Overall, the trends in attenuation of gamma and neutron intensities around the quiver lid computed in the present study were found to be in good agreement with those obtained in [7]. It was also worthwhile to note that just as in case of [7], the low gamma and neutron flux intensities above the quiver lid make verifying measurements from above difficult.

4.2 Flux values at the Fork instrument

4.2.1 Computational benchmark of the Fork model with BWR fuel

As described in section 3.4, the BWR19 assembly from SKB-50 was modeled along with the Fork instrument as was done in [11] and the gamma and neutron response of the detectors in the Fork instrument was simulated. It was found that approximately $200.8 \pm 9.8$ counts/second (quoted error
was statistical in nature) were registered in the cadmium-lined fission chambers (Channel B) of the Fork due to the neutrons from the BWR19 reference fuel assembly. This value was close to that reported by [11] wherein a value of 180.3 counts/second was found for the same fuel assembly. The difference in the results from the two studies can be attributed to several factors namely, the present analysis made use of Serpent2 with the ENDF/B-VI (release 8) cross-section library as the decay data and neutron-induced fission yield library as well as JEFF 3.1 [29] for particle transport calculations while [11] used MCNP6 [30] code with ENDF/B-VII.1 library to accomplish the same task. Table 1 shows the neutron radiation response of the detector compared to results from [11].

| Signal Type         | Benchmark values | Present study       |
|---------------------|------------------|---------------------|
| Neutron counts      | 180.3            | 200.8 ± 9.8         |

Table 1. Comparison of computed neutron (channel B) for the BWR19 assembly from SKB-50. Calculations for neutron signals are shown without any corrections. Fission chamber response has been benchmarked against values from [11].

The gamma response of the ionization chambers was obtained according to methodology described in section 3.5. It was discovered post discussion with authors of [11] that reproduction of the Fork gamma response was not feasible, since the coefficient of conversion from either [11] or [12] (which is heavily dependent on the selected electronics and directly impacts the detector gamma signal) used in previous work could not be calculated with the help of simulations alone owing to model uncertainties and lack of knowledge of electronics and detector variations. Therefore the benchmarking study in this evaluation has been limited to the comparison of the fission chamber response alone. The ionization chamber response in this study is reported as absorbed dose rate (in Sv/h) in the detector material. The dose rates were computed with both ANSI/ANS-6.1.1-1977 as well as ICRP-21 flux to dose conversion factors and were found to be 8.3 ± 0.6 kSv/h and 5.9 ± 0.4 kSv/h respectively.

4.2.2 Gamma and neutron flux from the BWR quiver at the Fork prongs

As the quiver is not a homogeneous object, but contains fuel rods with different properties in different positions, the radiation flux as seen by the detector will depend on the orientation of the quiver as well as the relative positioning of the quiver and the detector. The gamma and neutron flux from the BWR quiver were estimated in each of the three different detectors in each prong of the Fork (two fission chambers for measuring the neutron flux and one ionization chamber for gamma measurements). The flux values were tallied at the detectors in the Fork prongs in two locations around the quiver which have been labeled ‘North’ and ‘South’ (shown in figure 5) to make it easier to distinguish the two measurement positions.

The results from the particle transport calculation are shown in figure 9. It may be clearly observed that the intensities for both gamma photons and neutrons at the detectors in the Fork prongs were several orders of magnitude higher than that recorded above the BWR quiver lid (shown in
figure 8). The overall intensity of the gamma radiation was higher (10^8 photon/cm^2/s at the Fork versus 10^6 photon/cm^2/s above the lid) and the intensity was the highest in the ^{137}Cs gamma energy (662 keV) region. It may also be noted that the flux intensity was higher at the South position compared to the North, owing to placement of some high burnup rods closer to the South position of the Fork.

![Figure 9. Left: computed gamma spectra obtained from Serpent2 at the Fork prongs. Right: computed neutron spectra obtained from Serpent2 at various fission chambers in the detectors inside the Fork prongs.](image)

Additionally, the neutron flux spectrum at each of the two fission chambers in each prong is also shown in the right panel of figure 9. Upon looking at the intensity of neutron radiation, it may be observed that just like the gamma spectrum discussed previously, the intensity was higher at each of the detectors in the Fork prongs, irrespective of orientation, compared to that seen above the quiver lid (in figure 8). As before, the two locations of the Fork around the quiver labeled North and South hold the same meaning and were used for identifying the locations of the detector prongs. It may also be inferred that the intensities in the cadmium-lined fission chambers were lower than that of ones where the lining was absent, since cadmium absorbs low-energy neutrons. At higher energies, the spectra of all four chambers looked fairly similar. Identical to the case of gamma radiation, small differences in flux estimated at the North and South positions were seen mainly due to an asymmetry in the placement of high burnup rods in the quiver.

4.2.3 Rod-wise contribution to the total flux at the Fork instrument from the quiver

Due to the possible variations in burnup, initial enrichment and cooling times of the fuel rods within a single quiver (unlike regular fuel assemblies where these parameters are more or less uniform), understanding the rod-wise contribution of each fuel rod in the quiver to the modeled detector signal is of significance. Such information can prove to be useful for safeguards inspectors to make an assessment on how to best verify these objects, or for NPP operators to assess the impact of different rod arrangements in the quiver on the capability to conduct a safeguards verification in the future.

Rod-wise contribution to the total gamma and neutron flux was thus estimated with the help of several particle transport calculations in Serpent2, wherein the respective sources were defined on a single rod at a unique location and the particles were tallied at different detector locations, while keeping the overall model of the quiver and the Fork unchanged. Since nearly all rods placed in the BWR quiver had unique irradiation histories and cooling times and were placed in different positions inside the quiver, each rod contributed differently to the total flux seen at the gamma and
neutron detectors in the Fork prongs. This contribution was seen as a convolution of the individual fuel rod emission rates (which depends on rod’s irradiation history, total burnup and cooling time) and the geometrical factors such as distance to the detector, solid angle subtended at the detector, and shielding by surrounding rods.

The overall contribution from each fuel rod to the total gamma and neutron flux at each of the Fork prongs (at the North and South locations) was estimated and the results of the evaluations are shown in figure 10(a) and figure 10(c). Furthermore, the rod-wise contribution was evaluated at two additional locations, namely ‘West’ and ‘East’ in figure 10(b) and figure 10(d) respectively, in order to perform a sensitivity analysis on the placement of the prongs of the Fork instrument around the quiver. The contributions from each rod in figure 10 are expressed as a percentage of the total flux at the detector location. Individual contributions of each fuel rod to overall gamma flux are depicted in bold text along with the contributions to neutron flux shown below it in italicized text. Detector locations are demarcated in figure 10(a), figure 10(b), figure 10(c), and figure 10(d) by ‘North’, ‘West’, ‘South’, and ‘East’ labels respectively.

As far as contribution to overall gamma flux was concerned, figure 10 showed that rods closer to the detector contributed more to the overall gamma flux, while rods further away from the detector encountered more structural material such as zircaloy and stainless steel as well as other rods in front of them before reaching the Fork instrument. In the numerous detector-quiver configurations for measuring gamma radiation, a few important points to note include: a combination of rod burnup, cooling time and proximity of the rods to the detector location were deemed as the most important factors for the total contribution of each rod to the total flux recorded by the detector. In other words, the total contribution of high burnup (≥ 25 MWd/kgU) rods can range from just about 17% up to 56% of the total flux, depending on the location of the detector.

At the individual rod level, the rod with the highest burnup (≈ 40 MWd/kgU) had a contribution between 3% and 31% (approx.) depending on the placement of the detector around the quiver. At the same time, fuel rods in the interior of the quiver contributed a lot less to the overall flux with individual contributions, not exceeding 12% in any case. Furthermore, only fuel rods in the interior locations with high burnups (≥ 25 MWd/kgU) or cooling times < 10 years showed significant contributions to the overall flux at the Fork detector position. This can be explained by the shadowing effect of surrounding quiver tubes. Such large variations in flux contribution can only be explained by a strong dependence on geometrical effects. As far as dependence on cooling time was concerned, from figure 10 it may also be surmised that for similar burnups and rod placements within the quiver, rods with shorter cooling times contribute more to the overall flux at the detectors.

In case of rod-wise contribution to overall neutron flux, a similar evaluation was performed and the results have also been included in figure 10(a) and figure 10(c) for when the detector was placed in the North-South positions and figure 10(b) and figure 10(d) for West-East positions. The results showed that flux contribution for neutrons exhibited slightly different behavior when compared to gammas in figure 10 for similar detector positions and rod locations. This was primarily due to the fact that the gamma flux from the rods was strongly correlated to $^{137}$Cs (builds up linearly with burnup) content whereas the neutron flux was mainly from $^{244}$Cm in the fuel (builds up with $\approx 4$–5 power of burnup [31]). It should be pointed out that ORIGEN-ARP runs showed that $^{242}$Cm is the most prominent neutron emitter however its half-life is very short (162.8 days [32]) and it is nearly
absent in long-cooled fuel where $^{244}$Cm, with its much longer half-life (18.1 years [32]), became the dominant neutron emitter. Due to this fact, rods that were further away from the detector locations but had higher burnups, still contributed significantly to the overall neutron flux seen at the fission chambers in the Fork instrument. The second difference could be due to the fact that neutrons were not as heavily attenuated by structural material within the quiver as gamma radiation was.
The same effects seemed to dominate results when the Fork prongs were positioned in the West-East positions. Hence, as expected, fuel rods with high burnup tend to show much higher contributions to the overall flux at the fission chambers and their contributions did not show much impact of cooling times and placement within the quiver. The results shown in figure 10 indicate that high burnup (≥ 25 MWd/kgU) rods contributed between 62% to 89% to overall neutron flux in different quiver-detector configurations. It should be noted that the variation in contribution by the high burnup rods was not as pronounced as previously in case of gamma radiation. At the fuel rod level, individual contributions by high burnup rods ranged from 30% to 63% between different quiver-detector configurations. In contrast with the rod-wise contribution of inner rods to the overall flux for gamma radiation, in case of neutrons, the shielding effect of interior rods was not as pronounced.

4.2.4 Estimation of detector response — Gamma dose and neutron radiation counts for the BWR quiver

The fission chamber response for the Fork was computed in accordance with the methodology described in section 3.5, and the neutron radiation counts from the BWR quiver were found to be approximately 41 ± 3 counts per second in Channel A and 25 ± 3 counts per second in Channel B. Similarly, as described in section 3.5, usage of the appropriate ENDF MT = 100 option allowed the computation of gamma dose from the gamma flux using the ICRP-21 flux to dose rate conversion factors. Our results showed that the gamma dose rate from the BWR quiver was found to be approximately 403 ± 41 Sv/h at the Fork ionization chambers. Impact of quiver rotation on the Fork instrument response was also investigated and it was found that the detector counts for both gamma and neutrons did not change by more than 5% upon rotation of the quiver.

The detector response due to the gamma and neutron flux calculated in the Fork gamma and neutron detectors did not take into account detector nonlinearities [16] as well as the more prominent effects of subcritical neutron multiplication [11] which can have a significant impact on the counts. These effects remained outside the scope of the current study. However, [11] goes into greater depth on how effects such as subcritical neutron multiplication can be an important factor to consider, particularly in low burnup fuel since it has more fissile material left over after irradiation.

5 Discussion

The results from the present study have demonstrated that the approach of measuring quiver objects from the side would be better suited for a safeguards verification since the gamma flux in these locations was several orders of magnitude higher (roughly five orders of magnitude higher in the 662 keV region) compared to flux seen above the quiver lid. The same can be said regarding neutron flux at the fission chambers of the Fork instrument since the flux was at least three orders of magnitude higher when a Fork instrument was used to make measurements on the BWR quiver from the side.

The Fork system modeled in the present study was also benchmarked with previous work [11, 12] wherein the Fork’s neutron detector response was modeled and compared to measurements on SKB-50 assemblies. Our computations showed reasonably good agreement for fission chamber response of the Fork with past work. The benchmarking could not encompass the response of the
ionization chambers for gamma radiation due to the incalculable nature of coefficient of conversion used for estimating the gamma detector signal. Section 3.5 includes a more detailed discussion on the nuances of this conversion factor.

Additionally, it was established by means of a study on rod-wise contribution to overall flux at the Fork, that the high burnup rods in the quiver dominated the gamma and neutron signal at the Fork instrument. This was more noticeable in case of neutrons where up to 90% of the total flux detected could be attributed to these rods while in case of gammas, their contribution was about 60% of the total. The placement of rods inside the quiver was also deemed as an important factor for detection of gammas by the Fork since the inner row of rods was shielded by surrounding quiver tubes, and their contribution to the flux was greatly diminished due to gamma absorption by high-Z materials. For neutrons, this effect was not as pronounced and rod burnup remained the key factor for flux contribution. It should therefore be pointed out that from a safeguards verification standpoint, loading of quivers should be done in a manner as to not only satisfy criticality and decay heat restrictions, but also take into account the detectability of gamma and neutron radiation from rods within the quiver. To this end, it would be advisable to place fuel rods in the quiver tubes in a manner that gamma and neutron flux remain measurable with detection equipment such as the Fork.

It may be noted that using the Fork instrument, the counts due to neutrons from the BWR quiver considered in this study appear to be within limits of detection by the Fork instrument evaluated in this study since [11] has accounted for assemblies with much lower (as low as 5.1 counts per second) neutron emissions. Count rate for neutrons from the quiver was observed to be at the low end of detectability which can be attributed to several reasons. The first reason could be the low average burnup (21 MWD/kgU) in combination with high average cooling time (21 years) of the fuel rods in the quiver relative to typical fuel assemblies that are routinely measured with the Fork instrument. Additionally, the overall fuel content, i.e. number of rods was much lower in a typical BWR quiver as compared to a BWR fuel assembly. Furthermore, subtle effects such as subcritical neutron multiplication were not taken into account in the present study and it was known that these can have a measurable impact, particularly on underburned fuel.

6 Conclusions

The present evaluation has emphasized expected hurdles in conducting safeguards verification measurements on BWR quivers from above, due to heavy attenuation of gamma and neutron radiation by the quiver’s long-term storage lid. We have shown that by estimating flux above the quiver lid, the lid was thick enough to reduce the neutron flux to near-zero values while gamma flux suffers heavy attenuation and was reduced by several orders of magnitude in intensity. Under such circumstances, this analysis demonstrates that an alternative strategy would be to make measurements on the quiver object from its side by employing a Fork instrument. We have shown that the flux values in regions surrounding the quiver tubes that house the BWR fuel rods were substantially higher than the values encountered above the thick lid and the resulting count rates were within the limits of detectability of the widely used Fork instrument. It must also be highlighted that while the gamma and neutron radiation remain detectable on the sides of the BWR quiver analysed in the present study, they were found to be towards the low end of the Fork instrument’s detectability. Additionally, the study has also outlined some of issues surrounding impact of fuel
rod properties (burnup and cooling time) and their arrangement inside the quiver on the gamma and neutron flux at the Fork instrument’s prongs to give the operators and inspectors some useful insight on how to best verify such fuel objects.

In summation, this evaluation has highlighted some of the key obstacles that can impede routine safeguards verification of non-regular fuel objects with a focus on quivers. The analysis has ruled out verification from the top using existing instrumentation such as the SFAT due to its unsuitability in very low flux environments such as those that one might encounter in regions above the BWR quiver lid. We have shown that the problems posed by the low flux values from the quiver owing to their lower fuel content can be overcome with the use of other instruments such as the Fork detector which would be more viable albeit not without some unique challenges addressed in this work.

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References

[1] Svensk Kärnbränslehantering AB, Design and production of the KBS-3 repository, Tech. Rep., SKB TR-10-12, 2010 [https://www.skb.se/publikation/2167363/TR-10-12.pdf].

[2] Sverige Miljö och energidepartementet and Elanders Sverige AB, Sweden’s sixth national report under the Joint Convention on the safety of spent fuel management and on the safety of radioactive waste management: Sweden’s implementation of the obligations of the Joint Convention, https://www.regeringen.se/rattsliga-dokument/departementsserien-och-promemorior/2017/10/ds-201751/, 2017.

[3] International Safeguards in the Design of Facilities for Long Term Spent Fuel Management, https://www.iaea.org/publications/10806/international-safeguards-in-the-design-of-facilities-for-long-term-spent-fuel-management, 2018.

[4] Svensk Kärnbränslehantering AB, RD&D Programme 2019 – Programme for research, development and demonstration of methods for the management and disposal of nuclear waste, n.d. 389, Tech. Rep., SKB TR-19-24, 2019 [https://www.skb.se/publikation/2494395/TR-19-24.pdf].

[5] G. Af Ekenstam et al, Aspects on declared accountancy data for the Final Spent Fuel Disposal in Sweden, in Proceedings of the ESARDA Symposium 2019: 41st Annual Meeting, 2019.

[6] International Atomic Energy Agency (IAEA), Safeguards Techniques and Equipment:, International Nuclear Verification Series, no. 1 (Rev. 2), International Atomic Energy Agency (IAEA), Vienna (2011) [https://www.iaea.org/publications/8695/safeguards-techniques-and-equipment].

[7] Z. Elter, V. Mishra, S. Grape, E. Branger, P. Jansson, L. Caldeira Balkestål et al., Development of a modeling approach to estimate radiation from a spent fuel rod quiver, in Proceedings of PHYSOR 2020: Transition to a Scalable Nuclear Future, Cambridge, U.K., 2020.
[8] J. Leppänen, M. Pusa, T. Viitanen, V. Valtavirta and T. Kaltiaisenaho, The serpent monte carlo code: Status, development and applications in 2013, Ann. Nucl. Energ. 82 (2015) 142.

[9] Westinghouse Electric Company LLC., Westinghouse Quiver: The simple, safe solution for handling and storing failed fuel rods and fragments, https://www.westinghousenuclear.com/Portals/0/features/12823-Quiver-Digital-Handout-3-A4.pdf, 2017.

[10] S.M. Bowman, L.C. Leal, O.W. Hermann and C.V. Parks, ORIGEN-ARP, a fast and easy-to-use source term generation tool, J. Nucl. Sci. Technol. 37 (2000) 575.

[11] I. Gauld et al, In-Field Performance Testing of the Fork Detector for Quantitative Spent Fuel Verification, in Proceedings of 37th ESARDA Symposium on Safeguards and Nuclear Non-Proliferation, Manchester, U.K., 19–21 May 2015, https://www.osti.gov/biblio/1223656-field-performance-testing-fork-detector-quantitative-spent-fuel-verification.

[12] B.D. Murphy and P. De. Baere, Monte Carlo Modeling of a Fork Detector System, in Symposium on Safeguards and Nuclear Material Management, 2005.

[13] S. Tobin et al, Nondestructive Assay Data Integration with the SKB-50 Assemblies - FY16 Update, Tech. Rep., LA-UR-16-28290, Los Alamos National Laboratory, Los Alamos, NM, U.S.A. (2016) [DOI: 10.2172/1330638].

[14] Svensk Kärnbränslehantering AB, Spent nuclear fuel for disposal in the KBS-3 repository, Tech. Rep., SKB TR-10-13, 2010 [https://skb.se/publikation/2151488/TR-10-13.pdf].

[15] Z. Elter et al, Investigating the gamma and neutron radiation around quivers for verification purposes, in Proceedings of the ESARDA Symposium 2019: 41st Annual Meeting, 2019.

[16] S. Vaccaro, I. Gauld, J. Hu, P.D. Baere, J. Peterson, P. Schwalbach et al., Advancing the fork detector for quantitative spent nuclear fuel verification, Nucl. Instrum. Meth. A 888 (2018) 202.

[17] Fork Detectors (IAEA) B2102 Series, https://www.antech-inc.com/products/b2102/, 2020.

[18] P. Schwalbach et al, Euratom Safeguards: Improving Safeguards by Cooperation in R&D and Implementation. An overview, IAEA CN 220/145, 2014.

[19] W.B.J. Marshall et al, Overview of the Recent BWR Burnup Credit Project at Oak Ridge National Laboratory, 2019.

[20] C.L. Dunford, Evaluated Nuclear Data File, ENDF/B-VI, in S.M. Qaim ed., Nuclear Data for Science and Technology, Research Reports in Physics, pp. 788–792, Springer, Berlin, Heidelberg (1992).

[21] A. Borella, R. Rossa and K. van der Meer, Modeling of a highly enriched 235u fission chamber for spent fuel assay, Ann. Nucl. Energ. 62 (2013) 224.
[27] International Commission on Radiological Protection, Committee 3, *Radiation protection*, ICRP publication 21, recommendations of the International Commission on Radiological Protection: data for protection against ionizing radiation from external sources: supplement to ICRP publication 15; a report of ICRP Committee 3, adopted by the Commission in April 1971, Published for the International Commission on Radiological Protection by Pergamon Press (1973) [ISBN: 0080168728].

[28] A.E. Johnson, D. Kotlyar, S. Terlizzi and G. Ridley, *serpentTools: A python package for expediting analysis with serpent*, Nucl. Sci. Eng. 194 (2020) 1016.

[29] A. Santamarina et al, *The JEFF-3.1.1 nuclear data library: JEFF report 22, validation results from JEF-2.2 to JEFF-3.1.1*, Nuclear Energy Agency, Organisation for Economic Cooperation and Development (2009) [ISBN 9789264990746].

[30] T. Goorley, M. James, T. Booth, F. Brown, J. Bull, L.J. Cox et al., *Initial MCNP6 release overview*, Nuclear Technology 180 (2012) 298.

[31] K. Van der Meer, *Use of the FORK detector in safeguard inspections*, https://inis.iaea.org/search/search.aspx?orig_q=RN:40100153, 2009.

[32] National Nuclear Data Center, *information extracted from the NuDat 2 database*, https://www.nndc.bnl.gov/nudat2/, 2020.