

Monte Carlo-Based Assessment of Fork Detector Performance for Safeguards Verification of Spent Nuclear Fuel Assemblies

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Abstract

Abstract Fork Detector (FDET) is a powerful tool used for the verification of spent nuclear fuel stored in a water pool prior to dry storage cask loading for nuclear safeguards verification and to support nuclear security by ensuring that spent fuel assemblies are not diverted for malicious purposes. Fork measures passive neutron and gamma-ray emissions from irradiated fuel assemblies for safeguards purposes. This paper describes the Fork data analysis using Monte Carlo simulation code (MCNPX). The fuel assembly of PWR surrounded by the fork detector has been simulated. The paper focused on sensitive scenarios in case of missing fuel pins by noticing the fluctuations in neutron and gamma responses that were produced from the fuel. With enhanced reliability and fewer false positive alarms, this method aims to give safeguards inspectors reliable data analysis capabilities to quickly spot inconsistencies in operator reports and find probable partial flaws in spent fuel assemblies. By strengthening verification, the Fork Detector contributes to nuclear security by reducing the risk of unauthorized removal or tampering with nuclear material. The sensitivity of the detector to identify missing fuel pins will be concentrated on, while attempts to conceal the action with false declarations may be made by the diverter.

Full Text

Preamble

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Keywords: Spent Fuel, Nuclear Safeguards, Ionization Chamber, Fission Chamber, Fork detector, Monte Carlo simulation

Abstract

The Fork Detector (FDET) is a powerful tool used for the verification of spent nuclear fuel stored in water pools prior to dry storage cask loading, serving both nuclear safeguards verification and nuclear security by ensuring that spent fuel assemblies are not diverted for malicious purposes. The Fork measures passive neutron and gamma-ray emissions from irradiated fuel assemblies for safeguards purposes. This paper describes Fork data analysis using the Monte Carlo simulation code MCNPX, focusing on a PWR fuel assembly surrounded by the fork detector. The study concentrates on sensitive scenarios involving missing fuel pins, analyzing fluctuations in neutron and gamma responses to detect partial defects. With enhanced reliability and fewer false positive alarms, this method aims to provide safeguards inspectors with robust data analysis capabilities to quickly identify inconsistencies in operator reports and detect probable partial flaws in spent fuel assemblies. By strengthening verification, the Fork Detector contributes to nuclear security by reducing the risk of unauthorized removal or tampering with nuclear material. The sensitivity of the detector to identify missing fuel pins is emphasized, particularly in cases where diversions may be concealed through false declarations.

I) Introduction

The Fork Detector (FDET) is a transportable system designed for underwater measurements of spent fuel assemblies in storage ponds. Three types of FDET heads are in use for the common fuel types of commercial power reactors: PWR and BWR. While the principles of operation remain the same, the dimensions of the FDET detection heads differ depending on the size of the fuel elements. The FDET measures gross neutron signals with a pair of shielded neutron counters and total gamma-ray intensity with a pair of ionization chambers. Pairing detectors on two sides of an assembly minimizes sensitivity to assembly-detector geometry. Measurements are carried out either manually using the GRAND III (Gamma-Ray and Neutron Detector) electronics unit or in unattended mode using the UMS (Unattended Monitoring System) electronics [?]. Its benefits include: (1) compatibility with all commercially available neutron counting shift registers; (2) design for ease of decontamination; (3) easy assembly and dismantling for transportation between facilities; (4) highly reliable detector electronics; (5) leak-tested components prior to delivery; (6) detector heads and extension pipes supplied in reusable transportation containers; (7) IAEA configuration; and (8) BWR and PWR detector components based on a common design, apart from the polyethylene detector head, enabling substitution of detector head geometries.

The objective of safeguards efforts by the International Atomic Energy Agency (IAEA) is the “timely detection of diversion of significant quantities of nuclear material from peaceful nuclear activities to the manufacture of nuclear weapons or other nuclear explosive devices, or for purposes unknown, and deterrence of such diversion by the risk of early detection.” The materials of greatest concern

in spent fuel are ^{235}U and ^{239}Pu . A significant quantity of plutonium is defined as a mass of at least 8 kg. The amount of ^{235}U that is significant depends on enrichment: at least 25 kg of ^{235}U for enrichments above 20%, and at least 75 kg of ^{235}U for enrichments below 20%. Timeliness in detecting diversion also varies with the isotope [?].

For a pure compound of plutonium (such as PuO_2) or mixed oxide (MOX), the estimated minimum time required to convert the material to finished metal is one month; for plutonium in an irradiated fuel assembly, the minimum time is one to three months. For uranium containing less than 20% ^{235}U , the minimum conversion time is about one year. Not many light-water reactor (LWR) assemblies are required to provide significant quantities of ^{235}U and plutonium. A pressurized-water reactor (PWR) assembly with ^{235}U enrichment of 2.75% contains about 11 kg of ^{235}U initially; after an exposure of 30 gigawatt days per ton of uranium (GWd/tU), only about 3 kg of ^{235}U will remain, but 2 to 3 kg of ^{239}Pu will be present (among about 4 to 6 kg of total plutonium) [?, ?].

Many safeguards techniques can be applied to fuel at a reactor site. Book auditing and item counting are common. Fresh fuel can be verified just before loading into the core by measuring its enrichment and fissile material content. Seals can be applied to the reactor vessel, and a power monitor placed near the core can verify reactor operating history. Seals might also be applied to individual fuel assemblies, and cameras can record activities in storage areas. Night-vision devices, underwater television cameras, and periscopes have been used at spent fuel ponds to remotely examine irradiated assemblies. The fork detector measures radiation from assemblies stored underwater, and this study analyzes data from this system.

Diversion possibilities include substituting whole dummy assemblies for real ones or removing some fuel pins from an assembly. Cumbersome shielding would be necessary in any diversion of spent fuel. While very complex diversion strategies can be postulated that would pass virtually any inspection, achieving them in practice is quite another matter. This study does not attempt to consider all possible diversion strategies; it is limited to the removal of whole pins after an irradiation cycle and substitution with dummy pins that are not radioactive [?, ?]. An alternative strategy of adding fissile materials within assemblies for breeding purposes (for example, using PWR “control rod” clusters of uranium) is related but not discussed in detail here.

Successfully falsifying records, moving assemblies (and their shielding) without detection by surveillance systems, removing fuel from highly radioactive assemblies, returning real or substitute assemblies to the storage pond without observation, maintaining seal integrity, and finally having the assemblies produce proper radiation to pass examinations by night-vision devices and fork detectors is a daunting task. Use of a completely nonradioactive dummy assembly is simple to detect with the fork detector and need not be considered further. Construction of a dummy assembly with the proper mixture of neutron and gamma-ray emissions requires sophistication and materials that may be beyond

the capability of most potential diverters [?, ?]. The diversions considered here illuminate the sensitivities and capabilities of the fork detector. It is assumed that only a few pins from any one assembly are removed and that a small fraction of assemblies in a storage pond are modified to obtain a significant quantity of plutonium. For example, removing 15 PWR pins (out of 204 per assembly) from each of 30 assemblies (out of perhaps 1000 in a pond) could yield one significant quantity of plutonium. This will be referred to as a “small-scale” diversion. Under these conditions, the parameters in the consistency equations introduced later are insignificantly affected by the diversions. Data from assemblies in the pond will generally appear normal, but data from modified assemblies will appear out of bounds. Only the effect of the fork detector on a diverter will be considered in detail here; further restrictions from surveillance devices will only be mentioned casually where appropriate [?].

The aim of this work is to evaluate the performance of the Fork Detector in verifying spent nuclear fuel assemblies under sensitive scenarios involving missing fuel pins, using the Monte Carlo simulation code MCNPX. The study focuses on modeling the neutron and gamma responses of a PWR fuel assembly surrounded by the Fork Detector to assess its capability in detecting partial defects. By analyzing fluctuations in detector signals, this work seeks to enhance the reliability of safeguards verification, providing inspectors with robust data analysis tools to identify inconsistencies in operator declarations. In addition to supporting nuclear safeguards, this approach contributes to nuclear security by reducing the risk of diversion or unauthorized removal of nuclear material, thereby strengthening overall control and accountability of spent fuel assemblies.

II) Sensitivity to Missing Fuel

If a fraction of a fuel assembly is removed and replaced with nonradioactive material (or not replaced at all), what is the effect on neutron and gamma-ray measurements with the fork detector? The answer is complex and depends on the characteristics of the specific assembly, the distribution of removed material within the assembly, the boron concentration in the water, and the characteristics of the fork head itself [?]. So far, there has not been an opportunity to take measurements on an irradiated assembly before and after pin removal. Three BWR assemblies at Vermont Yankee were reconstituted with two or three pins missing, but details of the reconstitution process and its impact on reduced count rates are unclear.

Studies on a 15×15 PWR assembly with 204 pins and 21 guide tubes have been used to estimate the effects of missing pins on neutron and gamma-ray measurements. In these studies, neutron measurements were performed on a fresh fuel assembly using a ^{252}Cf source placed in different pin positions, while gamma-ray calculations assumed the presence of an air-filled collimator tube between the assembly and the detector. Similar studies on hexagonal WWER fresh fuel assemblies showed comparable results regarding the contribution of individual pins to neutron and gamma-ray signals. The neutron count rate

can be correlated with the mass of an assembly, as pin removal proportionally reduces the amount of uranium and plutonium and consequently the neutron count rate. Measurements considered cadmium-wrapped detectors at boron concentrations of 0 and 2000 ppm. For spent fuel, pin removal would further reduce the neutron count rate due to decreased multiplication compared to fresh fuel. Gamma-ray contributions from rows of pins were also analyzed, with the 661-keV gamma ray from ^{137}Cs being the dominant emission in spent fuel. Weighting factors were adjusted to account for end effects in the ionization chambers [?].

III) FDET System Specification

Table (1) summarizes the main specifications of the Fork Detector system used for spent nuclear fuel verification. It provides details on detector type, active dimensions, and efficiency for both neutron and gamma-ray detection. The neutron detectors are typically ^3He -filled proportional counters arranged in two prongs to surround the fuel assembly, while the gamma detectors are ionization chambers or scintillation detectors optimized for high-energy gamma-ray measurement. The table also lists key parameters such as operating voltage, energy response range, and count rate capabilities. These specifications are crucial for understanding the system's sensitivity and accuracy in detecting variations in neutron and gamma emissions, which are essential for identifying partial defects or missing fuel pins in spent fuel assemblies.

Table (1): The Fork Detector System—Detector Specification [?]

| Parameter | Neutron Detector | Gamma Detector |
|-----------------------|--|-------------------------------------|
| Detector Type | ^3He -filled proportional counter | Ionization chamber / Scintillator |
| Active Material | ^3He gas (at ~4-10 atm) | Argon gas or NaI(Tl) crystal |
| Typical Dimensions | Length: 50-100 cm; Dia.: ~2.5 cm | 5-10 cm active length |
| Efficiency | ~10-20% (thermal neutrons) | ~5-10% (for 661 keV γ -rays) |
| Operating Voltage | 800-1200 V | 500-1500 V |
| Count Rate Capability | Up to 10^5 cps | Up to 10^5 cps |
| Detector Arrangement | Two prongs, each with multiple tubes | Two gamma detectors on each prong |

The FDET system shall consist of the following three main components: (1) Mechanical components and transport container; (2) Interface cables and junction box; and (3) Detectors and preamplifiers to be provided by the IAEA.

Figure 1 illustrates the general arrangement of the Fork Detector (FDET) system when installed on the guard bar at the edge of a spent fuel storage pond. The detector consists of two prongs that extend into the water and are positioned on either side of the spent fuel assembly during verification measurements. Each prong contains multiple neutron and gamma-ray detectors that measure passive emissions from the fuel. The guard bar provides a stable mounting platform to ensure correct alignment of the detector with the assembly while allowing safe operation above the pond. This setup enables inspectors to perform measurements without fully removing the fuel assembly from its storage rack, making the system portable, efficient, and suitable for safeguards verification activities.

Figure 1 [Figure 1: see original paper]: The overall setup of the Fork Detector (FDET) system mounted on the guard bar at the perimeter of the spent fuel storage pond.

The Fork Detector (FDET) system, including the detector head and associated electronics, was originally developed at the behest of the IAEA to create a transportable instrument capable of rapidly verifying spent fuel assemblies in storage ponds [?, ?]. Since the early 1980s, this detector and its variants have been widely deployed at nuclear facilities worldwide by various national and international safeguards agencies [?]. Although the detector does not quantify uranium or plutonium content directly—because neutron emissions are dominated by transuranic isotopes (especially curium) and gamma emissions are obscured by fission products—its primary function is to confirm that assemblies are legitimate spent nuclear fuel and have not been altered since removal from the reactor core [?, ?].

The detector head, commonly known as the “fork,” is a U-shaped assembly of high-density polyethylene whose prongs house fission chambers and ionization chambers. It is supported by a watertight extension pipe that connects vertically to a bridge suspended over the storage pond; detector cables run through this pipe to interface with bridge-mounted control electronics. The original electronics, termed the ION-1, was developed by Los Alamos National Laboratory to power the detector tubes, count neutron pulses, and measure ionization currents. A commercial variant, the GRAND-I, is now available from D. S. Davidson & Co., providing similar capabilities via a user interface that includes a keypad and digital display—optionally with computer or printer connectivity for data logging and analysis [?, ?].

Data acquired by the Fork Detector consists of gross neutron count rates and ionization currents induced by gamma rays, typically collected from opposite sides of the assembly at one or more diagonal heights. The system features two sets of fission chambers: one set wrapped in cadmium and another left bare. This configuration enables inspectors to estimate boron concentration in the pond water—which can alter count rates—independently of operator declarations. Neutron count rates from cadmium-wrapped chambers are preferred during analysis due to reduced sensitivity to boron, while bare chambers provide more uniform response across varying neutron source distributions within

the assembly [?, ?, ?].

IV) MCNP Model Simulation

The MCNP input file describes a 17×17 fuel assembly in a cylindrical water tank, demonstrating MCNP's repeated structures lattice capability. The aim is to calculate induced fission in enriched and depleted uranium pins in the fuel assembly within the water tank when the starting neutron source is spontaneous fission. The full geometry diagonal view for the fuel assembly is shown in Figures 2-3 in XY and XZ coordinates. Figure 4 [Figure 4: see original paper] zooms into the lattice and shows the lattice indexing.

In this research, two scenarios were considered. In the first scenario, three different positions of missing fuel rods within the PWR fuel assembly were modeled to evaluate the impact of rod displacement on neutron flux distribution and gamma field. In the second scenario, the upper part of fuel rods was replaced with either Co-60 or Cs-137 sources, allowing investigation of how these strong gamma emitters affect overall radiation intensity and spectral characteristics.

IV-a: Scenario 1

Figure 2: Overall view of the fuel assembly surrounded by the fork detector (green). Position (1) shows a fuel assembly with missing rods in the core 7×7 region; Position (2) shows missing rods at the corners; and Position (3) shows missing rods at diagonal positions.

Figure 3 [Figure 3: see original paper]: MCNPX plot of fuel assembly in water tank. Cells are colored by material: red is water (m101), the two orange circles are neutron fission chambers, and the two red circles are gamma ionization chambers.

Figure 4: Expanded view of Position 2 in Figure 2 [Figure 2: see original paper] showing lattice indices. Blue indicates cladding material (m12). In this geometry, cell 21 is in universe $u=5$ and is a 17×17 rectangular lattice ($lat=1$). Each lattice element has an index $[i,j,k]$ corresponding to the x, y, z axes. Missing rods occupy different locations with different indices as shown in Figure 2. The i and j indices range from -8 to $+8$, specifying 17 lattice elements in the x - and y -directions; the k indices range from 0 to 0, indicating only one lattice element in the z -direction. The fork detectors occupy cells 104 and 105 for the fission chambers and cells 106 and 1107 for the ionization chambers.

The surfaces are RPP (right parallelepiped) and RCC (right circular cylinders). The RPP entries are $-x +x -y +y -z +z$. The RCC entries are the coordinates of the base center (x, y, z) , followed by the coordinates of the height vector in the x, y, z directions, followed by the cylinder radius.

SDEF is the source definition line that specifies the source as spontaneous fission (PAR=SF) in a cylinder with a base at the origin (POS=0 0 0) and axis in the z -direction (AXS=0 0 1). The height is sampled linearly according to distribution

EXT=D62, which ranges from -150 to +150 cm. All 289 active source cells are listed by i,j,k indices in the cell distribution (d63). Tally 4 is described in the tally comment (FC4) and tallies the neutron fission flux (F4:n) in the 289 fuel pins recorded by the fission chambers at cells 104 and 105 in the fork detector, while (F4:p) is the gamma flux registered from the gamma ionization chambers at cells 106 and 1107 as shown in Figure 5 [Figure 5: see original paper]. The tallies are calculated over an energy range from 0 to 4 MeV.

Figure 5: The cell numbers for the fork detector simulation.

IV-b: Scenario 2

In this scenario, a spent nuclear fuel assembly stored in a water pool is intentionally modified by replacing a portion of its fuel rods with sealed radioactive sources containing ^{60}Co and ^{137}Cs . The substituted rods are fabricated to have similar external geometry to actual fuel rods, allowing insertion into the assembly lattice without immediate visual detection. ^{60}Co emits high-energy gamma rays (1.17 MeV and 1.33 MeV), while ^{137}Cs emits a dominant 661 keV gamma ray, both of which can mimic part of the gamma signature of spent fuel. However, because these sources produce negligible neutron emissions compared to irradiated fuel, the overall neutron count rate from the assembly is significantly reduced. This scenario represents a diversion attempt in which an operator tries to deceive safeguards inspectors by inserting strong gamma-emitting sources to mask the removal of fissile material. Detecting this modification requires combined neutron and gamma-ray measurements, such as those provided by the Fork Detector, to identify inconsistencies in the expected neutron-to-gamma ratio and reveal the presence of non-standard components.

Figure 6 [Figure 6: see original paper] presents the first case of the second scenario, where the fuel rod at cell 20 of the fuel assembly is replaced by a sealed radioactive source containing ^{137}Cs . The replacement rod is designed to match the external geometry of the original fuel rod, allowing insertion into the lattice position without obvious visual detection. Cesium-137 is a strong gamma-ray emitter, producing a dominant 661 keV photon that can contribute to the overall gamma signature. However, since the substituted rods do not produce neutrons through spontaneous or induced fission, the neutron count rate measured by the Fork Detector is reduced compared to an intact assembly. This setup simulates a partial-defect diversion attempt, where the operator aims to conceal fissile material removal by inserting a high gamma-emitting source. Comparing neutron-to-gamma ratios and analyzing detector responses at different positions enables inspectors to detect this anomaly and confirm that the assembly no longer matches the expected radiation profile.

Figure 6: The red color indicates the $^{60}\text{Co}/^{137}\text{Cs}$ replacement at the upper parts of the fuel assembly.

In the second case, the fuel rod positioned at cell 120 of the fuel assembly is replaced with a sealed ^{60}Co radioactive source. The replacement rod is manu-

factured to have the same external geometry as a standard fuel rod, allowing insertion into the assembly lattice without obvious visual changes. Cobalt-60 is a strong gamma emitter that produces two prominent photons at energies of 1.17 MeV and 1.33 MeV, but it does not generate neutrons. Substituting a fuel rod with a ^{60}Co source therefore reduces the total neutron count rate detected by the Fork Detector while still producing a significant gamma signature. This scenario models a partial-defect case in which a diverter attempts to conceal fissile material removal by inserting a high-energy gamma source, enabling analysis of how combined neutron and gamma measurements can reveal inconsistencies in the assembly's expected radiation profile.

V) Results and Discussion

Scenario (1): Full and Missing Fuel Rods in the Assembly

Figure 7 [**Figure 7: see original paper**] presents the neutron flux distribution for the full fuel assembly and Position (1) over the energy range of 0–4 MeV. The spectrum clearly shows the dominance of thermal and epithermal neutrons in the lower-energy region, produced as fast neutrons from fission undergo successive moderation. As energy increases toward the fast region, the flux gradually decreases, reflecting the reduced population of high-energy neutrons that are less moderated and more likely to escape or be absorbed. The profile at Position (1) indicates localized variations in flux intensity, attributed to missing rods in the central assembly region that alter moderation and leakage characteristics. Rod removal reduces neutron production and introduces water-filled gaps that enhance moderation and neutron leakage, leading to net flux reduction. Moreover, the spectral distribution shifts toward lower energies due to increased moderation, further explaining the observed decrease in neutron flux within the 0–4 MeV interval. This distribution provides valuable insight into the balance between moderated and fast neutrons and highlights the sensitivity of neutron behavior to structural changes.

Figure 8 presents a comparison between the neutron flux distribution of the full fuel assembly and those obtained for Positions (1) and (2). For the full assembly, the neutron flux exhibits the expected profile with a pronounced peak in the thermal region and gradual decrease toward higher energies. For Position (1), where central rods are missing in a 7×7 configuration, the neutron flux shows noticeable reduction in the central spectrum region, reflecting enhanced leakage and reduced moderation. In contrast, Position (2), representing missing rods along assembly sides, shows different behavior: thermal flux remains relatively stable in the central region but decreases more prominently near the periphery, where rod removal affects the moderation environment. This comparison highlights the strong dependence of neutron flux distribution on the spatial location of missing fuel rods, with central removals primarily influencing core flux while side removals alter boundary neutron behavior.

Figure 9 [**Figure 9: see original paper**] illustrates the neutron flux distri-

bution for the full fuel assembly compared with Positions (1), (2), and (3), providing a comprehensive view of how different missing-rod configurations affect neutron behavior. For the intact assembly, flux maintains a balanced distribution with a clear thermal peak and smooth decline toward the fast region. At Position (1), corresponding to central 7×7 missing rods, neutron flux shows significant reduction in the moderated region, indicating enhanced leakage and diminished core absorption. Position (2), with rods missing along assembly sides, results in comparatively smaller change in central neutron flux but marked decrease near the periphery, reflecting the role of boundary rods in sustaining neutron economy. Position (3), characterized by diagonal missing rods throughout the assembly height, produces a more complex flux profile where both moderation and leakage effects are observed along the vertical axis, leading to broader reduction across energy ranges. Together, these results emphasize how the spatial distribution of missing rods—whether central, peripheral, or diagonal—introduces distinct alterations in neutron flux patterns that serve as identifiable signatures for fuel configuration changes. This comparison demonstrates the impact of missing rods on local neutron flux distribution, crucial for understanding changes in reactivity, neutron economy, and potential effects on power distribution and fuel burnup, while providing an important tool for nuclear safeguards and security by enabling detection of anomalies and unauthorized fuel removal.

Figures 10-12 illustrate the gamma flux distribution within the full fuel assembly for three rod configurations. **Figure 10** [**Figure 10: see original paper**] presents the gamma flux profile when the assembly includes missing rods at the center (7×7 array), creating distinct reduction in core region flux intensity. **Figure 11** [**Figure 11: see original paper**] depicts the distribution when missing rods are located along assembly sides, resulting in more pronounced shift of gamma flux toward the periphery. **Figure 12** [**Figure 12: see original paper**] demonstrates the case with missing rods arranged diagonally throughout the assembly, producing a characteristic flux pattern extending along the vertical axis. Comparative analysis highlights how spatial distribution of missing rods strongly influences the gamma flux field, with center, side, and diagonal modifications each producing unique signatures.

In gamma spectra measured by the fork detector inserted into polyethylene around the spent fuel assembly, a distinct peak appears near 2 MeV, corresponding to the well-known 2.223 MeV capture gamma ray from hydrogen. This peak arises because neutrons emitted from spent fuel, primarily due to spontaneous fission of isotopes such as ^{244}Cm , are slowed down in the hydrogen-rich polyethylene moderator. Once thermalized, these neutrons are readily captured by hydrogen nuclei, producing deuterium and emitting a characteristic gamma photon. The intensity of this peak thus reflects strong interaction between the spent fuel neutron field and surrounding moderator, providing a clear signature of neutron moderation and capture.

In addition to characteristic gamma lines from spent fuel and surrounding ma-

terials, a distinct peak at approximately 0.5 MeV was identified in measured spectra. This peak corresponds to the well-known 511 keV annihilation photon arising from pair production. High-energy gamma rays emitted from spent fuel, particularly those exceeding the 1.022 MeV threshold, interact with the nuclear field of the surrounding medium to generate electron-positron pairs. The positrons subsequently annihilate with electrons, producing two 511 keV photons detected as a sharp spectral peak. This confirms that the 0.5 MeV feature results from pair production and positron annihilation rather than backscatter, since backscattering from higher-energy photons appears at significantly lower energies (typically below 0.3 MeV).

Scenario (2): Replacing Part of Fuel Rod with Radioactive Sources

Scenario (2) involves replacing part of a fuel rod in the full assembly with sealed radioactive sources, specifically Cesium-137 (^{137}Cs) and Cobalt-60 (^{60}Co), to study their impact on both neutron flux and gamma flux distribution. This modification simulates a potential non-standard configuration relevant to safeguards verification and anomaly detection.

Results presented in Figures 13-a and 13-b reveal significant reduction in neutron flux distribution when upper fuel rod portions are replaced with sealed ^{137}Cs or ^{60}Co sources compared to the intact assembly. This pronounced difference arises from removal of substantial fissile material in the upper region, which normally sustains neutron population through continuous fission along the rod length. The absence of fuel in this region decreases neutron production and enhances axial leakage, as the assembly top represents a boundary with limited neutron reflection. Moreover, the substituted isotopes act solely as gamma emitters and do not contribute to neutron generation, eliminating an important source of secondary neutrons that would otherwise diffuse back into the core. Consequently, combined effects of reduced fission sites, increased leakage, and lack of neutron contribution from replaced segments produce the large deviation observed in neutron flux curves.

Figures 14-a and 14-b display corresponding gamma flux distribution for this scenario. Unlike neutron flux, gamma flux shows notable increase in regions surrounding inserted sources, reflecting high-energy gamma emissions from both ^{137}Cs and ^{60}Co . This elevated gamma field can serve as an indicator of source presence and location, especially useful for remote detection. For ^{60}Co , the spectrum shows significant increase in gamma field with two distinct peaks at 1.173 MeV and 1.332 MeV, corresponding to characteristic ^{60}Co emissions. Similarly, when ^{137}Cs replaces upper rod portions, a strong peak appears at 0.662 MeV, representing the principal gamma line of ^{137}Cs . These peaks are either absent or much less pronounced in the intact assembly spectrum, confirming that introduced sealed sources dominate the gamma profile. The clear appearance of these characteristic lines highlights the strong influence of replacement sources on the overall radiation field and demonstrates how such modifications alter the assembly's gamma signature, providing valuable insight for characterization

and safeguards applications.

Figure 13 [Figure 13: see original paper]: Neutron flux for the full fuel assembly and Scenario (2).

Figure 14: Gamma flux for the full fuel assembly and Scenario (2).

VI) Conclusion

Two scenarios were investigated to evaluate the impact of structural modifications on neutron and gamma flux distributions in a PWR-type fuel assembly. In Scenario (1), three cases of missing fuel rods were analyzed. Results showed that missing rod location strongly influences flux distribution. When rods were absent in the central assembly region (Position 1), neutron flux experienced the most significant reduction due to loss of fission sites in the core where neutron production is highest. For the second case, with rods missing at assembly sides, the effect was less pronounced, as the peripheral region contributes less to overall neutron population and is already subject to higher leakage. In the third case, with rods missing along the diagonal, flux distribution displayed intermediate behavior, with noticeable but less severe deviations compared to the central case. These findings emphasize the sensitivity of flux profiles to the spatial location of missing fuel elements.

In Scenario (2), upper segments of selected fuel rods were replaced with sealed radioactive sources of either ^{60}Co or ^{137}Cs . Results revealed pronounced reduction in neutron flux distribution across the assembly compared to the intact configuration, attributed to removal of considerable fissile material in the axial direction and enhanced leakage near the upper boundary. Simultaneously, gamma spectra were significantly modified by sealed source presence. Specifically, ^{60}Co introduction resulted in two strong peaks at 1.173 MeV and 1.332 MeV, while ^{137}Cs introduction produced a prominent peak at 0.662 MeV. These characteristic emissions were clearly distinguishable from the intact assembly gamma profile and confirmed the dominant contribution of substituted sources. Overall, the study demonstrates that both missing fuel rods and replacement with sealed radioactive sources have marked influence on neutron and gamma fields within the assembly. The degree and nature of these effects depend strongly on modification spatial location and material type introduced. Such analyses provide valuable insights for nuclear radiation field characterization, fuel integrity assessment, and development of safeguards verification methods.

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