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An Integrated Approach for the Verification of Fresh MOX Fuel Assemblies at LWR-MOX Recycle Reactors

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Abstract:

This paper presents an integrated approach for the verification of mixed oxide (MOX) fuel assemblies prior to their being loaded into the reactor. There is a coupling of the verification approach that starts at the fuel fabrication plant and stops with the transfer of the assemblies into the thermal reactor. The key measurement points are at the output of the fuel fabrication plant, the receipt at the reactor site, and the storage in the water pool as fresh fuel. The IAEA currently has the capability to measure the MOX fuel assemblies at the output of the fuel fabrication plants using a passive neutron coincidence counting systems of the passive neutron collar (PNCL) type [1]. Also, at the MOX reactor pool, the underwater coincidence counter (UWCC) has been developed [2] to measure the MOX assemblies in the water. The UWCC measurement requires that the fuel assembly be lifted about two meters up in the storage rack to avoid interference from the fuel that is stored in the rack. This paper presents a new method to verify the MOX fuel assemblies that are in the storage rack without the necessity of moving the fuel. The detector system is called the Underwater MOX Verification System (UMVS) [3]. The integration and relationship of the three measurements systems is described.

Keywords: MOX; verification; underwater; NDA

1. Introduction

With the increase in the use of light water reactors (LWR) that are fuelled with mixed oxide (MOX) fuel assemblies, it will be necessary to apply effective safeguards and material control for the fuel assemblies. Safeguards measurements are required for fresh MOX fuel assemblies at both the fabrication plants and reactor sites. An important part of the cycle is the transfer of the assemblies from the fabrication facility to the reactor sites, and the subsequent storage of the assemblies underwater in the reactor spent fuel storage pool prior to use. There needs to be effective verification that the plutonium mass remains intact during the transfer and subsequently in the underwater storage location.

This paper describes an integrated safeguards approach for the verification of fresh MOX fuel assemblies for the LWR-MOX fuel cycle based on three Non-Destructive Assay (NDA) systems. At the MOX fabrication facility, the passive neutron collar system is currently used as an in-plant NDA system to measure the finished fuel assemblies. For the MOX assemblies that have been shipped to a reactor site, the underwater coincidence counter (UWCC) has been used by the IAEA for the shipper-receiver verification in the underwater storage. Both of these instruments are based on neutron coincidence counting to verify the plutonium mass. For the interim verification of MOX fuel during water storage, a new NDA system called the underwater MOX verification system (UMVS) is presented in this study. The UMVS is designed to be lowered into the water to rest on the fuel assembly storage rack and verify the plutonium content in a target MOX fuel assembly. The new system is based on singles neutron counting, and it eliminates the necessity of the fuel assembly movement. The neutron cross-talk from neighbouring fuel assemblies is corrected for by the configuration of the multiple ^{3}He neutron detectors. The design characteristics, expected performance, and applicability of the NDA systems for the MOX fuel fabrication facility and for the fuel storage pool at LWR reactor site are discussed in this paper.

2. Integration concept

Figure 1 shows the relationship between the three measurements systems, and the connection to measurement standards at the MOX fabrication plant. The primary measurement takes place at the MOX fuel fabrication plant where a measurement precision of better than 1% is possible for installed systems such as the Fuel Assembly Assay System (FAAS) at the PFPF (Plutonium Fuel Production Facility) in Japan [4]. The IAEA is able to create an independently verified MOX fuel assembly standard during the fabrication process by sampling pellets and maintaining continuity of knowledge (C-o-K) for the standard fuel assembly. After the fuel assembly transfer to the reactor site, the UWCC can measure the ^{240}Pu effective as well as the neutron multiplication of the MOX assembly in the water. The ^{240}Pu calibration is linear after the multiplication correction as illustrated in Figure 2. The data shown in Figure 2 represents four different types of MOX assemblies with very different Pu loadings. The low mass data corresponds to a mock-up assembly at the SCK-CEN VENUS facility in Mol, Belgium; the mid range data corresponds to a MOX mock-up assembly at LANL; and the high mass data points correspond to data from MOX reactors in Europe.

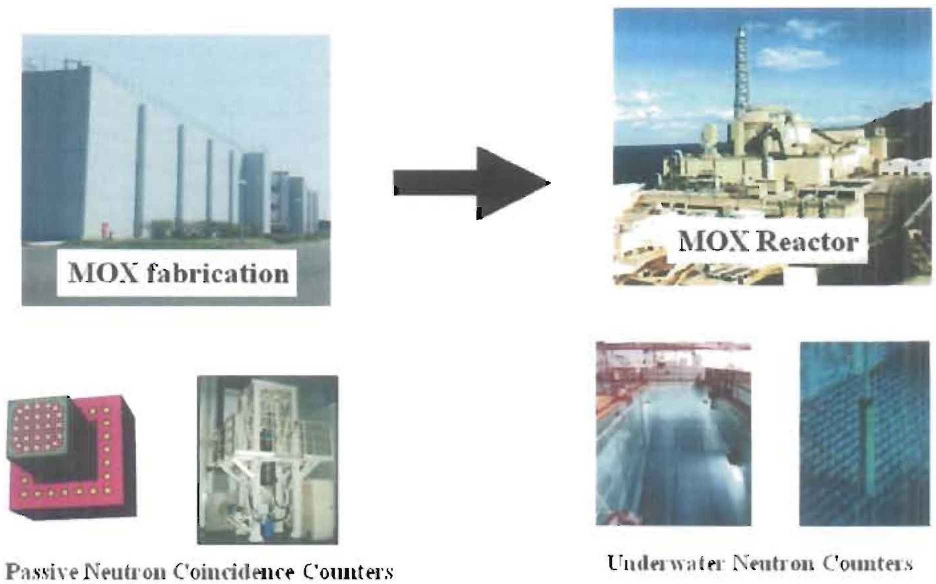

Figure 1: Fresh MOX fuel assembly shipper-receiver verification and storage pool verification.

There are three basic sources of neutrons from the MOX fuel assemblies:
1. the spontaneous fission neutrons from the 240Pu effective
2. the alpha,n reaction source neutrons from the plutonium oxide, and
3. the induced fission multiplication(M) from all sources of neutrons.

Because the UMVS measures the same basic neutron signature as the preceding verification systems (PNCL and UWCC) at the fabrication plant and during fuel receipts, namely the ^{240}Pu effective, the overall verification measurement can be considered as a neutron balancing approach between the fabrication plant, the shipment, and the underwater storage prior to filling the reactor core. This paper will describe the three measurements systems together with their interrelationship in the safeguards verification of the fuel assembly product in the advanced MOX reactor fuel cycle.

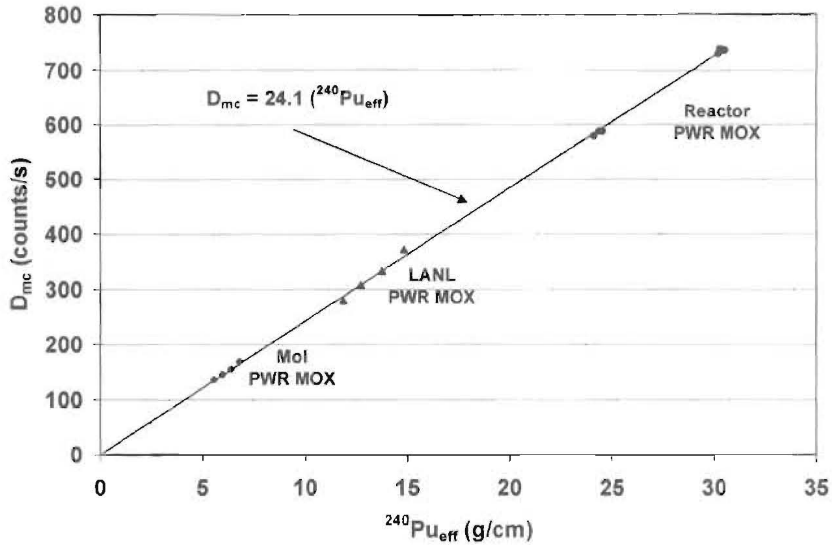

Figure 2: The UWCC calibration curve for the multiplication corrected doubles rate for the verification of the fresh MOX fuel assemblies in underwater storage.

3. Primary Measurement System

The PNCL shown in Figure 3 was developed to measure the ^{240}Pu at the MOX fuel fabrication plants in the attended mode. The instrumentation has been in use by the inspectorates for more than two decades. The neutron singles and doubles counting rates are measured and the neutron multiplication is calculated. More recently, the PNCL has been used by the IAEA in France to measure MOX assemblies prior to shipment providing an accuracy of ~ 1%. A similar measurement system, the FAAS, is installed at the PFPF in Japan (see Figure 4) for the IAEA verification of the Fast Breeder Reactor (FBR) MOX assemblies. This system operates in the unattended mode with continuous data collection. The MOX fabrication plants require a safeguards verification of the plutonium entering and leaving the plant. The measurement of the fabrication plant output is the first step in the integrated approach illustrated in Figure 1.

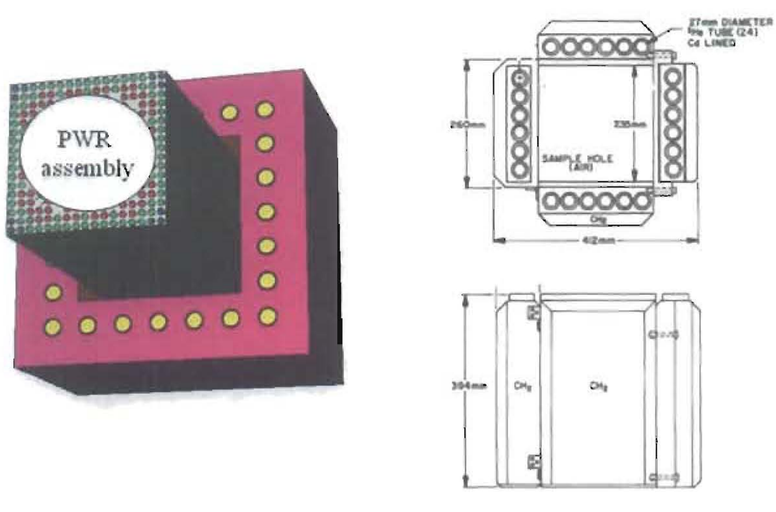

Figure 3: Schematic diagram of the Passive Neutron Coincidence Collar for application to MOX fuel assemblies.

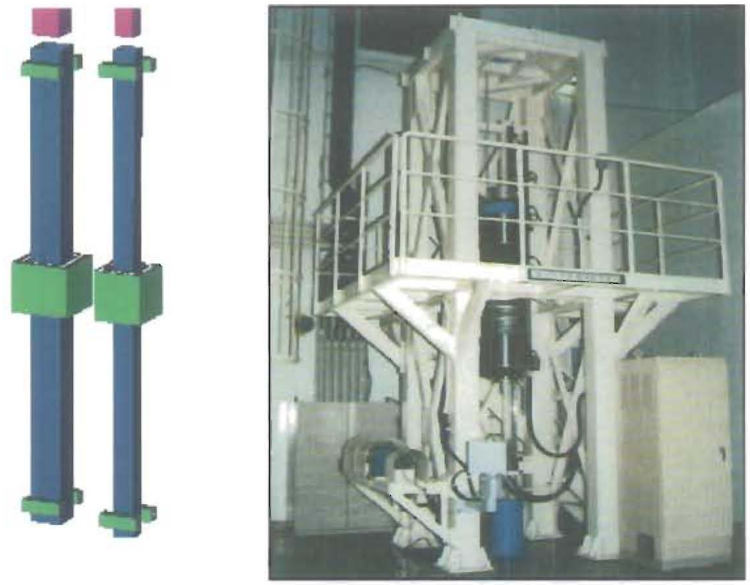

Figure 4: Fuel Assembly Assay System (FAAS) for MOX assembly.

4. Secondary Measurement System

4.1 The UWCC

The transfer of fuel assemblies from the fabrication plant to the reactor site is an important step for safeguards and material accountancy. Sometimes this transfer will cross national boundaries adding to the importance of the verification measurements. The MOX assemblies are placed in the storage pool at the reactor sites for protection and security. The UWCC, shown in Figure 5, has been used by the IAEA to verify the Pu content at the MOX assemblies in the underwater location. The UWCC is packaged similar to the Fork detector [5], except the fission chambers have been replaced by ^{3}He neutron detectors. The UWCC measures the fuel assemblies at positions that are above the storage rack, and after the UWCC measurement, the fuel assembly becomes a working standard for subsequent measurements using the UMVS.

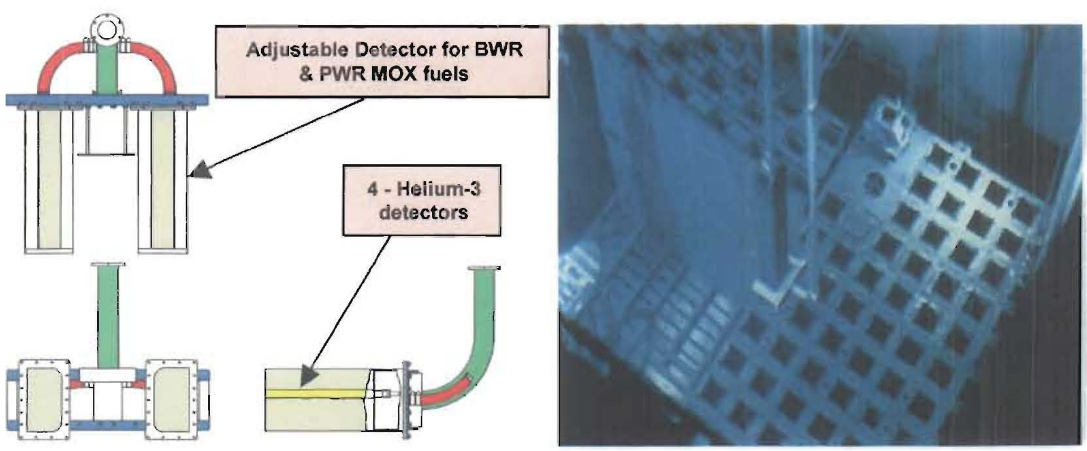

Figure 5: The UWCC detector head for verification of fresh MOX fuel assemblies in water.

4.2 The UMVS

The proposed UMVS was designed to provide a verification of the MOX assemblies in the underwater storage rack without the necessity of moving the fuel. The goal of the UMVS is to verify that the fuel assembly has not been modified after it was placed in the storage rack. The UMVS is not designed to measure the total Pu in the MOX assembly in that the measurement is only sensitive to the Pu in the upper third of the assembly. The capability of the associated UWCC, that is part of the IAEA instrumentation suite, limits the more extreme diversion scenario of modifying only the bottom section of the fuel assembly.

The UMVS measures the total neutron emission from the top of the assembly. The total neutrons that can be measured near the top of the fuel assembly is a combination of the three source terms listed above. The neighbouring assemblies in the storage rack also contribute to the neutron flux. The UMVS presents a method to correct for the cross-talk from the neighbouring assemblies in the rack. The system uses neutron detector ratios to correct for neutrons from the neighbouring assemblies in the storage rack. To obtain a high counting efficiency, the ^{3}He detectors are embedded high density polyethylene (HDPE) moderator with an air collimation channel to the centre detector. Figure 6 illustrates a cross sectional cut through the UMVS showing the central 5-cm diameter ^{3}He tube and the five perimeter ^{3}He tubes with 25-mm diameters. All tubes are 12.5-cm long with a ^{3}He pressure of 6-atm. The purpose of the perimeter tubes is to measure the neutrons from the neighbouring assemblies in the storage rack so that a correction can be made to the counting rate in the central ^{3}He tube. The correction algorithm is developed in the next section.

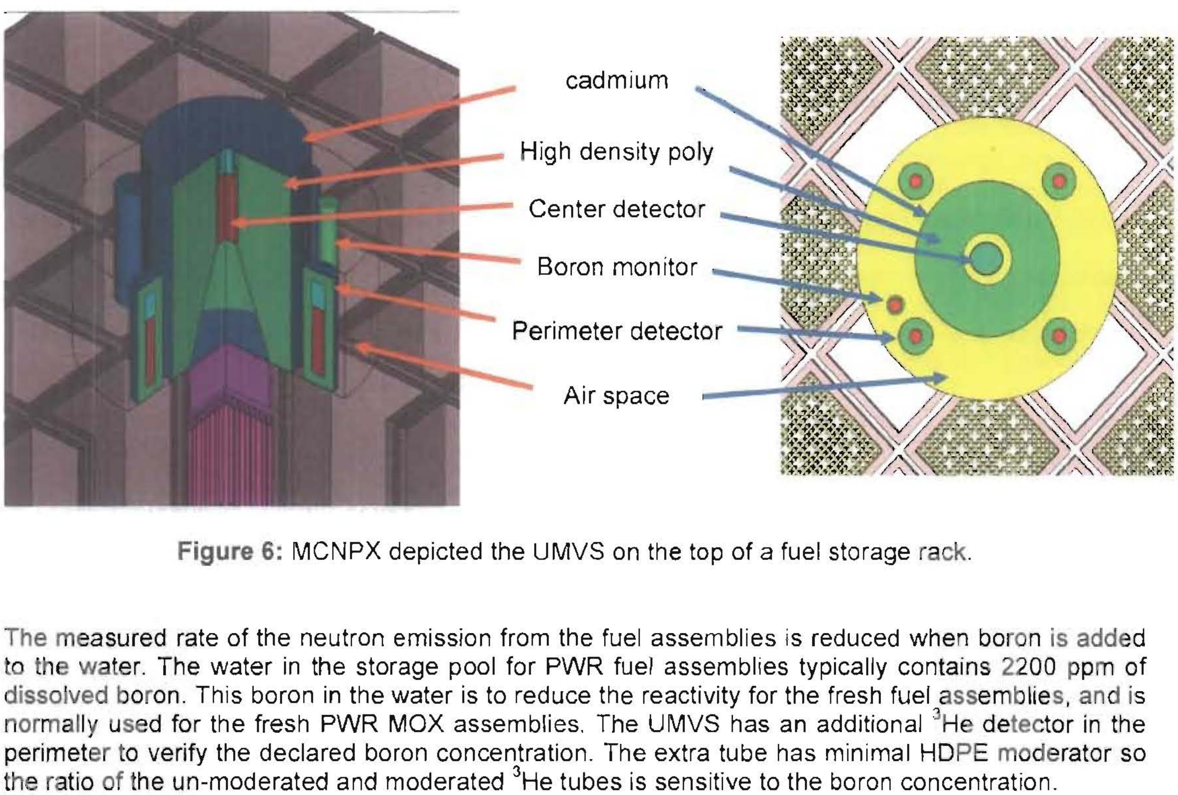

Figure 6: MCNPX depicted the UMVS on the top of a fuel storage rack.

The measured rate of the neutron emission from the fuel assemblies is reduced when boron is added to the water. The water in the storage pool for PWR fuel assemblies typically contains 2200 ppm of dissolved boron. This boron in the water is to reduce the reactivity for the fresh fuel assemblies, and is normally used for the fresh PWR MOX assemblies. The UMVS has an additional ^{3}He detector in the perimeter to verify the declared boron concentration. The extra tube has minimal HDPE moderator so the ratio of the un-moderated and moderated ^{3}He tubes is sensitive to the boron concentration.

4.2.1 Theoretical approach

The singles count rate S from the target assembly would depend on the mass of ^{240}Pu, neutron multiplication, and (α,n) neutrons. The overall multiplication in the storage rack is a function of number of assemblies, the fissile mass, and the storage pattern of the assemblies, and boron concentration of the water.

To develop a theoretical approach for UMVS measurement, following assumptions are made.

1. The neutron multiplication of an isolated target assembly, M_T is a known function of the mass by MCNPX simulation and calibration.
2. The space made by diverted fuel pins in a target assembly is filled with dummy pins, which are filled with depleted uranium oxide of the same density as the original MOX fuel pins.
3. The overall neutron contribution by neighbouring assemblies is considered as an additional neutron source, which is a function of number of assembly and the storage pattern.

With these assumptions, the singles count rate at a target assembly that is surrounded by multiple assemblies can be described by Eq. (1). A new term, β, is introduced to define the overall excess neutron sources including (α,n) neutrons from the target assembly and all neutrons from the neighbouring assemblies. The term β can be measured using the perimeter neutron detector configuration in the UMVS.

$$S' = m_T \cdot f \cdot \nu \cdot \varepsilon_T \cdot M_T \cdot (1+\beta) \quad (1)$$

where, m_T = mass of ^{240}Pu in target assembly,
f = spontaneous fission yield of ^{240}Pu (=473.5 fission/g-s),
ν = spontaneous fission multiplicity of ^{240}Pu (=2.16),
ε_T = efficiency of the neutron counter for target assembly,
M_T = neutron multiplication for the target assembly,
β= ratio of overall excess neutron to the spontaneous fission neutrons.

With Eq. (1), the singles count rate at a target assembly can be used to verify the content of the target assembly.

4.2.2 MCNPX simulations

The UMVS system illustrated in Figure 6 was simulated using the MCNPX code [6] to guide the design and to estimate the counting rates from the various detectors. The calculations were also used to develop a correction algorithm for the neighbour assemblies in the storage rack.

Because the measurement requires a correction for neutrons originating in the neighbouring assemblies, four side ^{3}He detectors were introduced to measure the effect of the neighbors. The combination of the polyethylene and cadmium sheet is also providing shielding to the side detectors for neutrons that originated from the target assembly.

The side detectors are located at four equally spaced positions around the perimeter of the system and covered with 2-cm thick annulus of polyethylene covered by cadmium (Cd). The perimeter detectors are embedded in the annular space that surrounds the main body of the detector. The distance of the side detectors from system's center detector is optimized for maximum efficiency for measuring neutrons from the neighbor assemblies and minimum efficiency to the target assembly. One of the side detectors is accompanied with an additional detector for boron concentration monitoring. The fifth detector is isolated from the HDPE in the UMVS detector body by cadmium sheet of 0.5 mm thickness so that the detector response is sensitive to the boron concentration in the water. Because the two detectors are positioned at about the same location, the neutron flux at the detectors is approximately the same regardless of orientation of the system, so the boron concentration can be verified by comparing two detectors' responses. Because of the buoyancy force of the water, total net weight of the system in water is approximately 5 kg.

The PWR MOX fuel assembly that was used for the simulation has the same geometrical configuration as the Westinghouse 17×17 PWR fuel assembly design. The assembly is composed of low, middle, and high Pu content fuel rods, and the average Pu fissile content is 11 wt%. To reduce the computing time to get a reasonable error (< 5 %), only the top 100 cm of the fuel is considered in the simulations. Additional calculations were performed to investigate the penetration depth of the neutron signal from the top of the assembly. The plutonium sensitivity decreases as a function of distance from the top of the assembly with limited signal sensitivity down to ~ 0.6 m.

A storage rack of 7×7 assembly array in a storage pool is modeled for this simulation. Borated stainless steel of 1.6 cm thickness is used for the structural material of the storage rack. Potential assembly storage patterns are illustrated in Figure 7. The centre circle in the Figure 7 is the location of the target assembly at which the UMVS is located for the verification measurement.

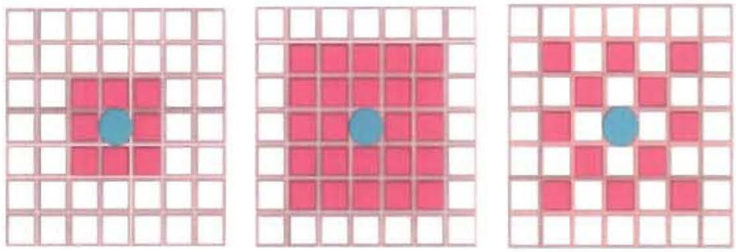

Figure 7: Fuel assembly storage patterns used for the MCNPX simulations.

4.2.3 Results

Figure 8 shows the normalized multiplication of the target assembly as a function of ^{239}Pu mass for 2200-ppm boron concentration. The neutron multiplication and the detector efficiency are for the target assembly that contains 89.9 kg of Pu, which is equivalent to 36.83 kg of effective ^{240}Pu. The multiplication and efficiency of the detection system could be determined by a calibration measurement using one of the MOX assemblies in the pool that was measured using the UWCC. We have used the MCNPX code to calculate the multiplication and detector responses. For the computational experiment, a single assembly in borated water of 2200 ppm is considered as a base case.

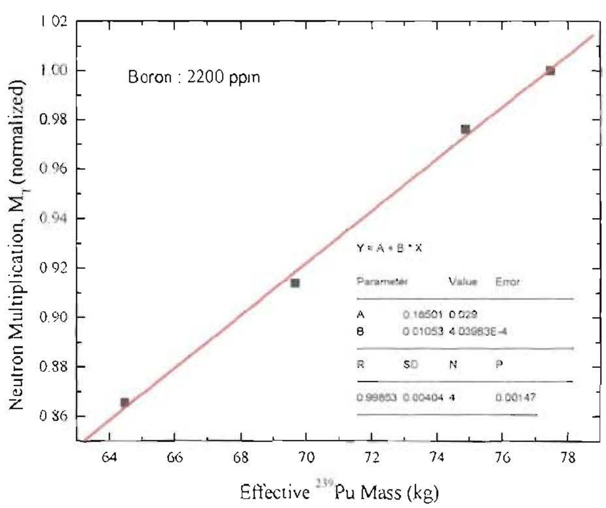

Figure 8: Neutron multiplication by ^{239}Pu mass in a target fuel assembly.

The measured neutron totals rate is a function of (1+β) as shown in Eq. (1), and it needs to be calculated for a given storage pattern and boron concentration. The response of (1+β) can be estimated by the function as shown in Figure 9. We note that the neutron gain by multiplication in checkerboard pattern (see Figure 7) is only slightly greater than the neutron loss by absorption. The more dense storage pattern (1-row deep) shows the strong neutron contribution from neighbour assemblies, but it eventually becomes saturated at the 2-row deep case because of the separation distance and the absorption of neutrons in the water.

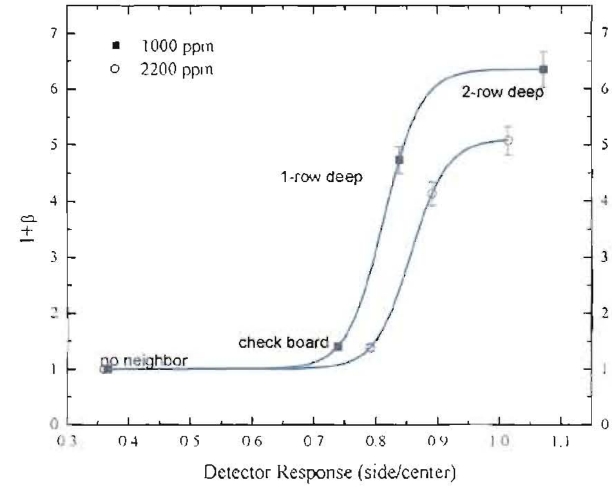

Figure 9: Response of (1+β) as a function of storage pattern.

The boron monitor of the UMVS can verify the concentration by measuring the Cd ratio in the two perimeter detectors as shown in Figure 10.

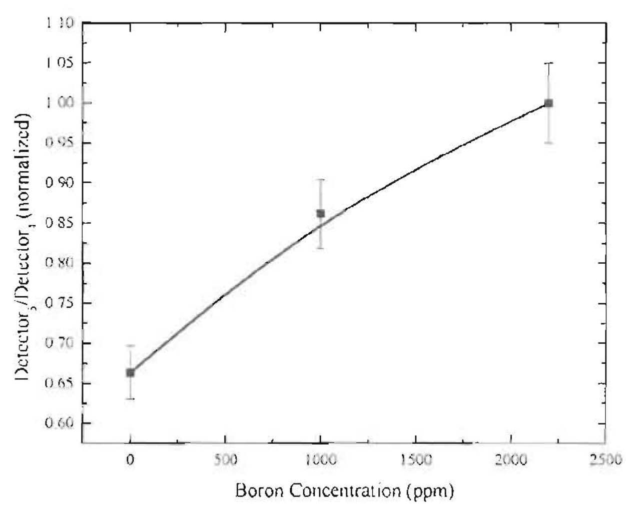

Figure 10: Response of UMVS for boron concentrations.

Figure 11 shows the averaged singles rates after (1+β) correction factor that is based on the response ratio between canter and perimeter detectors. Because the (1+β) is correcting the excess response from neighbour assemblies, the corrected $S_{(1+\beta)}$ become a single response curve regardless of storage patterns. It was determined that ~1 % of random error could be achieved with less than 100 sec of counting time.

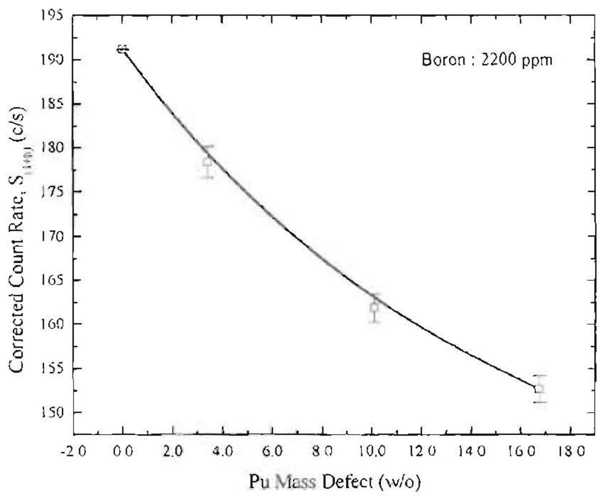

Figure 11: The corrected counting rate from the central ^{3}He tube versus the Pu mass removal from the MOX assembly.

The response of the UMVS has a slight dependence on the radial location of the pin removals and the curve shown in the Figure 11 corresponds to a uniform removal pattern. If the pins are removed from the central section of the assembly, the change in the measurement will be greater than the values shown, and if the pins are removed from the extreme corners, the response change will be less than indicated. However, the measurement is sensitive to all pin positions. In general, the UMVS should be used to verify the consistency of the declared loading and not to quantify the remaining Pu mass.

5. Summary

The verification of MOX fuel assemblies can benefit from the coupling between the fabrication plant measurements and the measurements at the reactor site. These measurements at the fabrication plant and the reactor site are useful to establish effective safeguards for shipper-receiver accountability. In general, NDA measurements make use of one or more standard samples to calibrate the NDA measurements. The proposed connection between the fabrication plant and the reactor site can provide working standards for the subsequent fuel verification using the UMVS.

The PNCL type measurement at the fabrication plant can provide a precision of better than 1% in 10 min. The accuracy will depend on how well the standard is known and its match to the unknown assemblies. The UWCC has a precision and accuracy that is similar to the PNCL. On the other hand, the UMVS is used to measure the fuel assemblies after they are lowered into the storage rack. If C-o-K is maintained between the fuel transfer to the storage rack and the initial UMVS measurement, then the initial measurement provides a calibration for the UMVS. The precision of the UMVS is ~ 1% in 100s; however, there will be additional errors related to positioning the detector head and the correction for the neighbouring fuel assemblies. For the case where there is no fuel movement between subsequent measurements from more than one inspection period using the UMVS, the relative accuracy of the UMVS will be as good as the positioning reproducibility. In this case, the UMVS measurement is similar to a fingerprint type of verification.

For the case of fuel pin substitution, the change in the UMVS response is almost linear with the fuel removal mass as shown in the Figure 11. Note that a 10% fuel pin reduction results in a 10% change in the UMVS response. The sensitivity to the position of the pin is small where the outside perimeter pins have less ^{239}Pu content than the central pins. There are no blind spots in the response. In the vertical direction, the top of the fuel assembly dominates the response with penetration to a depth of about 1 m.

The UMVS has the capability to verify fresh MOX assemblies with a measurement time of only 100 s, and with no movement of the fuel assemblies. The detector package would weigh ~ 40 kg in air and about 5 kg in water, so that its weight on the storage rack is negligible. The detector head could be connected to the bridge crane by a flexible cable for hand positioning.

The status of the UMVS development is that it exists only in MCNPX simulation space, and no prototype hardware has been fabricated or tested. The electronics required to support the UMVS are the same as for the attended mode UWCC (i.e. the JSR-12 or equivalent) [7]. Additional calculations are in progress to better define the spatial response of the system to different fuel storage configurations. As the use of MOX recycle fuel becomes more widespread, the effective and efficient safeguards of the fuel will become more important. The capability to verify the fresh MOX fuel assemblies in the under water storage without fuel movement will take on added importance.

6. Acknowledgements

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7. References

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