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Neutron Physics and Detectors

Analysis of experimental measurements of PWR fresh and spent fuel assemblies using Self-Interrogation Neutron Resonance Densitometry

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ABSTRACT

Self-Interrogation Neutron Resonance Densitometry (SINRD) is a new NDA technique that was developed at Los Alamos National Laboratory (LANL) to improve existing nuclear safeguards measurements for LWR fuel assemblies. The SINRD detector consists of four fission chambers (FCs) wrapped with different absorber filters to isolate different parts of the neutron energy spectrum and one ion chamber (IC) to measure the gross gamma rate. As a result, two different techniques can be utilized using the same SINRD detector unit and hardware. These techniques are the Passive Neutron Multiplication Counter (PNMC) method and the SINRD method. The focus of the work described in this paper is the analysis of experimental measurements of fresh and spent PWR fuel assemblies that were performed at LANL and the Korea Atomic Energy Research Institute (KAERI), respectively, using the SINRD detector. The purpose of these experiments was to assess the following capabilities of the SINRD detector: 1) reproducibility of measurements to quantify systematic errors, 2) sensitivity to water gap between detector and fuel assembly, 3) sensitivity and penetrability to the removal of fuel rods from the assembly, and 4) use of PNMC/SINRD ratios to quantify neutron multiplication and/or fissile content. The results from these simulations and measurements provide valuable experimental data that directly supports safeguards research and development (R&D) efforts on the viability of passive neutron NDA techniques and detector designs for partial defect verification of spent fuel assemblies.

1. Introduction

The development of non-destructive assay (NDA) capabilities to improve verification of spent fuel has become increasingly important with the worldwide expansion of nuclear power, adoption of enhanced safeguards criteria for spent fuel verification, and recent efforts by the International Atomic Energy Agency (IAEA) to incorporate an integrated safeguards regime [1]. Under comprehensive safeguards agreements, states declare the nuclear material composition of the LWR spent fuel based on the operating records of the reactors and results of reactor core simulations. Declarations are formulated per spent fuel item. In addition, reactor operators provide operating records and irradiation histories for each fuel assembly. For routine verification, the IAEA deploys verification measures meant to confirm the presence of declared items in the spent fuel storage by means of continuous C/S measures or approved nondestructive verification supporting attribute tests. During an onsite inspection, IAEA inspectors verify the spent fuel inventory declared by the facility operator via item accounting and, when needed, use the appropriate technology to measure a sample of the assemblies to ensure the validity of the operator's accountancy system [2].

As opposed to simple attribute test which is normally sufficient, under special circumstances such as loss of continuity of knowledge during open core periods or when spent fuel is transferred to dry storage, the IAEA engages more powerful verification methods supporting the independent verification of the irradiation history or the completeness of the fuel assembly (i.e. the absence of pin removal or substitution). Avenues for improvement of current spent fuel verification methods include: the ability to verify LWR spent fuel assemblies independent of the operator's declaration and the existence of a measurement method that can be used for all types of fuel assemblies regardless of initial fuel enrichment, burnup, or cooling time [3,4].

1.1. Objectives

Self-Interrogation Neutron Resonance Densitometry (SINRD) is a new NDA technique that was developed at Los Alamos National Laboratory (LANL) to improve existing nuclear safeguards measurements for LWR fuel assemblies. The basic physics concept of the SINRD measurement technique was originally developed in 1968 at LANL using the name, Self-Indication Neutron Resonance

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Absorption Densitometry (SINRAD). Two experiments were performed in 1968 and 1969 with SINRAD which used a reactor beam as the interrogating neutron source to measure the fissile concentration in ^{235}U and ^{239}Pu metal plates and MOX fuel rods, respectively [5–7]. The results from these experiments demonstrate that SINRAD can accurately measure the fissile content in both metal plates and MOX fuel rods. The primary objective of this research was to develop the same basic physics signature as SINRAD but applied to LWR spent fuel assemblies (SFAs). However, in spent fuel, there is an adequate neutron source from the spontaneous fission of ^{244}Cm to be self-interrogating and no reactor beam is necessary. Thus, the original name was modified to the current name, Self-Interrogation Neutron Resonance Densitometry, for spent fuel applications to reflect the different neutron sources. It is important to note that SINRD can also be used to measure fresh FAs. Since the spontaneous fission rate of ^{238}U is very low, a ^{252}Cf source can be used to reduce the required count time. Recent interest in this approach was stimulated by an IAEA request related to spent fuel verification. The main application of SINRD is for use at a spent fuel storage facility for measurements in water, although SINRD could also be used for measurements in different mediums, such as air or sodium and at reprocessing facilities that have spent fuel pools [8].

The focus of the work described in this paper is on the experimental measurements of fresh and spent PWR fuel assemblies were performed at LANL and the Korea Atomic Energy Research Institute (KAERI), respectively, using the SINRD detector. SINRD has the potential to be a low-cost, robust hardware system deployed for verification of spent fuel assemblies. In addition, SINRD could also be easily integrated with a Fork detector or ^{252}Cf Interrogation with Prompt Neutron Detection (CIPN) detector given the complementary nature of the hardware. The purpose of these experiments was to assess the following capabilities of the SINRD detector:

1) reproducibility of measurements to quantify systematic errors
2) sensitivity to water gap between detector and fuel assembly (FA)
3) sensitivity and penetrability to the removal of fuel rods from the assembly
4) use of different fission chamber (FC) ratios to quantify neutron multiplication and/or fissile content in the FA

The results from these simulations and measurements provide valuable experimental data that directly supports safeguards research and development (R&D) efforts on the viability of passive neutron NDA techniques and detector designs for verification of spent fuel assemblies.

1.2. Theory and background

The neutron resonance cross-section structure is unique for each fissile isotope such as ^{235}U, ^{239}Pu, and ^{241}Pu, and the resonance structure can provide a signature for the measurement of these materials of importance for safeguards and non-proliferation. The sensitivity of SINRD is based on using the same fissile materials in the sample and fission chamber because the effect of resonance absorption in the transmitted flux is amplified by the corresponding (n,f) reaction peaks in the fission chamber. For instance, a ^{235}U fission chamber has a high sensitivity to the neutron resonance absorption in ^{235}U present in the sample, and similarly for other fissile isotopes. SINRD uses spontaneous fission neutrons from ^{244}Cm to self-interrogate the spent fuel pins. The concentration of ^{235}U and ^{239}Pu in the spent fuel is then determined by measuring the distinctive resonance absorption lines from ^{235}U and ^{239}Pu using ^{235}U and/or ^{239}Pu fission chambers (FCs) placed adjacent to the side of the fuel assembly. Thus, the self-interrogation signature is a result of having the same fissile material in the FC and the sample [9].

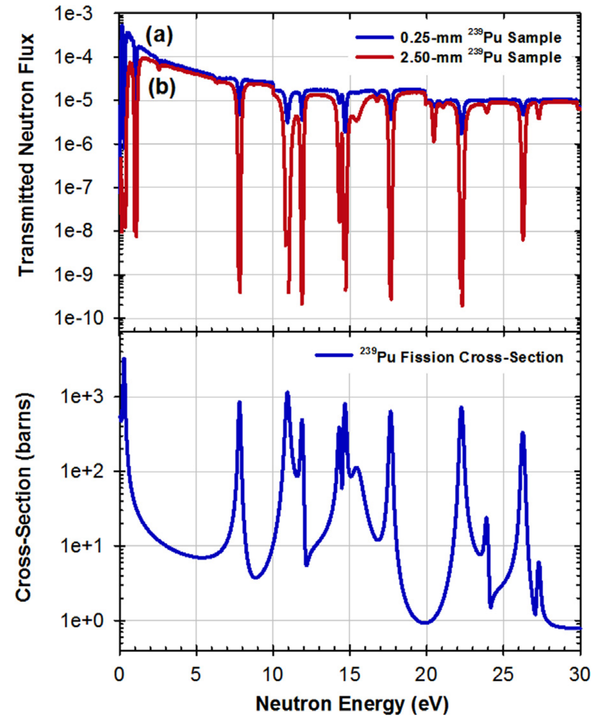

Fig. 1. Comparison of absorption lines in neutron flux after transmission through Gd filter and (a) 0.25-mm and (b) 2.5-mm ^{239}Pu metal sample (upper plot) to ^{239}Pu fission cross-section (bottom plot).

In Fig. 1, the ^{239}Pu fission cross-section is compared to the resonance absorption lines in the neutron flux after transmission through a 0.11-mm Gd filter and ^{239}Pu metal samples 0.25-mm and 2.5-mm thick. It is important to note that as the sample thickness increases, the self-interrogation signature decreases due to self-shielding effects from saturation of the large ^{239}Pu fission resonance at 0.3-eV [4]. The results shown for the transmitted flux through ^{239}Pu metal samples of different thicknesses were obtained from MCNP simulations and the ^{239}Pu fission cross-section was obtained from the JANIS ENDF-VII cross-section database [10].

2. Design of SINRD detector

The SINRD detector system was designed for measuring LWR fuel assemblies. Since the fuel assemblies considered in this research have square lattices, we designed the SINRD detector unit to be rectangular. The SINRD detector unit consists of one ion chamber (IC) and the following four FCs:

- Bare ^{235}U FC: measures thermal neutrons leaking from the FA
- Boron Carbide (B_4C) ^{235}U FC: measures fast neutrons leaking from the FA
- Gd covered ^{235}U FC: measures neutrons above 0.13-eV leaking from the FA
- Cd covered ^{235}U FC: measures neutrons above 1.25-eV leaking from the FA

It is important to note that two different techniques can be utilized using the same SINRD detector unit and hardware. These techniques are the Passive Neutron Multiplication Counter (PNMC) method and the SINRD method. The PNMC method uses the ratio of the fast-neutron emission rate to the thermal-neutron emission rate to quantify the neutron multiplication of the item. It should also be noted that throughout the rest of this paper, we refer to the B_4C FC as FFM (or Fast Flux Monitor) and the Bare ^{235}U FC as TFM (or Thermal Flux Monitor).