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Development of prototype induced-fission-based Pu accountancy instrument for safeguards applications

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HIGHLIGHTS

- Prototype safeguards instrument for nuclear material accountancy has been developed and characterized.
- The prototype system is based on a hybrid measurement technique (FNEM and PNAR).
- Various detector parameters (i.e., efficiency profile, dead time, and stability) were evaluated.
- The system's capability to measure the difference in the average neutron energy for the FNEM signature was evaluated.

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ABSTRACT

Prototype safeguards instrument for nuclear material accountancy (NMA) of uranium/transuranic (U/TRU) products that could be produced in a future advanced PWR fuel processing facility has been developed and characterized. This is a new, hybrid neutron measurement system based on fast neutron energy multiplication (FNEM) and passive neutron albedo reactivity (PNAR) methods. The FNEM method is sensitive to the induced fission rate by *fast* neutrons, while the PNAR method is sensitive to the induced fission rate by *thermal* neutrons in the sample to be measured. The induced fission rate is proportional to the total amount of fissile material, especially plutonium (Pu), in the U/TRU product; hence, the Pu amount can be calibrated as a function of the induced fission rate, which can be measured using either the FNEM or PNAR method. In the present study, the prototype system was built using six ^{3}He tubes, and its performance was evaluated for various detector parameters including high-voltage (HV) plateau, efficiency profiles, dead time, and stability. The system's capability to measure the difference in the average neutron energy for the FNEM signature also was evaluated, using AmLi, PuBe, ^{252}Cf, as well as four Pu-oxide sources each with a different impurity (Al, F, Mg, and B) and producing (α,n) neutrons with different average energies. Future work will measure the hybrid signature (i.e., FNEM × PNAR) for a Pu source with an external interrogating neutron source after enlarging the cavity size of the prototype system to accommodate a large-size Pu source (~600 g Pu).

1. Introduction

One of the promising components of future spent-fuel management schemes in Korea is an advanced PWR fuel process that recovers U and U/TRU via electrochemical separation. One of the main design-based objectives of the process is to minimize, for safeguards and safety reasons, the amounts of TRU elements in the U product and wastes. On the other hand, the U/TRU product is produced with almost all the TRU elements in the spent fuel. Accordingly, nuclear material accountancy (NMA) for the U/TRU product is of great interest in terms of safeguards; however, there are some technical challenges in the nondestructive assay (NDA) of U/TRU products, including high neutron emission yields from spontaneous fission of ^{244}Cm, neutron multiplication by induced fission from fissile materials (^{235}U, ^{239}Pu, and ^{241}Pu), and the complex compositions of U and TRU elements as well as rare earth elements. Because the NDA technique is essential for near-real time accountancy (NRTA) (Pillay, 1989; Burr et al., 2015; Johnson and Ehinger, 2010), a very significant collaborative effort in developing an NDA technique suitable for NMA of the U/TRU product has been made by the Korea Atomic Energy Research Institute in partnership with the Los Alamos National Laboratory. The

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preferred characteristics of the NDA technique for NMA of the U/TRU product is (1) a passive method due to the limited availability of the active interrogating source with the higher neutron emission yield than that of the U/TRU product itself and (2) a direct measurement method independent of the Cm ratio technique (Miura and Menlove, 1994) due to the chance of an inconsistent Cm ratio between the input and output materials and the difficulties in measuring the Cm ratio by the NDA technique due to the complex isotopic composition. There are some existing passive-neutron measurement techniques based on coincidence and multiplicity counting (Reilly et al., 1991); however, their applicability is questionable in that the high neutron emission yield and high neutron multiplication might require dead-time and multiplication corrections, which usually are error prone when both (i.e., neutron emission yield and multiplication) are considerably high.

In the present study, a prototype induced-fission-based Pu accountancy instrument was developed, the performance of which was evaluated for various detector parameters including a high-voltage plateau, efficiency profiles, dead time, and stability. Its capability to measure the change in the average neutron energy, which is to say the FNEM signature, also was evaluated using AmLi, PuBe, ^{252}Cf, as well as four Pu-oxide sources each with a different impurity (Al, F, Mg, and B) and producing (α,n) neutrons with different average energies.

2. Structure of prototype FNEM × PNAR system

The prototype is a hybrid-type neutron measurement system based on the fast neutron energy multiplication (FNEM) and passive neutron albedo reactivity (PNAR) methods (Menlove and Beddingfield, 1997). The physical basis of the FNEM method is that the average neutron energy is increased as the induced fission rate by the fast neutron increases, which is proportional to the amount of fissile materials, especially Pu, in the sample to be measured. Accordingly, the Pu mass can be calibrated as a function of the average neutron energy that can be measured by using a ring ratio technique (i.e., the count ratio of the far to the close rings). To measure the FNEM signal, the prototype system has two ^{3}He detector rings close to and far from the sample, respectively. The physical basis of the PNAR method is that the induced fission rate by the thermal neutrons is increased as the number of reflecting thermal neutrons from the surrounding material increases. The PNAR signal can be measured by the so-called Cd ratio (i.e., the neutron count ratio of with- to without the Cd liner), which is proportional to the Pu mass. To measure the PNAR signal, the prototype system has two sample containers with and without the Cd liner, respectively. In summary, the FNEM and PNAR methods are based on the fast- and thermal-neutron-induced fission rates, respectively.

The basic structure of the prototype system is shown in Fig. 1. It is equipped with two sets of ^{3}He detector rings (close and far rings) to measure the difference in average neutron energy as a function of the Pu mass for an FNEM signature. The distance between the detector rings was set as 10 cm. An additional sample container with and without the 1-mm-thick Cd linear was used to measure the PNAR signature. The outer dimensions of the sample container were 9.5 cm (D) × 25.8 cm (H) with a cavity size of 7.5 cm (D) × 20 cm (H). Three ^{3}He tubes (RS-P4–0820-220, GE Reuter-Stokes, USA) of 6.7 atm filling pressure and an active volume of 1 in (D) × 20 in (H) were used for each ring. The quench gas, CF_4, was filled into the ^{3}He tube. The PDT 110A module (http://www.pdt-inc.com/products/100series/100series_datasheet.htm) was used for signal processing of each detector. The PDT 110A has the capabilities of a charge-sensitive preamplifier, amplifier, and leading-edge discriminator. The logic signal produced in each module was fed into the external OR circuit, which has three input channels and one ORed output channel for each ring. Finally, there are two ORed output signal channels for the detector rings, the signals of which were recorded and analyzed by a shift register (JSR-14, Canberra, USA) (http://www.canberra.com/products/waste_safeguard_systems/pdf/JSR-14-SS-C37278.pdf) and IAEA Neutron Coincidence Counting (INCC) software version 5.1.2 (Krick and Harker, 2009).

A 53.2 cm (D) × 56.5 cm (H) high-density polyethylene (HDPE) neutron moderator with a 10 cm (D) × 26.5 cm (H) cavity was used. To enhance the detection efficiency, 10 cm (D) × 15 cm (H) graphite reflectors were positioned in the top and bottom of the cavity. To improve the FNEM signature, the ^{3}He tubes in the close ring were partly covered by a 20 cm-long Cd sheet in the top and bottom regions. The top cover has connectors for signal outputs and a high-voltage (HV) input for the detectors as well as a low-voltage (LV) input for the preamplifiers and OR circuit. The top cover also has a window for LED indicators and a door for maintenance. The overall size and weight of the system is 60 cm × 60 cm × 92 cm including the cover and ~200 kg, respectively. The system specifications and components are summarized in Table 1. Photographs of the prototype system are shown in Fig. 2.

3. Performance evaluation of prototype system

3.1. Signal processing circuit

A simple signal processing circuit for an OR logic and LED driver was developed (instead of using the OR logic capability of the PDT 110A), for summing of the signals from each detector ring and for external visual monitoring of the individual detector status by LED lights. The signal processing circuit diagram for one ring is shown in Fig. 3. The TTL logic signal produced in each PDT 110A module

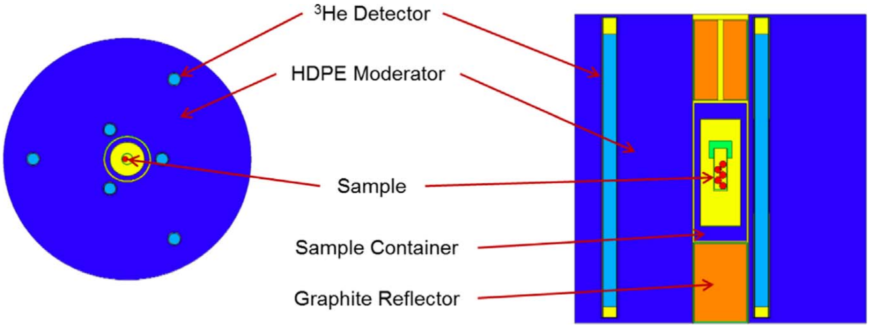

Fig. 1. Schematic of prototype Pu accountancy instrument for U/TRU product: top-view (left) and side-view (right).