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Determination of spent nuclear fuel assembly multiplication with the differential die-away self-interrogation instrument

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ABSTRACT

We present a novel method for determining the multiplication of a spent nuclear fuel assembly with a Differential Die-Away Self-Interrogation (DDSI) instrument. The signal, which is primarily created by thermal neutrons, is measured with four ^{3}He detector banks surrounding a spent fuel assembly. The Rossi-alpha distribution (RAD) at early times reflects coincident events from single fissions as well as fission chains. Because of this fact, the early time domain contains information about both the fissile material and spontaneous fission material in the assembly being measured. A single exponential function fit to the early time domain of the RAD has a die-away time proportional to the spent fuel assembly (SFA) multiplication. This correlation was tested by simulating assay of 44 different SFAs with the DDSI instrument. The SFA multiplication was determined with a variance of 0.7%.

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1. Introduction

Nondestructive assay (NDA) is a type of analysis technique used to evaluate properties of a material, component or system without causing damage. In the context of international safeguards such kind of techniques are often used to characterize and/or verify type and amount of nuclear material. While characterization is identification of discriminating features when measuring an unknown sample, the verification is performed by confirming that the declared characteristics of a sample are correct. Verification may also require detection of gross and partial defects, which in relation to spent nuclear fuel may represent complete (gross) or strategic (partial) substitution of material from the fuel assembly [1]. The complexities of the materials that compose spent fuel make it challenging to characterize. Parameters of interest for characterization include initial enrichment (IE), burnup (BU), cooling time (CT), plutonium mass, as well as multiplication as an intermediary item to determine the aforementioned quantities. Multiplication affects the overall neutron count rate and is indicative of the fissile, and neutron absorber content in an assembly, making it a particularly useful measured quantity. It can also be used to determine total plutonium content [2] and burnup credit, and to aid in detecting possible pin diversions (this is the subject of work in progress). Independent deduction of these physical parameters without operator declaration is a goal of several NDA systems currently under development through the Next Generation Safeguards Initiative (NGSI) [3]. These include Differential Die-Away (DDA) [4], Passive Neutron Albedo Reactivity (PNAR) [5], Californium Interrogation of Prompt Neutrons (CIPN) [6], Self-Interrogation Neutron Resonance Densitometry (SINRD) [7], and Differential Die-Away Self-Interrogation (DDSI) [8]. This paper focuses on the ability of DDSI instrument to measure multiplication through Rossi-alpha distribution (RAD) analysis.

The DDSI approach for spent fuel assembly (SFA) assay is a passive technique that utilizes the spontaneous fission and (α,n) neutrons in the assemblies as an internal interrogating radiation source. Since the neutrons released in spontaneous fission are thermalized in the surrounding medium (e.g. water) they become efficient in inducing fission preferentially on fissile isotopes such as ^{235}U, ^{239}Pu, and ^{241}Pu, thereby creating a measurable signal from isotopes of interest that would be otherwise difficult to measure by passive neutron measurement methods [9]. The DDSI technique will employ neutron coincidence counting with ^{3}He tubes and a list-mode-based data acquisition to allow for production of RADs in the post processing [10]. While the shift register technique with pre-determined gates has been the predominant method used in neutron multiplicity counting, the list-mode approach to data collection will enable construction of RADs which, in turn, expand our analytical capabilities. One of the main advantages is that the measured signal in the form of a RAD can be analyzed in its entirety including determination of die-away times (τ) in different time domains, while still preserving our capability to perform traditional gate analysis. This technique will also have the added benefit of flexible gate timing post data-collection.

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The RADs measured by the DDSI instrument can be broken down to reflect two primary correlations within the system: coincident neutrons from single fission events and coincident neutrons from multiple fission events in a single fission chain [11]. These correlations can be approximated by single exponentials termed the "*fast*" and "*slow*" components, respectively. We have found through extensive high-fidelity simulations that assembly multiplication can be determined from a die-away constant of a fitted exponential function to the early time domain of a RAD which we call "early τ". The die-away of this exponential fit is ruled by the sum of the fast and slow components in that time domain and is found to be linearly correlated to the net multiplication as calculated by the Monte Carlo N Particle eXtended (MCNPX) code [12], which is a function of net neutron gain from fission as well as non-fission multiplicative reactions, such as (n, 2n) reactions. The relation of "net" multiplication with respect to the more commonly used "leakage" multiplication may vary significantly depending on the geometry and nature of the simulated problem, however in our case, due to isolation of ^{3}He detectors from the sample region by the Cd liner, these two quantities can be considered nearly identical and thus multiplication also represents the number of neutrons available for counting per primary neutron produced. The original work on the use of the DDSI technique to characterize spent nuclear fuel utilized a doubles/singles ratio to determine multiplication [13], however the new RAD analysis method presented here provides a more simplified prediction under less restrictive conditions and with improved accuracy. We continue the work began by Schear et al. and expand upon their analysis to approach the measured signal in a different way. Analysis with the RAD is performed on 44 different simulated SFAs from Spent Fuel Library 2a (SFL-2a) [14] and the results are presented in this paper.

2. DDSI methodology

DDSI is a passive technique that utilizes neutrons emitted primarily from spontaneous fission (SF) nuclides within a spent fuel assembly as an internal source to interrogate the fissile content. The fast SF neutrons thermalize in the water surrounding and within the SFA and a fraction of them re-enter the fuel pins where they can be absorbed or induce fission. In this process the fissile content is preferentially interrogated because of the high thermal neutron induced fission cross-section of fissile isotopes and relatively low cross-section of fertile isotopes at that energy. In this way fissile material provides a measurable neutron signal which is otherwise difficult to detect in the absence of an external, active source.

The original work [8] on DDSI utilized Fig. 1 to demonstrate the separate contributions from the spontaneous and fast-neutron fission (FF) neutrons from the induced fission neutrons. This figure is intended to accentuate the fact that different fission processes become the primary contributors at different time domains following a trigger, which is defined as any detected neutron. The gates established in the figure are integrals of different time domains of the RAD.

Although it is true that all SF and FF coincident neutrons will contribute at early times after the trigger if a true coincidence is detected, Fig. 1 may be misinterpreted to imply that induced fission (IF) neutrons do not contribute to the fast component depicted as a red curve. On the contrary, the fast component is composed of coincident fission neutrons that were emitted from the same fission event that produced the trigger neutron (i.e. the first neutron detected), regardless of whether the fission was SF, FF, or IF.

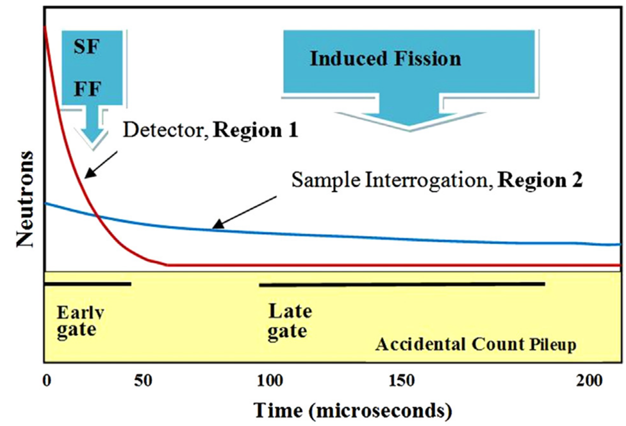

Fig. 1. Original DDSI concept demonstration highlighting different fission contributions at different time domains following a trigger [8].

If two neutrons are detected in coincidence from the same fission event, there is a finite amount of time that those neutrons must spend traveling from the location of the fission before being captured. One neutron will arrive before the other and that will be considered the trigger neutron. The time to arrival of the second neutron will vary based on time to travel across the SFA and DDSI detector and time to thermalize before being captured inside the ^{3}He detector. Therefore the die-away time of neutrons detected from the same fission event is determined largely by the geometry of the measurement system and the source. Overall, a single exponential distribution can well-approximate the instrument's die-away only when the detector has been designed with a uniform thickness of moderator surrounding every ^{3}He tube. Most thermal-neutron detectors will have multiple die-away time components. This distribution is the fast component from the sample, and because the instrument's die-away is considerably longer than the SF process, the total die-away of this component of the distribution is determined by the detector system.

If two neutrons are detected in coincidence from two fission events that are part of the same fission chain (i.e. multiplication), the time between capture of the neutrons can vary significantly more than in the case of a pair of neutrons from the same fission event. If, for example, the trigger neutron comes from a fission event that released a second neutron that induced fast fission, the neutron released from that second fission event could be detected very close after the first neutron. If, however, the trigger neutron comes from a fission event that released a neutron that set off a long fission chain containing several additional fission events before a second neutron was captured, the time between detections could be up to hundreds of microseconds. The die-away of these neutrons is much longer than the instrument's die-away time and therefore is affected very little by detector setup and geometry. The shape of a capture-triggered distribution can still be well-approximated by a single exponential though its magnitude and die-away constant vary widely with assembly isotopic content and water moderator conditions [9]. This distribution is the slow component and it is present in any measured sample where fission chains are likely to occur and have considerably longer die-away behavior than the detector.

The design of the DDSI instrument intended for spent fuel assay has significantly evolved since its inception in 2009, though the utilized physics principles remain the same. Because the DDSI technique relies on self-interrogation, neutron thermalization in the immediate area surrounding the fuel assembly is necessary to the design. For this reason, measurements with the DDSI instrument take place directly within a spent fuel pool with close coupling to the assayed SFA. The instrument incorporates ^{3}He detectors embedded in polyethylene surrounding the assembly