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Simulation of differential die-away instrument's response to asymmetrically burned spent nuclear fuel

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ABSTRACT

Previous simulation studies of Differential Die-Away (DDA) instrument's response to active interrogation of spent nuclear fuel from a pressurized water reactor (PWR) yielded promising results in terms of its capability to accurately measure or estimate basic spent fuel assembly (SFA) characteristics, such as multiplication, initial enrichment (IE) and burn-up (BU) as well as the total plutonium content. These studies were however performed only for a subset of idealized SFAs with a symmetric BU with respect to its longitudinal axis. Therefore, to complement the previous results, additional simulations have been performed of the DDA instrument's response to interrogation of asymmetrically burned spent nuclear fuel in order to determine whether detailed assay of SFAs from all 4 sides will be necessary in real life applications or whether a cost and time saving single sided assay could be used to achieve results of similar quality as previously reported in case of symmetrically burned SFAs.

The results of this study suggest that DDA instrument response depends on the position of the individual neutron detectors and in fact can be split in two modes. The first mode, measured by the back detectors, is not significantly sensitive to the spatial distribution of fissile isotopes and neutron absorbers, but rather reflects the total amount of both contributors as in the cases of symmetrically burned SFAs. In contrary, the second mode, measured by the front detectors, yields certain sensitivity to the orientation of the asymmetrically burned SFA inside the assaying instrument. This study thus provides evidence that the DDA instrument can potentially be utilized as necessary in both ways, i.e. a quick determination of the average SFA characteristics in a single assay, as well as a more detailed characterization involving several DDA observables through assay of the SFA from all of its four sides that can possibly map the burn-up distribution and/or identify diversion or replacement of pins.

1. Introduction

The Differential Die-Away (DDA) method is one of the techniques which is being investigated within the Next Generation Safeguards Initiative (NGSI) spent fuel project of the U.S. Department of Energy [1]. The main objectives of the NGSI spent fuel project are to develop and to test instrumentation for plutonium mass content determination inside commercially utilized spent fuel assemblies (SFAs), verify the operator's declarations in terms of the irradiation history parameters such as initial enrichment (IE), burn-up (BU), and cooling time (CT) and to test the SFA for partial defects which could signal a deliberate illicit diversion of nuclear material.

Originally, 14 different non-destructive assay (NDA) techniques were chosen to be possibly applicable for spent fuel assay [1]. Following thorough simulations and evaluations, the DDA technique based instrument turned out to be highly promising and comprehensive method with a capability to measure multiplication of the assayed SFA [2], determine its fissile [3] as well as total Pu content [4], and quantify IE and BU [5]. Thus in the current, i.e. later, stages of the NGSI project, the DDA instrument research focuses on practical aspects of real life measurements and conditions of its deployment. Within this paper, we address the effects of asymmetric BU on the response of the DDA instrument, which, if significant enough, may dictate the final instrument design or force the assay of the SFA to be performed from all of its sides, thus potentially significantly increasing time and cost requirements of the measurement.

During its lifecycle, a fuel assembly in a commercial nuclear reactor utilized for electrical power production undergoes typically

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three or four cycles of irradiation [6]. After each cycle, its position within the reactor core is changed according to a sophisticated shuffling scheme dedicated to maximize the power production efficiency. As a result of such maneuvers, BU across the fuel assembly will not be constant since it reflects the conditions within the reactor at the positions where the fuel assembly was situated.

In particular, those fuel assemblies, which during their life cycle occupy one of the positions on the outer edge of the reactor core, may end up with a significantly asymmetric BU. As will be presented in later sections of this paper, under certain conditions, the differences in concentrations of isotopes that are being consumed or created during irradiations (be it fissile ^{235}U, ^{239}Pu or strong neutron absorbing fission products such as ^{155}Gd) may vary even by tens of percent from side to side of the fuel assembly [7]. Therefore the primary objective of this work was to investigate, by means of simulations, how an asymmetric BU across a nuclear spent fuel assembly (SFA) influences the outcomes of an assay performed with a DDA instrument.

2. The Differential Die-Away technique

The DDA technique is an active nondestructive assay technique which uses a short (~10's–100's of μs) external neutron pulse from a neutron generator (NG) to deliver fast neutrons, which penetrate into the SFA where they start fission reaction chains that essentially assay the entire SFA. The neutrons from these induced fission reaction chains are detected using a set of neutron detectors surrounding the SFA, and their detection time distribution is analyzed to deduce information about its properties.

The typical distribution of times when neutrons are detected, following an interrogation pulse of 10 μs, peaks around 20 μs and then falls off approximately exponentially. The dominant part of the DDA signal in these very early time domains (<100 μs) consists, however, of “burst neutrons”, i.e. neutrons that do not cause any fission and reach the neutron detectors either straight from the neutron generator or with only minimal scattering. In absolute terms, the contribution of burst neutrons is almost independent of the characteristic parameters of the assayed SFA and can be subtracted as a constant background as shown in [2]. The remaining part of the DDA signal, in the form of the distribution of neutron detection times, peaks typically between 50 and 70 μs after the interrogation pulse, and then falls off with a die-away constant that is initially ruled by the characteristic parameters of the SFA but later by the overall multiplication of the system.

Die-away time is therefore one of the most significant parameters of the instrument's response. It has been traditionally defined as a neutron mean lifetime in a certain environment [8]. However, in our case of SFAs with a rather large multiplication, the die-away time reflects the mean lifetime of an entire neutron population that consists of multiple neutron generations which are simultaneously created and die away as rather long fission chains develop and progress through the instruments various materials. Should the interrogated item contain no fissile material, the injected neutron population will die away quickly reflected by fast decrease in neutron count rate registered by the detectors. If any fissile material is present inside the assayed item, the life of the neutron population is extended by birth of new neutron generations by induced fission, resulting in a slower decrease of observed neutron count rates, i.e. longer die-away time. In contrast to fissile isotopes, the isotopes with high cross sections for neutron absorption shorten the life time of the neutrons, thus shortening the die-away time and changing both the shape as well as the magnitude of the distribution of times when the neutrons are detected [5]. In case of the DDA instrument, the die-away time is thus an implicit indicator of the balance between the neutron-producing fissile material and neutron-absorbing fission products and actinides.

In traditional passive neutron counting based techniques the neutron population evolution in time can be approximated by a single exponential, with the decay constant being the die-away time [8]. In the case of DDA, the neutron population evolution is more complicated, since the neutron spatial as well as energy distribution undergoes dramatic changes on the way from the NG to the SFA and then out to the individual detectors. Therefore, since it cannot be approximated by a single exponential, when a detection time distribution is obtained, an analysis of the DDA signal is performed in limited time domains where such approximation can be justified. Our attention was primarily focused on the time domain of 100–200 μs, which in previous studies [2,5] has been identified as the most promising time domain to extract unique information about SFA multiplication, IE, and BU.

Apart from the die-away time determined (if possible) for each time domain, the overall number of neutrons detected within each particular time domain is called the DDA signal and is generally related to the absolute amount and type of fissile material in the SFA. An example of a modeled detection time distribution of neutrons detected by all individual detectors of the DDA instrument is illustrated in Fig. 1. A pressurized water reactor (PWR) SFA with 4% IE, 15 GWd/tU BU, and 5 years CT has been chosen to demonstrate differences between the detection time distributions of burst and fission neutrons, and their sum. In this particular case, a burst neutron distribution reaches its maximum shortly after the end of the interrogating neutron pulse (~20 μs) while the distribution of fission neutrons detection times peaks around 60 μs. The total DDA signal reaches its maximum and levels off at around 30 μs, and then decreases quasi-exponentially. While the fractions of detected burst and fission neutrons are about the same at ~40 μs, the fraction of detected fission neutrons increases to ~90% at ~120 μs and rises above 99% after ~220 μs since the beginning of the neutron interrogation pulse.

Another important quantity that is characteristic of each SFA and can be measured by the DDA technique is *multiplication* (*M*) [2]. When defined as the number of neutrons produced in the SFA and the surrounding setup per incoming neutron from the neutron generator, it is referred to as “active multiplication”. This is however linearly related to “passive multiplication” that is defined as the number of neutrons produced in the SFA per neutron originating inside the SFA, primarily in spontaneous fission. In general, the multiplication, be it passive or active, is closely related

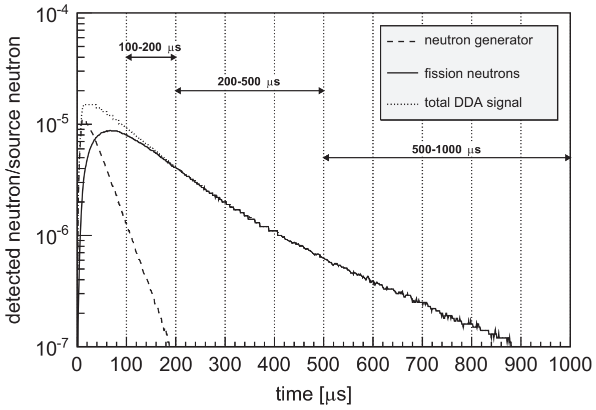

Fig. 1. Simulated distribution of neutron detection times as registered by all DDA detectors for a 4% IE, 15 GWd/tU BU, 5 y CT PWR SFA. The evolution of total neutron signal (dotted line), fission neutron signal (solid line) and burst neutron signal (dashed line) is shown 0–1000 μs after the start of the neutron interrogation pulse. Three different time windows (100–200 μs, 200–500 μs and 500–1000 μs) typically utilized in the analysis are also displayed.