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Passive gamma analysis of the boiling-water-reactor assemblies

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ABSTRACT

This research focused on the analysis of a set of stationary passive gamma measurements taken on the spent nuclear fuel assemblies from a boiling water reactor (BWR) using pulse height analysis data acquisition. The measurements were performed on 25 different BWR assemblies in 2014 at Sweden's Central Interim Storage Facility for Spent Nuclear Fuel (Clab). This study was performed as part of the Next Generation of Safeguards Initiative–Spent Fuel project to research the application of nondestructive assay (NDA) to spent fuel assemblies. The NGSI–SF team is working to achieve the following technical goals more easily and efficiently than in the past using nondestructive assay (NDA) measurements of spent fuel assemblies: (1) verify the initial enrichment, burnup, and cooling time of facility declaration; (2) detect the diversion or replacement of pins, (3) estimate the plutonium mass, (4) estimate the decay heat, and (5) determine the reactivity of spent fuel assemblies. The final objective of this project is to quantify the capability of several integrated NDA instruments to meet the aforementioned goals using the combined signatures of neutrons, gamma rays, and heat.

This report presents a selection of the measured data and summarizes an analysis of the results. Specifically, trends in the count rates measured for spectral lines from the following isotopes were analyzed as a function of the declared burnup and cooling time: ^{137}Cs, ^{154}Eu, ^{134}Cs, and to a lesser extent, ^{106}Ru and ^{144}Ce. From these measured count rates, predictive algorithms were developed to enable the estimation of the burnup and cooling time. Furthermore, these algorithms were benchmarked on a set of assemblies not included in the standard assemblies set used by this research team.

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1. Introduction

Through the Next Generation of Safeguards Initiative–Spent Fuel (NGSI-SF) project, research on the application of nondestructive assay (NDA) to spent fuel assemblies is underway at the Central Interim Storage Facility for Spent Nuclear Fuel (Clab) in Oskarshamn, Sweden [1–3]. The measurement campaign is a collaboration between the United States (US) Department of Energy (DOE); European Commission, DG Energy, Euratom Safeguards (EURATOM); the Swedish Nuclear Fuel and Waste Management Company (SKB); Uppsala University; and several US national laboratories and universities.

The research goals include (1) verifying that a given spent fuel assembly is the assembly that the facility has declared to the International Atomic Energy Agency (IAEA) or other regulators, which involves verifying the initial enrichment, burnup, and cooling time of each assembly; (2) verifying that the integrity of a spent fuel assembly is maintained by developing the capability to detect missing or replaced fuel pins; and (3) estimating the plutonium mass in an individual assembly. In addition, the interests of the Swedish facility and/or domestic regulations motivate the inclusion of the following goals: (4) rapidly estimating the heat content in each individual assembly and (5) measuring the reactivity of each assembly to ensure that all potential fuel configurations are safe in terms of heat and criticality.

The passive gamma measurements reported here are subsets of passive gamma measurements performed by our collaborative research team. Pulse height analysis was applied to spectral measurements made while the fuel was stationary, as reported in [4]. Also, analysis of spectra obtained while the fuel was scanned axially and rotationally in front of the collimator can be found in [5]. In this paper we report the analysis of the passive gamma

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spectrum obtained from SKB boiling water reactor (BWR) spent fuel assemblies. Of particular interest is the production of five main isotopes: ^{137}Cs ($T_{1/2}$=30.1 years), ^{154}Eu ($T_{1/2}$=8.6 years), ^{134}Cs ($T_{1/2}$=2.1 years), ^{106}Ru ($T_{1/2}$=1.0 year), and ^{144}Ce ($T_{1/2}$=0.78 years). This work builds on the analysis done by presenting algorithms for predicting the burnup and cooling time, as reported in [6]. This work is novel because it includes assemblies not part of the data set being used by all the other NDA techniques planned for deployment as part of this overall research project. Measurements at Clab for the NGSI-SF project are focused on 25 pressurized water reactor (PWR) and 25 boiling water reactor (BWR) assemblies (i.e., the SKB50). However, passive gamma measurements of BWR assemblies were performed for not only the primary 25 BWR assemblies being considered for the project but also for 5 others that were at Clab. The other 5 were originally planned to be part of the SKB50 but were ultimately excluded.

2. Background on measurements

Two different passive gamma measurement campaigns were performed for BWR assemblies at Clab: one during March 2014 and one in December 2014.

2.1. First measurement campaign

Seventeen BWR assemblies were measured in March 2014 [4]. One corner of each assembly was measured—a corner arbitrarily labeled as the 45° corner. All assemblies were measured with the fuel at rest at positions 92, 187, and 281 cm from the top of the fuel-containing part of the assembly along the axis. (The active part of the assembly is 368 cm long.) Assemblies BWR1, BWR8, and BWR9 also were measured at other positions from 5 cm to 366 cm along the active length of the assemblies. Table 1 shows the measured assemblies. Fig. 1 shows an example of the spectrum of BWR1 with the isotope names placed above the major peaks of the isotopes.

The numbering order of the assemblies looks odd because the five assemblies (BWR26–BWR30) were renumbered after they were measured. The characteristics of these five assemblies come from a different database than those of all other assemblies.

2.2. Second measurement campaign

In December 2014, 12 previously measured BWR assemblies and 13 new BWR assemblies were measured using a different detector system and filters. This time all four corners (with angles 45°, 135°, 225°, and 315°) of the assembly were measured. The axial location for these December 2014 measurements was 138 cm (±5 cm) down from the top of the fuel-containing part of the fuel assembly. Table 2 shows the measured assemblies.

For this work, we analyze the data of the December 2014 measurement campaign and from that obtain the relationships of the measured results to initial enrichment, burnup, and cooling time. The correlation results from that work are then applied to the spectra of the BWR assemblies measured in March 2014 to calculate the burnup, cooling time, and initial enrichment, to test the validity of the analysis technique.

3. Analysis results

The SKB BWR assemblies consist of a wide variety of fuel types, burnup, cooling time, initial enrichment, and irradiation histories. The first step taken was to sort the assemblies into groups to study them systematically. From our initial study, we found that the assemblies can be categorized into three families, consisting of different types:

- 10 × 10 type, which includes all four 10 × 10 types
- 8 × 8 types 1 and 2
- 8 × 8 type 5, which is significantly different than types 1 and 2

.

From the assemblies in each family, we then selected the ones that were burned continuously (i.e., burned for ~1 year, stopped for ~1 month for reactor refueling, and then burned again) for the initial study. Nine assemblies of the 10 × 10 type, five assemblies of the 8 × 8 types 1 and 2, and three assemblies of the 8 × 8 type 5 were burned continuously. We use the code Fixed-energy, Response function Analysis with Multiple efficiencies (FRAM) [7,8] to analyze the spectra to obtain the parameters used in the analysis: the rate of the 662-keV peak of ^{137}Cs and the ^{154}Eu/^{137}Cs, ^{134}Cs/^{137}Cs, ^{106}Rh/^{137}Cs, and ^{144}Ce/^{137}Cs mass ratios. The FRAM code was used and described in more details in Reference [6]. Each family of assembly types is analyzed separately in the following three sections.

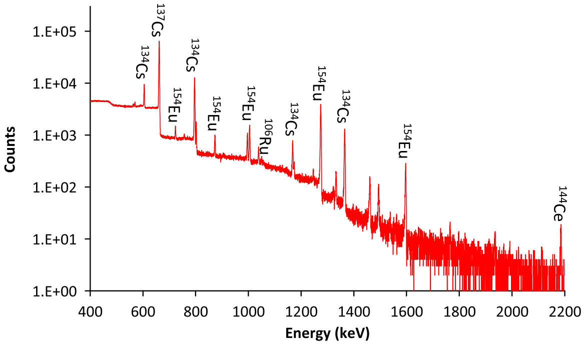

Fig. 1. Spectrum of BWR1. The isotope names are placed above the major peaks of the isotopes.

Table 1
Fuel characteristics for the BWR assemblies measured in March 2014.

Assembly	Assembly type	Initial enrich. (^{235}U%)	Burnup (GWd/tU)	Cooling time (y)	Assembly	Assembly type	Initial enrich. (^{235}U%)	Burnup (GWd/tU)	Cooling time (y)
BWR1	10 × 10 type 1	3.14	46.41	7.5	BWR10	10 × 10 type 1	3.14	39.50	7.5
BWR2	10 × 10 type 2	3.20	43.76	9.5	BWR29	8 × 8 type 5	3.08	38.77	10.6
BWR26	8 × 8 type 5	3.60	43.63	12.6	BWR12	10 × 10 type 4	2.96	33.51	8.7
BWR27	10 × 10 type 1	4.03	43.03	7.5	BWR13	10 × 10 type 4	2.96	36.83	8.7
BWR5	10 × 10 type 1	3.15	42.02	7.5	BWR30	10 × 10 type 2	3.09	31.92	13.5
BWR28	8 × 8 type 5	3.60	41.39	12.6	BWR20	10 × 10 type 4	2.97	26.43	8.7
BWR7	10 × 10 type 2	3.15	41.24	9.5	BWR22	10 × 10 type 4	2.97	20.41	8.7
BWR8	10 × 10 type 3	3.15	39.75	8.8	BWR23	10 × 10 type 4	2.97	15.99	8.7
BWR9	10 × 10 type 1	3.14	40.44	6.5					