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ScienceDirect

Energy Procedia 131 (2017) 250–257

Energy Procedia

www.elsevier.com/locate/procedia

5th International Symposium on Innovative Nuclear Energy Systems, INES-5, 31 October–2 November, 2016, Ookayama Campus, Tokyo Institute of Technology, JAPAN

A Simple Method to Create Gamma-ray-source Spectrum for Passive Gamma Technique

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Abstract

A simple but sufficiently accurate method for constructing a gamma-ray source for photon-transportation calculations is developed for canisters containing fuel debris from the Fukushima Daiichi nuclear power plant. The new method couples a baseline spectrum evaluated using the ORIGEN2 code with a line spectrum obtained from fission products (FPs) of interest. One of the advantages of the method is its ability to take bremsstrahlung X rays into consideration using the bremsstrahlung libraries of ORIGEN2. The new gamma-ray source is used to calculate the response of a high-purity germanium (HPGe) detector, and these results are compared with a benchmark test of experimental measurements of irradiated fuel pins. The shape of the simulated gamma-ray spectrum agrees well with that of the spectrum obtained by experiment. Moreover, bremsstrahlung X rays are confirmed to have little effect on spectrum shape formation because the baseline gamma-ray spectrum is mainly formed by Compton scattering of strong gamma rays from FPs such as Cs-137 and Eu-154. Gamma-ray source data are created for a debris composition recently evaluated at JAEA, and subsequent photon-transportation calculation is performed to evaluate the leakage gamma-ray spectra from a canister containing fuel debris for nuclear-material-accountancy purposes.

Keywords: Fukushima Daiichi Nuclear Power Station, fuel debris, passive gamma technique

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Peer-review under responsibility of the organizing committee of the 5th International Symposium on Innovative Nuclear Energy Systems.
10.1016/j.egypro.2017.09.446

1. Introduction

Severe loss-of-coolant accidents at the Fukushima Daiichi Nuclear Power Station (1F) produced fuel debris in the reactor cores of Units 1–3. Since then, JAEA's Integrated Support Center for Nuclear Nonproliferation and Nuclear Security has been promoting the development of passive gamma techniques, principally in collaboration with the Tokyo Institute of Technology. Some fission products (FPs) such as Ce and Eu seem to have very low volatility, even in high-temperature environments under severe accidents, and they are supposed to chemically coexist with fuel elements such as uranium and plutonium. Using our passive gamma technique, we first measure the gamma rays from such FPs and estimate their amount and burnup; then, we multiply the mass ratio of FPs and nuclear materials to obtain the mass of the nuclear material of interest. Feasibility studies have been performed based on experiences from Three Mile Island Unit 2 and using numerical [1-4] and material-science approaches [5]. Recently, the inventory of core materials in the 1F unit 1 was carefully estimated based on three-dimensional core-burnup and -depletion calculations with assumptions as reasonable as possible. Currently available "*best estimates*" are prepared by JAEA [6]to be utilized as fundamental data for further R&D of non-destructive-assay technologies for nuclear-material-accountancy purposes [7]. Gamma-ray-source data should be developed for the debris composition based on the inventory, and a subsequent photon-transportation calculation should be performed to evaluate leakage-gamma-ray spectra according to the fuel debris. However, the creation of a line-spectrum source is considerably time consuming.

In this paper, we develop a relatively simple but sufficiently accurate method for building up a gamma-ray source by coupling a baseline spectrum evaluated by the ORIGEN2 code [8] with several line spectra of interest. One of the advantages of this method is the capability of taking bremsstrahlung X rays into consideration utilizing the bremsstrahlung libraries of ORIGEN2. The new gamma-ray source is used to calculate the response of an HPGe detector, and the results are compared with a benchmark test of experimental measurement of irradiated fuel pins. After that, the gamma-ray-source data are developed for the debris composition based on "*best estimates*" using the new method, and a subsequent photon-transportation calculation is performed to evaluate the leakage-gamma-ray spectra from a canister containing fuel debris for nuclear-material-accountancy purposes.

2. Methodology

2.1. Coupling method

The gamma-ray spectra from spent fuels cooled for several years comprise line-spectrum and baseline parts, which can be seen, for example, in Fig. 2–6 of Sato et al. [9] and in Fig. 3 of Uetsuka et al. [10]. The part containing the line spectrum is generated by strong gamma emitters, such as Cs-134, Cs-137, Eu-154, and Co-60, even after several years of cooling [10], and the part containing the baseline is formed of the following components: Compton scattering from strong gamma-emitting FPs as mentioned above, gamma rays from FPs whose peaks are not visibly prominent, especially in a logarithmic graph, and a bremsstrahlung continuum. Sagara et al. have created source-photon data line-by-line to perform a characteristic study of gamma-ray emission from hypothetical fuel debris [2]. However, the creation process of the source-photon data is considerably time consuming because too many line spectra need to be considered.

The development process of the new method is relatively simple compared to the line-by-line creation of gamma-ray sources, but it is accurate enough for our purposes. In our source creation, the baseline spectra (divided into 18 energy groups) are evaluated with the ORIGEN2 code using a photon library without the FPs of interest. To build the line spectra of those FPs, we multiplied their activities by the gamma-ray intensities of each of their decays. Descriptions of the decay-gamma-ray energy and intensities can be obtained from the Evaluated Nuclear Structure Data Files available on the website for the National Nuclear Data Center [11]. Subsequently, both the 18-group baseline spectrum and the line spectrum were used as input data for the photon-transportation calculation performed using the MCNP5 code [12]. This new technique is hereafter called the *"coupling method."* A schematic view of the calculation flow of the coupling method is shown in Fig. 1. One of the advantages of this method is that it enables bremsstrahlung X rays to be taken into consideration using the bremsstrahlung libraries of the ORIGEN2 code.