Progress in Nuclear Energy 94 (2017) 46–54

Contents lists available at ScienceDirect

Progress in Nuclear Energy

journal homepage: www.elsevier.com/locate/pnucene

Examination of scintillator-photovoltaic cell-based spent fuel radiation energy conversion for electricity generation

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A R T I C L E I N F O

Article history:
Received 12 July 2016
Received in revised form
10 October 2016
Accepted 14 October 2016
Available online 21 October 2016

Keywords:
Spent fuel
Conversion of gamma radiation energy
Scintillation
Photovoltaic cell
Electric energy generation
Computational model-based analysis

A B S T R A C T

Using computational models, this research examined electricity generation from spent nuclear fuel and its possible uses. The proposed approach was based on converting gamma radiation energy into electricity using scintillators and photovoltaic cells. The work includes performing gamma radiation environment analysis around spent fuel, scintillated photon analysis, and photovoltaic cell analysis for electricity generation. The OrigenArp code was used for gamma radiation environment analysis and the MCNPX 2.7.0 code was used for analyzing scintillation process. For the scintillated photon analysis and photovoltaic cell analysis, a new simulation model was developed and validated based on comparison with experimental data. The effect of self-absorption and radiation damage within the scintillator was described by using experimental data. Based on using 14 energy conversion system units in a spent fuel storage pool in a PWR with $CdWO_4$ as scintillator and SiO2 as photovoltaic cell, generation of electric energy was estimated to range between a few hundred watts and a few watts depending on the cooling time. The estimated amount of electric power generation from spent fuel energy conversion was not enough for large scale applications. But the converted electric power could be utilized as emergency power source in an operating nuclear power plant for various detection and monitoring purposes and for the support of spent fuel pool cooling pump operations.

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1. Introduction

Used nuclear fuel, typically called “spent fuel”, becomes a major source of concern once it is removed from nuclear reactors. Due to the presence of fission products and actinides, used fuels retain intense levels of radiation and at the same time valuable materials for recycling for civilian or military purposes. Whether they are disposed of permanently or treated for recycling, spent nuclear fuel is controlled under the strictest nuclear security requirements and requires very specific handling. During the wet or dry storage periods at a nuclear power plant, spent nuclear fuels are a liability with no useful purpose.

Researchers investigated a number of alternatives for utilizing spent fuel radiation for useful purposes. One promising example converts the radiation from spent fuel into electric energy. This energy conversion approach (Pfann and Roosbroeck, 1954; Flicker et al., 1964; Rowe, 1978; Horiuchi et al., 2005; White et al., 2005; Lee and Yim, 2016) can be performed in two ways, i.e., the thermoelectric method and the radiation voltaic method. The thermoelectric method generates electricity using the electron density difference in a metal plate, caused by temperature differences (Rowe, 1978). Unfortunately the thermoelectric method is not suitable to convert radiation into electricity, because the temperature in a spent fuel storage system is controlled within a narrow range. However, the radiation voltaic method produces electricity by generating electron hole pairs inside a semiconductor material. The radiation voltaic approach can be classified into alphavoltaic, betavoltaic and gammavoltaic methods, depending on the radiation particle used. The alphavoltaic and betavoltaic methods (Pfann and Roosbroeck, 1954; Flicker et al., 1964; Kirkpatrick, 1965) use charged particles and are known to have a much higher efficiency than the gammavoltaic method which uses photons. The alpha and betavoltaic methods are not applicable for spent fuel applications, as alpha and beta particles cannot penetrate the physical barriers of spent fuel (e.g., cladding, fuel assembly structure, rack, etc.). In the 1990s, the efficiency of the gammavoltaic method was improved by combining a semiconductor with a scintillator material (Horiuchi et al., 1997). In the 2000s a similar approach was suggested using an electric power source for spent

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http://dx.doi.org/10.1016/j.pnucene.2016.10.004
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fuel transportation monitoring or as a radiation battery (Horiuchi et al., 2005; White et al., 2005). Our previous study (Lee and Yim, 2016) also explored the use of gammavoltaic method for electricity generation using spent fuel. The study investigated the use of a single unit energy conversion system with CsI(Tl) scintillator and a-Si photovoltaic cell. We assumed complete transparency and no radiation damage to the scintillator material. Through the use of computational models, the study investigated the amount of electricity that could be generated and its potential uses.

This research is an extension of the previous study. It examines electricity generation in a spent fuel storage pool at a nuclear reactor through the use of computational models. The models used to quantify the electric energy generation from radiation energy conversion were validated using experimental data. Limitations of the previous study were addressed by adding another candidate scintillator material, CdWO4, to compare the performance with the original CsI(Tl) scintillator; (2) analyzing the self-absorption effect on scintillator performance; (3) analyzing the effect of radiation on scintillator performance degradation; and (4) determining the number of energy conversion units needed in a spent fuel storage pool to generate sufficient electricity. Finally, potential applications of the electricity generated from spent fuel radiation energy conversion were also examined, along with the feasibility of implementing each application.

2. Analysis of electricity generation inside a spent fuel storage pool

2.1. Methods for electricity conversion using scintillator with photovoltaic cell

A “test case” using the energy conversion units developed in our previous study (Lee and Yim, 2016) analyzed the electricity generation inside a spent fuel storage pool in a nuclear power plant. The test case is defined by the following assumptions:

1. The capacity of a single spent fuel storage pool is 32 × 36 fuel assemblies.
2. Thermal power during nuclear power plant (NPP) operation is constant at 3,400 MW.
3. The spent fuel design is 3.5w/o enriched Westinghouse advanced 16 × 16 fuel assemblies. The fuel cycle consists of two 18 month irradiation periods and 50 day overhaul period between each period. A half of the fuel assemblies are replaced during a refueling outage. Spent fuel assemblies are stored in the storage pool 100 days after shutdown. Spent fuel assemblies disposed to a spent fuel pool right after 100 days storage are defined to be a “fresh spent fuel assembly”.
4. The unit electricity conversion system is surrounded by eight fresh spent fuel assemblies for 18 months. Fresh spent fuel assemblies are replaced every 18 months to maximize the electricity generation.
5. Non-fresh spent fuel assemblies were assumed to have a 10 year storage period.

Fig. 1a) and b) are schematic depictions of the energy conversion unit inside a spent fuel pool, surrounded by spent fuel assemblies. The design of the energy conversion unit can be summarized as follows.

1. A unit energy conversion system consists of 720 unit slices as described in Fig. 1b). The thickness of a system slice is 4.1 mm and the gap between two slices is 0.9 mm.
2. The size of a system slice is 205.7 × 205.7 × 4.1 mm. It consists of photovoltaic cell (205.7 × 205.7 × 1mm), scintillator plate (205.7 × 205.7 × 3mm), and Al reflector (205.7 × 205.7 × 0.1 mm). Al reflector guides scintillated photons entering photovoltaic cell. Compared to the previous study, the thickness of the scintillator was changed from 1 mm to 3 mm based on the results of a sensitivity study.
3. CsI(Tl) and $CdWO_4$ were selected as a candidate scintillator material. CsI(Tl) is a scintillator with high photon emission yield but with low radiation resistance. $CdWO_4$ is a scintillator with low photon yield and high radiation resistance.
4. Amorphous silicon (a-Si) photovoltaic cell was used because of its high radiation resistance, low price, and appropriateness of the bandgap energy. The bandgap energy of a-Si photovoltaic cell is 730 nm and the spectral sensitive wavelength region of the material which corresponds to high efficiency wavelength region is 400–700 nm (Jha, 2009). The maximum emission wavelengths of CsI(Tl) and CdWO4 are 540 nm and 475 nm respectively, which fall to the high efficiency wavelength range in the a-Si photovoltaic cell (as depicted in the spectral response of the a-Si photovoltaic cell in Fig. 4). Therefore, CsI(Tl) and CdWO4 are considered to be a good scintillator for the given photovoltaic cell.

Six different spent fuel storage pool configurations with different numbers of energy conversion units were used in this study to calculate the amount of electricity generated inside a spent fuel storage pool. The six configurations were 2, 4, 6, 9, 12, and 14 energy conversion system units installed in a 32 × 36 spent fuel storage pool. Thus the study examined the changes in electricity generation as the number of energy conversion units increased inside the pool. Fig. 2 shows the distribution of energy conversion system units in a spent fuel storage pool for each of the configurations. The red and blue areas in Fig. 2 indicate the locations of the energy conversion system units and spent fuel assemblies respectively.

To determine the amount of generated electricity the following analysis (Lee and Yim, 2016) were preformed: gamma radiation environment analysis, scintillated photon analysis, and photovoltaic cell analysis. Additional information on the specifics of these calculations are described below.

The gamma radiation environment of spent fuel assemblies was calculated using the OrigenArp code (Oak Ridge National Laboratory (ORNL), 2010). The gamma radiation from spent fuel is the source of energy being converted to electricity since the contribution from neutrons were found to be negligible (Lee and Yim, 2016). The intensity and wavelength distribution of the scintillated photons were calculated by using the MCNPX 2.7.0 code (Los Alamos National Laboratory (LANL), 2011). The published results of scintillator characteristics in the literature (Aslam et al., 2015) were also used in the analysis. To quantify electricity generation after the scintillator photons interact with the photovoltaic cell, basic photovoltaic cell equations, as described in the literature (Sinton and Cuevas, 1996), were used.

2.2. Electricity generation analysis in a spent fuel storage pool

Fig. 3 describes the energy distribution of gamma radiation per one spent fuel assembly over spent fuel storage time. As shown in the figure, the changes in the gamma activity of one spent fuel storage assembly does not change significantly between 0 and 18 months of storage. But the drop in the activity is evident when the storage period increases to 10 years.

The number of scintillated photons was calculated as the product of the scintillation yield of the scintillator material as a function of energy and the energy deposited by charged particle in a scintillator (Pozzi et al., 2004). Fig. 4a) and b) show the results of

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