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Examination of spent fuel radiation energy conversion for electricity generation

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HIGHLIGHTS

- Utilizing conversion of radiation energy of spent fuel to electric energy.
- MCNPX modeling and experiment were used to estimate energy conversion.
- The converted energy may be useful for nuclear security applications.
- The converted energy may be utilized for safety applications through energy storage.

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ABSTRACT

Supply of electricity inside nuclear power plant is one of the most important considerations for nuclear safety and security. In this study, generation of electric energy by converting radiation energy of spent nuclear fuel was investigated. Computational modeling work by using MCNPX 2.7.0 code along with experiment was performed to estimate the amount of electric energy generation. The calculation using the developed modeling work was validated through comparison with an integrated experiment. The amount of electric energy generation based on a conceptual design of an energy conversion module was estimated to be low. But the amount may be useful for nuclear security applications. An alternative way of utilizing the produced electric energy could be considered for nuclear safety application through energy storage. Further studies are needed to improve the efficiency of the proposed energy conversion concept and to examine the issue of radiation damage and economic feasibility.

Purpose of the research

- To characterize the amount of electric energy that can be generated from spent nuclear fuel by way of converting gamma and neutron energy into electricity.
- To perform computational modeling work to estimate the amount of electric energy through spent fuel energy conversion.
- To examine the use of the generated electric energy.

Approaches

- Characterization of radiation field of spent fuel.
- Modeling of modulated energy conversion by using MCNPX and an empirical polynomial.
- PV cell output analysis by using experiment.
- To perform an integrated experiment to validate the computational modeling work.
- To estimate the amount of electric energy generation from spent fuels based on a conceptual design of an energy conversion module.

1. Introduction

Supply of electric power to nuclear power plant under all circumstances is one of the most important considerations for nuclear safety and security. This has been clearly illustrated by the Fukushima accidents where loss of electric power led to devastating reactor core damage and environmental releases. With increasing demand for enhanced security for nuclear materials in nuclear power plants amid terrorism concerns worldwide, long-term stable supply of electric power may also enable implementation of new security measures beyond the current capabilities. With regards to this consideration, developing innovative ways of supplying

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electricity in nuclear power plant should be examined beyond the existing means.

Although radiation is widely available in nuclear power plant from many sources, utilization of radiation energy for electric power generation has not been utilized. If conversion of radiation energy to electric energy can be realized, it may open new opportunities. Several researchers have shown that converting radiation energy into electricity is possible. Rosenzweig (1962) suggested electric current generation inside semiconductor materials using external radiation. Scharf (1960) showed the feasibility of direct electric conversion of radiation energy by using photovoltaic cells (Muller et al., 1964; Musilek and Fowles, 1982).

Horiuchi et al. (1997) studied conversion of radiation energy from spent nuclear fuel to electric energy. This study applied inorganic scintillators to amorphous and crystalline photovoltaic cells to improve the efficiency of energy conversion and concluded that spent fuel can be utilized as a source of electric power generation (Horiuchi et al., 2005). Researchers at University of Massachusetts Lowell also studied radiation to electric energy conversion by using gamma emitting isotope. They showed that a self-powered spent nuclear fuel cask management system could be developed by using the energy conversion. Gadolinium oxide scintillator and dye sensitized solar cell were used in the system (White et al., 2005).

This study builds on these previous findings. Feasibility of using spent nuclear fuel as a source of electric energy in a nuclear power plant was examined in the study. The main goal of the study was to characterize the amount of electric energy that can be generated from spent nuclear fuel by way of converting gamma and neutron energy into electricity. To support the study a preliminary design of an electric energy conversion module was developed and computational modeling work was performed along with experiment to assess electric energy generation. An integrated experiment of radiation energy conversion to electricity was also performed to validate the computational modeling approach. Results of the assessment were discussed in terms of how the generated electric energy could be utilized.

2. Characterization of radiation field of spent fuel

To examine radiation to electric energy conversion by using spent fuel, a typical type of spent fuel was selected in the study. The spent fuel was assumed to be 3.5 w/o enriched Westinghouse advanced 16 × 16 fuel assembly. It was also assumed to have burnt for 19.21 MWth per assembly (3400 MWth/177 assemblies) which is the same with Korea's Shin Kori2 nuclear power plant. It was further assumed that the spent fuels were stored for 500 days after removal from the core and before use as a radiation source for electric energy generation. The 500 day time period was selected to reduce the radiation damage to the electric energy conversion system used in this experiment. The fuel rods were assumed to have burnt for 3 fuel loading cycles, with 18 months irradiation periods. Also 50 days of overhaul period was assumed in between the cycles. Spent fuel assemblies located next to an electric energy conversion system have to be 'fresh' to maximize generated electricity. This study defined fresh spent fuel as fuel stored less than 10 years.

The OrigenArp code was used to calculate the gamma radiation and neutron field of the spent nuclear fuel assembly (ORNL, 2010). As the number of fission products was too large to be counted individually, gamma radiation was classified by the energy. Neutrons were also classified by the energy. Gamma radiation energy was grouped by the 47GrpSCALE6 group structure and neutron energy was grouped by the 44GrpENDF5 structure. Fig. 1(a) and (b) shows the results, as energy distribution of gamma and neutron activity per fuel assembly as a function of storage time, respectively. The result indicates that the most abundant energy of the gamma radiation is below 2 MeV and the gamma activity steadily decreases as the storage time increases. In the case of neutron, most of the neutrons released by the spent fuel is at about 1 MeV. The activity of gamma radiation was at the level of 10^{15}–10^{16} Bq per fuel assembly. The activity of the neutrons, in contrast, was in the order of 10^8 Bq indicating that the activity of spent fuel is dominated by the gamma rays.

3. Conversion of radiation energy to visible lights

Radiation energy from spent nuclear fuel can be converted into the electric energy via either direct energy conversion or energy modulation. Direct conversion is through exposing photovoltaic cells to radiation. Energy modulation is through the use of scintillator material and includes two steps: (1) Converting the energy of gamma radiation and neutron into long-wavelength photons through the scintillation process, and; (2) Passing the long-wavelength photons through amorphous silicon photovoltaic cell (a-Si PVcell) to generate electricity. The first step, i.e., the scintillation process, can further be divided into electron–hole pair production, energy migration to luminescence center, and light emission.

The electron–hole pair production process converts the incoming radiation into a number of (primary or secondary) electron–hole pairs through ionization. The process of energy migration to luminescence center occurs as the secondary pairs diffuse to the luminescence center if the position of pair generation and luminescence center is different. The light emission process produces long-wavelength photons from the recombination of the secondary pairs bound to the luminescence center. The excited secondary pair releases its energy by photon emission (Bizarri, 2010).

There are a number of materials that can work as scintillator as long as the material, when struck by an ionizing radiation, absorbed energy and re-emits the absorbed energy in the form of light (Knoll, 2011). The requirements for the scintillator material in this study were long output wavelength, high output light yield, high radiation resistance, low price, and high temperature resistance. The scintillator that produces long wavelength photons was desirable because the incident photon energy should closely match the bandgap energy of the photovoltaic cell (typically in the order of few eV). The candidate material for photovoltaic cell in this research is a-Si type whose bandgap energy is 1.1 eV. The scintillator with high output light yield was suitable as it directly translates to higher energy conversion efficiency inside the scintillator. Radiation resistance is important as the scintillator material has to survive the high radiation dose near spent fuel. Low price of the material is desirable for economic feasibility. High temperature resistance may be required for application in dry spent fuel storage. In this regard, use of the organic or plastic scintillator is eliminated due to the radiation (and high temperature) resistance concern. Among the inorganic scintillators, ceramic scintillators may be most appropriate due to the same concern. Some crystalline scintillators may have an issue with the build-up of optical defects under irradiation. At the same time, the light output yield characteristic is the highest among the crystalline scintillators compared to the ceramic scintillators.

As this study is focused on demonstrating the proposed concept, a scintillator material with high output yield characteristic and a reasonable price was chosen. Table 1 shows the properties of some candidate scintillation material, NaI(Tl), CsI(Tl), or $CdWO_4$, as an inorganic compound with high yield characteristic of relatively long-wavelength photons. To maximize the benefit of concept demonstration, CsI(Tl) with high output photon yield, and a long output wavelength was chosen in this study.