Examination of the Properties of a Spent Fuel based Electricity Generation System – Scintillator Performance Analysis

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1. Introduction

Studies on the generation of electricity using radiation were performed by a number of research groups. In the early period, alphavoltaic and betavoltaic were the main targets of interest rather than gammavoltaic because of their high efficiency. However, gammavoltaic is a more feasible technology compared to alpha and betavoltaic in the spent fuel environment, as a radiation source. Spent fuel is protected by several physical barriers (i.e. cladding, fuel assembly structure, cask…), for this reason charged particles generated by spent fuel cannot penetrate these barriers.

Gammavoltaic was proposed by Karl Scharf in 1960 [1]. The low efficiency resulted in gammavoltaic being used as a radiation detector [2]. In the 1990s the efficiency of gammavoltaic increased by the use of a scintillator [3]. Gammavoltaic was further studied as a power source for spent fuel transportation and a nuclear battery in the 2000s [4, 5].

Haneol Lee and Man-Sung Yim also suggested electricity generation system based on spent fuel stored inside the fuel pool of a nuclear power plant [6]. This study proposed the systematic design of an electricity conversion system using CsI(Tl) scintillator and a-Si photovoltaic cell. As such, this study is selected to be a reference paper. It also calculated the amount of generated electricity using a computational model. The principle of generating electricity in this paper is described below;

- Incident radiation (gamma) is converted into visible photons via a scintillator
- Converted photons generate electricity using a photovoltaic cell

The paper calculated generated electricity based on ideal case assumptions. This caused two main limitations on the scintillator analysis in this paper. The first one is the self-absorption effect inside scintillator material and the second one is scintillator degradation due to irradiation. Including these two effects will provide a more realistic value of generated electricity, for inclusion in future work.

2. Methods and Results

The self-absorption inside a scintillator occurs because the scintillator material is not perfectly transparent. This effect was analyzed using transparency adjustment equation. The scintillator degradation due to irradiation was analyzed using an experimental setup.

2.1 Self-Absorption inside a Scintillator

Self-absorption inside a scintillator was applied using the scintillator adjustment equation. The definition of scintillator transparency is described in Figure 1 (T). The amount of generated electricity has a linear relationship to the thickness of a scintillator if the material is perfectly transparent. This effect can be characterized by the absorption coefficient of the material. The absorption coefficient of a material is calculated using equation (1). The values of the parameters used in equation (1) are from the experimental result reported in a reference paper [7].

$$a(\lambda) = \frac{1}{d}\ln\left(\frac{1}{T(\lambda)}\right) \quad (1)$$

where,
a absorption coefficient (cm^{-1})
d material thickness (cm)
T transmittance of material
λ entering photon wavelength (nm).

The transparency adjustment equation of the scintillator was derived based on the following assumptions and scenario;

- Photons are generated uniformly inside the scintillator
- Scintillated photons follow a one-dimensional model. Scintillated photons can be emitted in an upper and lower direction with the same yield
- Gamma photons penetrate the reflector (Figure 1) while visible photons are reflected by the reflector
- The radiation source is located at the top of the scintillator (Figure 1)

Based on the schematic design of the scintillator and equation 1, the scintillator adjustment equation (equation 2) was derived. Photon generation inside a scintillator slice is described as $I_o \frac{dt}{d}$. Scintillator transmittance can be calculated by integrating the transparency of a scintillator slice. The transparency adjustment equation is described in equation (2).

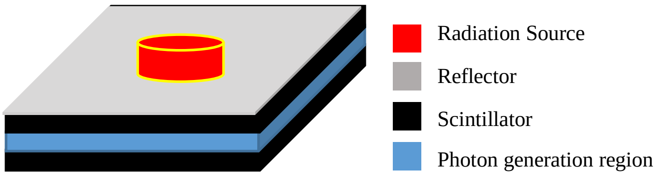

Fig. 1. Overview design of transparency adjustment analysis;

I_o	photon generated inside a scintillator
I	photon emitted outside of a scintillator
d	total scintillator thickness(cm)
dt	photon generation region thickness
t	distance to the photon generation region
T	Scintillator transmittance (I/Io)

$$T(\lambda, d) = \frac{exp(-\alpha(\lambda)d)}{2\alpha(\lambda)d}[1 - exp(-2\alpha(\lambda)d)] \quad (2)$$

where,

a	absorption coefficient (cm^{-1})
d	scintillator thickness (cm)
T	transmittance of scintillator
λ	wavelength of scintillated photon (nm).

The transparency adjustment equation is applied to the CsI(Tl) scintillator used by the computational model in the reference research [6]. The result for 1mm CsI(Tl) scintillator is described in Figure 2. Figure 2 indicates the CsI(Tl) scintillator used in the computational model can be said to be almost perfectly transparent (0.95~0.99) for CsI(Tl) output light yield region.

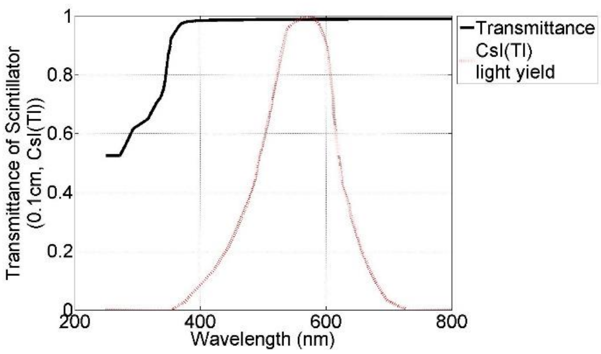

Fig. 2. Transparency of 1mm thickness CsI(Tl) scintillator using the transparency adjustment equation

2.2 Scintillator Irradiation Experiment

The objective of this research is to apply this electricity generation system in the spent fuel environment. The performance of scintillator material, in a severe radiation environment must be validated. However, it is almost impossible to perform an experiment with spent fuel. Cs-137, whose activity is 8.51GBq was used to demonstrate the irradiation effect on a scintillator.

Dose rate to target was calculated using the MCNPX code. The value was 27kGy/month (10.4mGy/sec). The sample was irradiated for 3 months. The scintillator degradation was measured for three cases; one month, two months, and three months.

The scintillator used in the experiment was CsI(Tl) and the size was 20x20x1mm. The degradation of the scintillator was measured by comparing the generated current of a non-irradiated scintillator and an irradiated scintillator. The method to calculate the degradation is described in equation (3).

$$\text{Deg.} = (I_{non-irr} - I_{irr})/I_{non-irr} \quad (3)$$

where,

Deg.	scintillator degradation caused by radiation
$I_{non-irr}$	generated current using non-irradiated scintillator
I_{irr}	generated current using irradiated scintillator

Figure 3 describes the results. Each data point in the figure is the averaged value of 450 data points in the experiment. The figure indicates CsI(Tl) is degraded after being irradiated over a few 10kGy gamma-ray. Dose rate in the spent fuel environment is much higher than 10kGy (MGy scale). It indicates system scintillator have to be shielded or the scintillator have to be replaced into more radiation resistance scintillator.

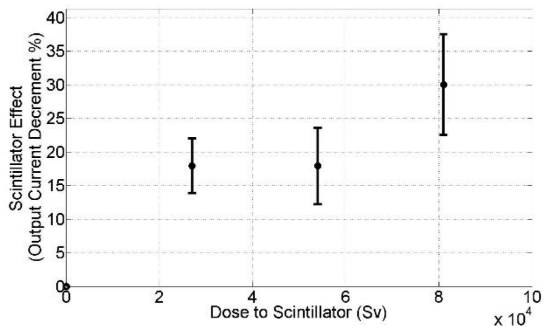

Fig. 3. Results of scintillator irradiation experiment

3. Conclusions

The analysis of the scintillator used in the 'electricity generation system using gamma radiation from spent fuel' was performed to evaluate the ideal electricity generation in the reference research [6].

The results of this paper indicate a self-absorption effect from the reference model. This effect is negligible while the irradiation degradation has to be considered. Two main ways to reduce radiation induced degradation are scintillator shielding and replacing scintillator material with a material having higher radiation resistance.

Further studies on radiation caused scintillator degradation will be performed. An irradiation experiment with high flux neutron having equivalent displacement per atom (DPA) will be performed in the high dose environment. $CdWO_4$ which is a scintillator with higher radiation resistance will also be examined.

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