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Investigation of Electricity Generation by Using Gamma Radiation from Spent Fuels

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1. Introduction

Supply of electric power to nuclear power plant under all circumstances is one of the most important requirements for nuclear safety and security as clearly illustrated by the Fukushima accidents. With regards to this consideration, developing innovative ways of supplying electricity in nuclear power plant should be examined beyond the existing means.

Several researchers have shown that converting radiation energy into electric energy is possible. Karl Scharf studied the direct electric conversion of radiation energy by using photovoltaic cells [1]. Researchers in University of Massachusetts Lowell have studied radiation-electric energy conversion by using gadolinium oxide scintillator and dye sensitized solar cell (DSSCs) [2] and N. Horuichi et al. studied radiation-electric energy conversion by using inorganic scintillators and amorphous and crystal photovoltaic cells [3].

This study builds on these previous studies and proposes to use spent nuclear fuel as a source of electric energy. Spent fuels are always present in an operating nuclear power plant in the storage pools or throughout various stages of nuclear waste management. Due to the intense levels of radiation emitted, spent fuel management is always focused on prevention of harms. But if the radiation energy from spent fuels can be utilized for beneficial purposes, its management can open up new opportunities.

The purpose of this research is to demonstrate the conversion of radiation energy from spent fuel to electric energy and examine ways to utilize the generated electric energy to enhance nuclear safety and security. In the present study, only the gamma radiation was examined for the investigation of energy conversion.

2. Methods and Results

2.1 Methods of Radiation Energy Conversion to Electric Energy

The gamma radiation from spent nuclear fuel was converted into the electric energy by following two steps in this study. The first step was modulating gamma radiation into visible light with NaI(Tl) scintillator. The second step was generating electric energy by applying amorphous silicon photovoltaic cell (a-Si PVcell) to the visible light.

Generated current and voltage by photovoltaic cell is calculated by the equation (1) and (2) [4].

$$J = J_D\left[exp\left(\frac{qV_a}{kT}\right) - 1\right] - J_{ph} \quad (1)$$

$$J_D = qn_i^2\left[\frac{D_n}{N_a L_n} + \frac{D_p}{N_d L_p}\right], \quad J_{ph} = qGW, \quad \text{and} \quad G = aI(1-R)\,exp(-ad)$$

$$V = \left(\frac{kT}{q}\right)\ln\left(\frac{J_{ph}}{J_D} + 1\right) \quad (2)$$

Where,

V_a	Applied voltage,
q	Boltzmann constant,
T	Temperature,
n_i	Intrinsic carrier concentration,
$D_{n,p}$	Diffusion coefficient for n, p region,
$N_{a,d}$	Doping concentration for n, p region,
$L_{n,p}$	Diffusion length for n, p region,
W	Space charge region length,
a	Absorption coefficient [5],
I	Photon intensity
R	Reflectivity [5]
d	Cell depth

2.2 Modeling of Radiation Energy Conversion to Electric Energy

Given the difficulty in performing experiment with spent nuclear fuel, modeling-based analysis was performed in this research to examine the feasibility of the proposed approach. The model includes the description of an energy conversion system and spent nuclear fuel inside wet storage. The overview of the energy conversion system is described in Figure 2. Each unit of the system (205.7x205.7x2mm) included single scintillator plate (205.7x205.7x1mm) and photovoltaic cell (205.7x205.7x1mm). A single energy conversion system consisted of 720 system units which are 5mm apart due to the gap between each unit.

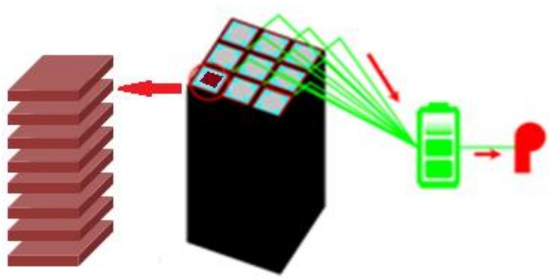

Fig. 2. System overview: energy conversion system unit, spent fuel storage pool, 2nd battery, and power output

2.2,1 Modeling of Gamma Radiation Field from Spent Nuclear Fuel

The spent nuclear fuels analyzed in this study were assumed to be relatively "fresh spent fuel" with less than 10 years of storage period. It was also assumed that each electric power generation system is surrounded by eight spent fel assemblies. The system surrounded by assemblies was named as the "duncker type" [6]. The spent fuel was 3.5w/o enriched Westinghouse advanced 16x16 fuel assembly. It had burnt for 19.21MWth per assembly (3400MWth/177assemblies) which is the same with Shin Kori2 nuclear power plant. Spent fuel was stored 500 days after shutdown. The fuel were burnt under the fuel cycle which has burnt for 3 periods with 18 months and has cooled for 2 periods with 50 days.

OrigenArp code was used to calculate the gamma radiation field of the spent nuclear fuel assembly [7]. Gamma radiation was not classified by fission product isotopes but classified by the energy range because the number of fission product was too many to be described individually.

2.2.2 Modeling of Gamma Energy Conversion to Visible Photon

Gamma radiation generated by spent nuclear fuel was converted into visible photon via scintillator. The energy modulation process inside scintillator was analyzed by the Monte Carlo N-Partcle Extended (MCNPX) code [8] which uses the Monte Carlo method. Asterisk pulse height tally (*f8 tally) was used to calculate the energy deposition [9].

The calculated energy deposition was converted into the visible photon by the light yield scintillator [10]. Nonproportionality for low energy particle deposition was reported for the NaI(Tl) scintillator [11] but conservative value (38,000 photons/MeV) was used in this study because MCNPX calculates not the energy deposition of an individual particle but the normalized energy deposition. The generated visible photon flux was distributed by the wavelength distribution of the NaI(Tl) scintillator [12].

2.2.3 Modeling Conversion of Visible photon to Electric Energy

The generated visible photon flux distribution became the source of the photovoltaic cell. Amorphous silicon photovoltaic cell was analyzed based on both experimental and modeling approach.

Photovoltaic cell experiment was performed to estimate the unknown parameters of the photovoltaic cell: doping concentration related parameter, bandgap width.

The equation (3) and (4), which are modified equations based on the equation (1) and (2), indicate unknown parameters: A, B, C, and D. These equations below indicate photovoltaic cell – wavelength response.

$$J_{ph}(I,\lambda) = I \cdot f(\lambda) \cdot (a(\lambda) \cdot A \cdot (1 - R(\lambda))) \cdot e^{-a(\lambda) \cdot B} \quad (3)$$

$$V_{OC}(I,\lambda) = C \cdot \log\left(\frac{J_{SC}(I,\lambda)}{D} + 1\right) \quad (4)$$

Where,

A~D Unknown parameters

Electric energy generation was modeled to calculate the unknown parameters by using the experiment result and calculated electric current and voltage of the energy conversion system.

The unknown parameters were estimated by the least square method (LSM). Electric current, voltage, and energy generation was calculated by applying photovoltaic cell – wavelength response to the wavelength distribution.

2.2.4 Design of Energy Conversion System

The generated current was stored to the secondary battery because it was estimated to be too small to be used directly. The secondary battery was supposed to supply electric energy under the severe accident situation or unexpected external invasion occurs. It was able to cope with existing safety system or operate security related system based on the scale of generated electric energy.

2.3 Performance of the Energy Conversion System

Results of the experiment and modeling were described below: gamma radiation field, visible photon conversion, electric energy conversion, and system design.

2.3.1. Result of Gamma Radiation Field from Spent Nuclear Fuel

Gamma radiation activity per fuel assembly as a function of time calculated by OrigenArp code is described in figure 3. Gamma radiation activity was classified by 47 energy groups. The activity decreased as storage time increases as expected.

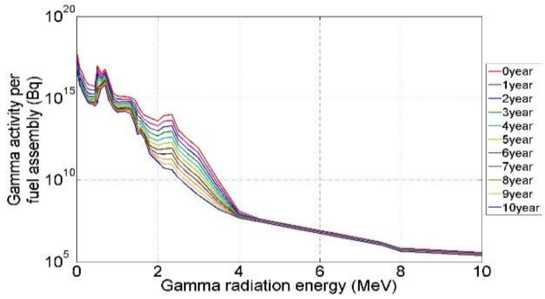

Fig. 3. Energy distribution of gamma radiation activity per spent fuel assembly as a function of time

2.3.2. Result of Visible Photon Generation from Gamma Radiation

MCNPX code calculated average energy deposition per each source photon (MeV/photon). Average energy deposition rate for one system unit (MeV/sec), which includes one electric energy generation system and 8 spent fuel assemblies, was calculated by applying energy distribution of gamma radiation to energy deposition per source gamma photon. Visible photon generation rate inside scintillator (#/sec) was calculated by applying scintillation yield to the energy deposition. Calculated values are described in the table 1.

Table 1. Scintillator analysis per system unit

Storage time (year)	Avg. E dep. per photon (MeV/gamma)	Avg. E dep. rate per system (MeV/sec)	Visible photon generation rate per system (#/sec)
0	8.9795E-05	1.3502E+15	5.1308E+19
1	1.0471E-04	8.7258E+14	3.3158E+19
2	1.1841E-04	6.1070E+14	2.3207E+19
3	1.2287E-04	4.4015E+14	1.6726E+19
4	1.1894E-04	3.2855E+14	1.2485E+19
5	1.0936E-04	2.5259E+14	9.5984E+18
6	9.7518E-05	1.9904E+14	7.5635E+18
7	8.5494E-05	1.5972E+14	6.0694E+18
8	7.4742E-05	1.3060E+14	4.9628E+18
9	6.5604E-05	1.0870E+14	4.1306E+18
10	5.7786E-05	9.1560E+13	3.4793E+18

The generated photons were distributed by scintillator output light yield function, f(λ). The function which was fitted by digitizer is shown in figure 4.

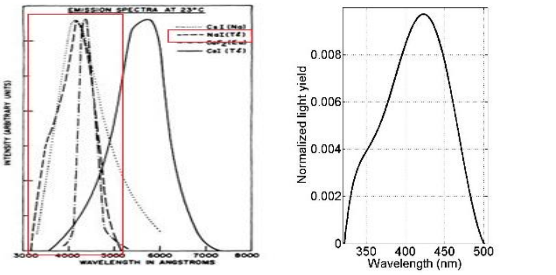

Fig. 4. Scintillated output light yield of reference paper [13] and fitted curve

2.3.3. Result of Electric Energy Conversion

Experiment results are described in the table 2-a) and 2-b). Average, 10 percentile, 90 percentile values of the generated current and voltage are described.

Table 2-a). Average, 10 percentile, and 90 percentile of the generated current

Wavelength	Generated current (A)		
	405nm	450nm	532nm
10%	3.579E-4	4.997E-4	1.0518E-3
Average	4.497E-4	6.211E-4	1.309E-3
90%	5.639E-4	7.276E-4	1.546E-3

Table 2-b). Average, 10 percentile, and 90 percentile of the generated voltage

Wavelength	Generated current (V)		
	405nm	450nm	532nm
10%	2.7844	3.1934	3.6090
Average	2.9886	3.3613	4.1019
90%	3.2608	3.6112	4.4641

By applying the LSM, unknown parameters are calculated in table 3. Comparison between the current experiment datapoints and calculated current is provided in the figure 5-a). Comparison between the voltage experiment datapoints and calculated voltage is provided in the figure 5-b).

Table 3. Unknown parameters

A	1.8629E-25
B	4.0750E-06
C	1.5280E+00
D	9.5900E-05

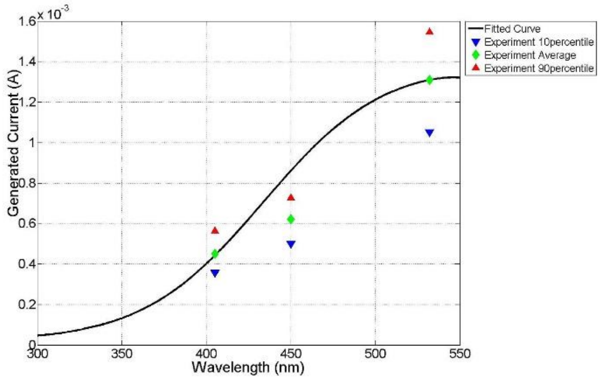

Fig. 4-a). Comparison between calculated current and experiment datapoints

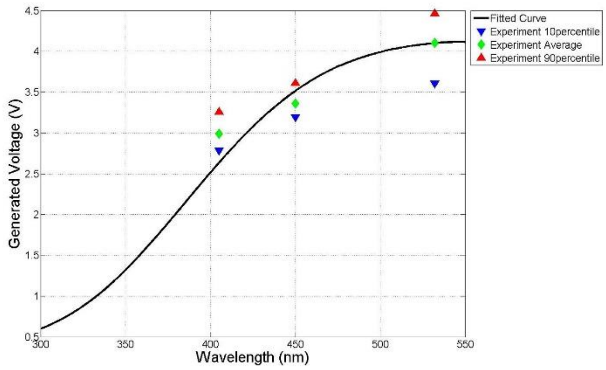

Fig. 4-b). Comparison between calculated voltage and experiment datapoints

Current, voltage, electric power, and system efficiency was calculated based on the photovoltaic cell equation and parameter A~D. Each value are described in the table 4, figure 6.

Table 4. Current, voltage, and power generation of each photovoltaic cell system unit

Storage period (year)	Current per system (A)	Voltage per system (V)	Power per system (W)
0	2.2530	5.3715	1.2102E+1
1	1.4560	4.7292	6.8857
2	1.0193	4.2133	4.2946
3	7.3345E-1	3.7500	2.7542
4	5.4823E-1	3.3471	1.8350
5	4.2148E-1	2.9959	1.2627
6	3.3213E-1	2.6887	8.9297E-1
7	2.6652E-1	2.4158	6.4384E-1
8	2.1792E-1	2.1768	4.7437E-1

9	1.8138E-1	1.9686	3.5707E-1
10	1.5278E-1	1.7833	2.7246E-1

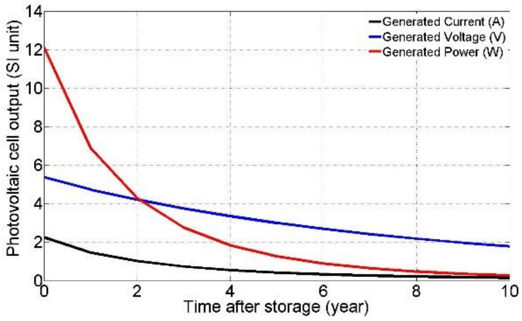

Fig. 6. Current, voltage, and power generation of each photovoltaic cell system unit

2.3.4. Result of Energy Conversion System Design

With the assumption that the system is operated under the ideal case (i.e. no material damage, no self-discharge, no charge loss to the 2nd battery), total charged electric energy inside 2nd battery for 10 year was estimated to be 8.0690E+8J per each system unit. With this electric energy, it is possible to supply 29.892kW to the spent fuel storage system without any external electric power source. If the charge uncertainty were considered about 99 percent for the conservative case, it is possible to supply kW scale of electric power to the spent fuel storage which is enough to isolate storage from outside.

3. Conclusions

The purpose of this study is to investigate the electric power generation with scale spent fuel. OrigenArp has analyzed gamma radiation environment of spent fuel assembly, MCNPX has analyzed the scintillator behavior, and experimental work has analyzed the electric output of photovoltaic cell.

Gamma radiation environment analysis result indicates gamma source rapidly decreases for the early storage period. Scintillator analysis result calculates the photon flux distribution which enters photovoltaic cell. Photovoltaic cell experiment calculates electric current, voltage current generation per each system unit. Generated electric power can be used to cope with existing safety system (i.e. storage monitoring system) under severe accident or to operate security system under external invasion situation (i.e. passive physical barrier system).

Although this research has been performed with real spent fuel case, there are several limitations. The biggest challenge is the material property under extreme radiation environment. Generated electric energy charge and storage is another challenge. Material property of the scintillator material and photovoltaic cell material will be tested in the future work.

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