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Simulation-based Investigation of Electric Power Generation by Using Gamma Radiation from Spent Nuclear Fuel

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1. INTRODUCTION

Sustained supply of electric power is important to minimize the consequence of nuclear reactor accident. This study investigates the feasibility of using gamma radiation energy from spent nuclear fuels to produce electricity as emergency power source. The proposed electric power system includes electricity generation and storage. Electricity generation was based on conversion of gamma energy to light energy using a scintillator and then to electric energy using a solar cell. Generated electricity was to be stored in a battery as a power source. [1, 2]. The efficiency of energy conversion and the extent of the resulting electric power source capability were examined by computer model-based simulation.

Main factors which affect to total electric power generated include thermal power of nuclear power plant, average burn-up period for fuel rod, battery charging time, and scintillator thickness. The estimated total power generation and its possible application is discussed.

2. METHODS AND RESULTS

The scheme of electric power source system by using the radiation energy from spent nuclear fuels includes four parts: the radiation source (spent nuclear fuel), the scintillator, the solar cell, and the battery. Once gamma radiation from spent fuel enters a scintillator, it generates visible light. The generated visible light is converted to electric energy by a solar cell. The generated electric energy is stored in a battery and as an emergency power supply source.

The materials used for the system are $CdWO_4$ for the scintillator, and c-Si solar cell for solar cell. $CdWO_4$ was chosen because of long wavelength of its output light and high radiation resistance. Selection of c-Si solar cell was based on the consideration of cost and accessibility. Sample spent nuclear fuel storage system was assumed to have 36x32 fuel assembly array. A simplified geometry for the power conversion system is shown in Figure 1. The unit system is attached to each fuel assembly.

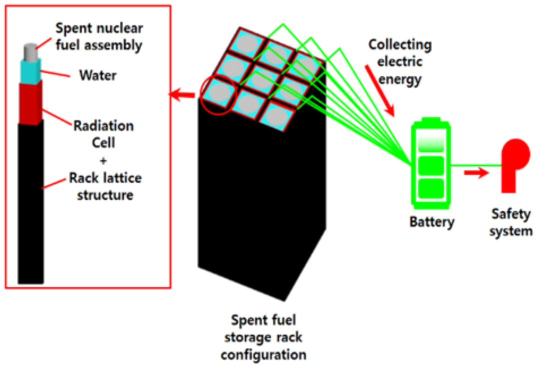

Figure 1. Geometry for power conversion device

Simulation of electric power generation was based on the following steps:

(1) First, the radiation environment around spent nuclear fuel, such as gamma ray source strength and energy as a function of time, was analyzed. [3] IAEA nuclide livechart data is used for this purpose. The strength of gamma rays per fuel assembly for each cases was in the range of 10^{15}~10^{16}Bq (gamma) per fuel assembly.

(2) Second, the intensity of light output from the scintillator was calculated by using MCNPX-Polimi_v2.7.0 [4, 5] for all of the gamma rays from spent nuclear fuel.

(3) Third, the electricity generation was estimated by using fundamental solar cell equations which are shown in equation (1) as a function of the wavelength of the scintillated light [6]

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

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

$$G = a(\lambda)I(1 - R(\lambda))\exp(-a(\lambda)d) \quad (1\text{-b})$$

Where, Va: Applied voltage, k: Boltzmann constant
T: Temperature, ni: Intrinsic carrier concentration,
$D_{p,n}$: Diffusion coefficient for n, p region,
$N_{d,a}$: Doping concentration for n, p region,
$L_{n,p}$: Diffusion length for n, p region,
W: Space charge region width, a: absorption coefficient,
I: Light intensity, R: Reflectivity, d: Depth of target material

(4) Lastly, the amount of electric energy available to use was estimated by assuming the time periods for charging the battery. The battery was assumed to be charged for the specified storage period.

The amount of electricity power available to use as emergency power source is expected to vary depending upon the irradiation history and burnup of spent fuel, the charging period of the battery, performance characteristics of the battery and other design parameters, such as type and thickness of scintillator or solar cell material It was assumed that the battery performs in such a way that there is no loss in charging and transferring electric power.

Test case calculations were made to test the effect of varying the values of selected parameters on the amount of electricity generation. Parameters considered include thermal power rating of nuclear power plant, spent fuel burnup, and the thickness of scintillator. The values used in this test calculation are shown in Table 1.a) ~ b). The battery charging period was assumed to be 60 year.

Tables 1.a) to 1.b) show the results of calculations. The results show the amount of generated electric energy and possible electric power for 8 hour for specific thermal power of nuclear power plant and average burnup period for fuel rod by changing scintillator thickness and charging period.

- Table 1.a) Cumulative generated energy and electric power supplement for 3000MWth

Time [yr]	Generated energy [MJ]				Power supplement [kW]			
	Scintillator thickness 10μm		Scintillator thickness 1000μm		Scintillator thickness 10μm		Scintillator thickness 1000μm	
	Burnup 18m	Burnup 72m	18m	72m	18m	72m	18m	72m
5	0.10	0.35	45	130	0.003	0.012	1.6	4.5
10	0.14	0.57	62	210	0.005	0.020	2.2	7.3
15	0.17	0.75	77	280	0.006	0.026	2.7	9.7
20	0.19	0.91	90	330	0.007	0.032	3.1	11
25	0.22	1.0	100	380	0.008	0.035	3.5	13
30	0.24	1.2	110	430	0.008	0.042	3.8	15
35	0.25	1.3	120	470	0.009	0.045	4.2	16
40	0.26	1.3	130	500	0.009	0.045	4.5	17
45	0.27	1.4	130	530	0.009	0.049	4.5	18
50	0.28	1.5	140	560	0.010	0.052	4.9	19
55	0.29	1.5	140	580	0.010	0.052	4.9	20
60	0.30	1.6	150	600	0.010	0.056	5.2	21

- Table 1.b) Cumulative generated energy and electric power supplement for 4000MWth

Time [yr]	Generated energy [MJ]				Power supplement [kW]			
	10um		1000um		10um		1000um	
	18m	72m	18m	72m	18m	72m	18m	72m
5	0.15	0.50	62	180	0.005	0.017	2.2	6.3
10	0.20	0.82	86	290	0.007	0.028	3.0	10
15	0.25	1.1	110	380	0.009	0.038	3.8	13
20	0.29	1.3	120	460	0.010	0.045	4.2	16
25	0.32	1.5	140	530	0.011	0.052	4.9	18
30	0.35	1.7	150	590	0.012	0.059	5.2	20
35	0.37	1.8	160	650	0.013	0.063	5.6	23
40	0.39	1.9	180	690	0.014	0.066	6.3	24
45	0.41	2.0	180	730	0.014	0.069	6.3	25
50	0.42	2.1	190	770	0.015	0.073	6.6	27
55	0.43	2.2	200	800	0.015	0.076	6.9	28
60	0.44	2.3	200	830	0.015	0.080	6.9	29

Results shown in Table 1.a) ~ b) indicates that total generated energy increases with the increase in reactor thermal power, the burnup, and the scintillator thickness.

This study also calculated conceptual sensitivity for each variables to analyze which variable affects to total generated power. Definition of sensitivity in this study for variable x was shown in equation 2.

$$S(x) = Avg\left(\frac{\left|\frac{-\Delta E}{E}\right|}{\left|\frac{-\Delta x}{x}\right|}\right) \qquad (2)$$

Sample cases for sensitivity analysis were 4000MWth, 72m, 60 year storage, 10um and 1000um. Results for these are shown in table 2. According to the result, thin scintillator shows high sensitivity to scintillator thickness, whereas thick scintillator shows almost linear sensitivity to scintillator thickness.

- Table 2. Sensitivity for each variables for 10um case and 1000um case

	10um	1000um
Rx. P(th)	0.314	0.369
Storage T	1.29	1.13
Burnup T	1.14	0.992
d_scint	2.18	1.12

3. CONCLUSION

Although the output power increases as scintillator becomes thicker, thick scintillator can be problem because of its high price. There are two ways to solve this problem. The first one is to use thin scintillator to whole fuel assembly area. The second one is to use thick scintillator to limited region. But the current per fuel assembly for the first case for 4000MWth, 72month burnup is about several to tens of microampere scale, which is too small to charge. Because of this the system is supposed to have thick scintillator system with limited region.

Based on the results, the generated electricity is expected to be insufficient to operate the safety injection pumps even at the maximum power output. However, the generated electric power may be useful for triggering purpose, such as startup trigger for class D passive safety system, or MOV operation inside nuclear power plant.

Also this proposed system may be useful outside nuclear power plant. For example, electric power can be supplied to an interim spent fuel storage system or geological repository for extended time periods. This may be important for security purposes.

Based on the current design, the solar cell efficiency is estimated to be around 1.5-4%. As the efficiency is a strong function of scintillation wavelength, improving the efficiency may be possible by broadening the wavelength through the use of multiple scintillators.

Future work will also include validation of the results through experiments, and material reliability study under severe radiation environment.

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