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Examination of the Effect of Neighboring Spent Fuel Assemblies to a Scintillator Based Partial Defect Detector (SPDD)

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1. Introduction

The objective of safeguards is "timely detection of diversion of significant quantities of nuclear material and deterrence of such diversion by the risk of early detection" [1]. Spent fuel assemblies need to be safeguarded since it contains fissile material which can be diverted into nuclear explosive devices. "Defect" of a spent fuel assembly in safeguards indicate some fraction or an entire assembly is missing or replaced into a dummy material. IAEA defines partial defect as an item or batch that has been falsified to such an extent that some fraction of the declared amount of material is actually present [2]. If the fraction of diverted fuel pins in an assembly is less than 50%, it becomes an assembly with partial defect [3]. Since every spent fuel process is monitored and managed by each country, fissile materials in spent fuel assemblies can be diverted. Spent fuel assemblies are inspected by international agencies, such as IAEA, to prevent the probability of diversion. Partial defect detection is a challenging issue among spent fuel verification.

Conventional partial defect devices include SMOPY [4], PDET [5], gamma emission tomography [6], and DCVD [3]. However, since SMOPY, PDET, and gamma emission tomography take time to analyze a spent fuel assembly, they cannot inspect every spent fuel assembly. DCVD cannot be applied out of cooling pool since DCVD detects partial defect based on Cerenkov radiation. This research proposes a scintillator based partial defect detector (SPDD) for inspecting spent fuel, which can detect partial defects within a short time and both in and out of a cooling pool.

2. Methods and Results

Since there are limitations described above, conventional partial defect detectors cannot inspect every spent fuel assemblies. This research suggests two step partial defect detection using SPDD. The first step is to screen every spent fuel assemblies within a short time to identify suspicious spent fuel assemblies using SPDD. The second step is to inspect suspicious spent fuel assemblies using high resolution detectors.

2.1 Conceptual design of SPDD

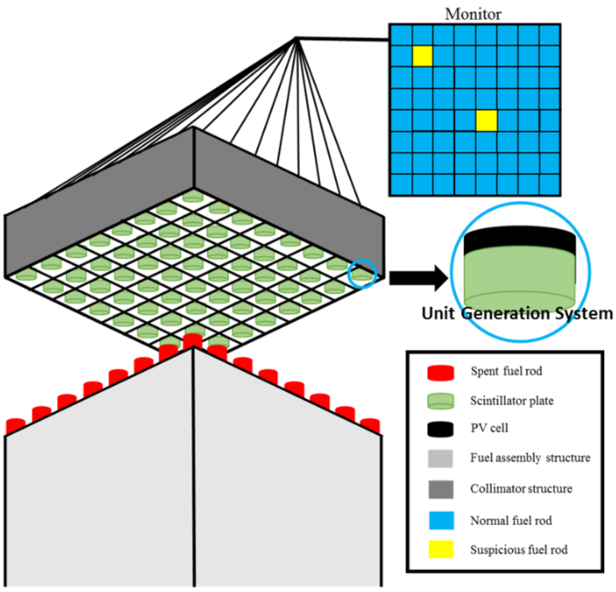

Fig 1. Conceptual design of a SPDD

Figure 1 depicts the conceptual design of a SPDD. Each unit generation system, which consists of a $CdWO_4$ scintillator plate and amorphous Si photovoltaic cell, are located above each spent fuel pin. Radiation generated by each spent fuel pin is converted into visible photons via scintillator plate of a unit generation system. Photovoltaic cell generates electric current and voltage using the scintillated photons. Since there is a collimator, each unit generation system is mainly affected by corresponding fuel pin.

SPDD detects partial defect by following two methods. The first method compare the amount of generated electricity using target assembly to the result of a reference assembly.

1. Setup a reference electricity generation of each unit generation system using a normal spent fuel assembly.
2. Calculate the relative electricity generation for a target assembly compared to the reference assembly for the same unit generation system.
$$Rel. generation\ at\ unit\ "n", R1_n \equiv \left(\frac{I_{n,case}}{I_{n,ref}}\right) \quad (1)$$
3. If the target assembly contains value out of compliance boundary, it becomes a suspicious assembly.

The second method compare the relative electricity generation of each unit generation system within a target assembly.

1. Calculate relative electricity generation of each fuel pin compared to the maximum electricity generation within a target assembly.

   $$Rel.\,generation\ at\ unit\ \text{"n"}, R2_n \equiv \left(\frac{I_{n,ass.}}{I_{max,ass.}}\right) \quad (2)$$

2. Generate the pattern of an assembly using the calculated relative electricity.
3. If the pattern is distorted out of compliance boundary of a normal assembly, it becomes a suspicious assembly.

2.2 Feasibility demonstration of SPDD

Since direct use of spent fuel is extremely dangerous and requires complex process, computational model was used in this study. The computational model was developed and validated in previous studies [7].

SPDD performance was analyzed using test case spent fuel assemblies with different partial defects. 16x16 PLUS7 type PWR spent fuel assembly was selected and 1/8 symmetry was used to gamma source analysis and 1/4 symmetry was used to MCNPX simulation for calculation time reduction.

Pin-wise spent fuel radiation was calculated using the SCALE-DEPL and OrigenArp code for a given irradiation history and cooling time. Three irradiation cycles with 40 days irradiation step. The downtime between each cycle was 50 days. Total discharge burnup and cooling time for a test case spent fuel assembly was 47.34 GWd/tU and 10 years. The geometry and location of defective fuel pins of three different partial defect assemblies are depicted in Figure 2.

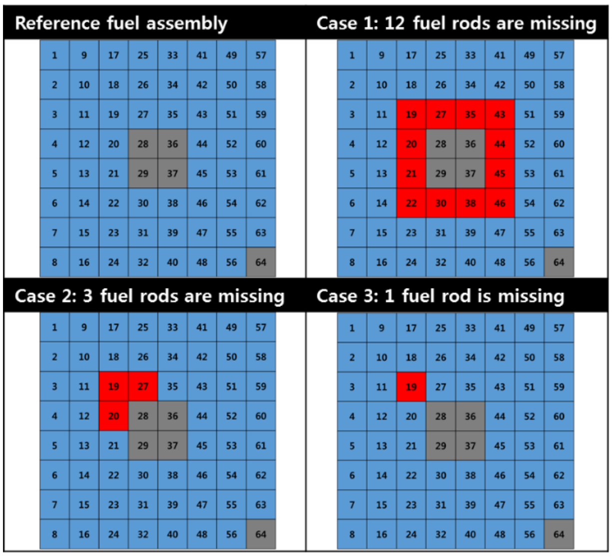

Fig. 2. Geometry of reference fuel assembly and test case fuel assemblies. (Blue: normal pin, Gray: guide tube, Red: defective pin)

The intensity of scintillated photons using the calculated radiation source was analyzed using the MCNPX code. The amount of generated electric current was calculated using the method in the literature [7]. Since the MCNPX simulation results contain statistical error, SPDD results also contain uncertainty. This research suggested uncertainty range of a normal spent fuel assembly for distinguishing defective assemblies using SPDD.

The MCNPX simulation was performed that each tally results contains relative error $\left(\mathrm{R} = \frac{STDEV}{Mean}\right)$ [8] less than 0.075. Equation (1) and (2) describe the relative electricity generation is a value containing error divided by another value containing error for both method 1 and 2. The error for the relative electricity generation at "n" is calculated using equation (3) [9].

$$\delta R1_n = R1_n \times \sqrt{\left(\frac{\delta I_{n,ref}}{I_{n,ref}}\right)^2 + \left(\frac{\delta I_{n,case}}{I_{n,case}}\right)^2},$$

$$\delta R2_n = R2_n \times \sqrt{\left(\frac{\delta I_{n,\,assembly}}{I_{n,\,assembly}}\right)^2 + \left(\frac{\delta I_{max,\,assembly}}{I_{max,\,assembly}}\right)^2} \quad (3)$$

Since the relative electricity generation and relative error of each unit generation system is different, this research applied the most conservative value, which are described in equation (4). Since the Monte Carlo simulation results follow normal distribution as the number of random particle increases, this research considered that the assembly is suspicious if it contains relative electricity generation out of 95% boundary (1.96 STDEV). Applying conservative conditions in equation (4) into equation (3) indicates that "If a target assembly contains a unit whose relative current difference is larger than 0.2079 compared to the value of a reference assembly, it is called to be a suspicious assembly both for method 1 and 2"

$$R1_n = R2_n = 1$$
$$\frac{STDEV(I_{n,\,ref})}{I_{n,\,ref}} = \frac{STDEV(I_{n,\,assembly})}{I_{n,\,assembly}} = 0.075 \quad (4)$$

Results of SPDD feasibility demonstration for both method 1 and 2 are depicted in Figure 3 and 4 respectively. Table 1 describes the number of unit generation system out of 95% confidence interval for each method and case. Method 1 demonstrated that SPDD can even distinguish defective spent fuel assembly with single fuel pin diversion. However, establishing reference assembly is needed to apply method 1 in the real case. Method 2 demonstrated that SPDD can distinguish defective spent fuel assembly without reference spent fuel assembly. However, method 2 cannot distinguish defective spent fuel assembly with single fuel pin missing. The spatial resolution needs to be improved.

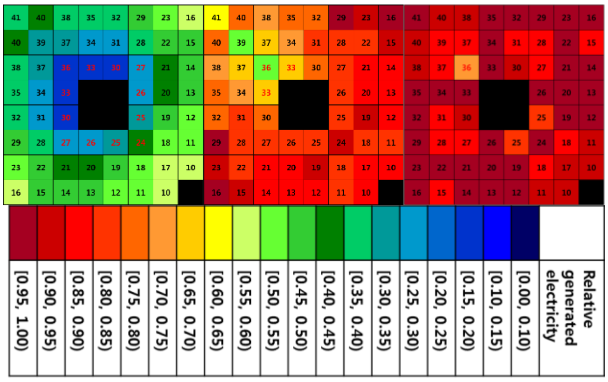

Fig. 3. SPDD feasibility demonstration using method 1 and color legend for relative electricity generation (Left: case 1, Center: case 2, Right: Case 3).

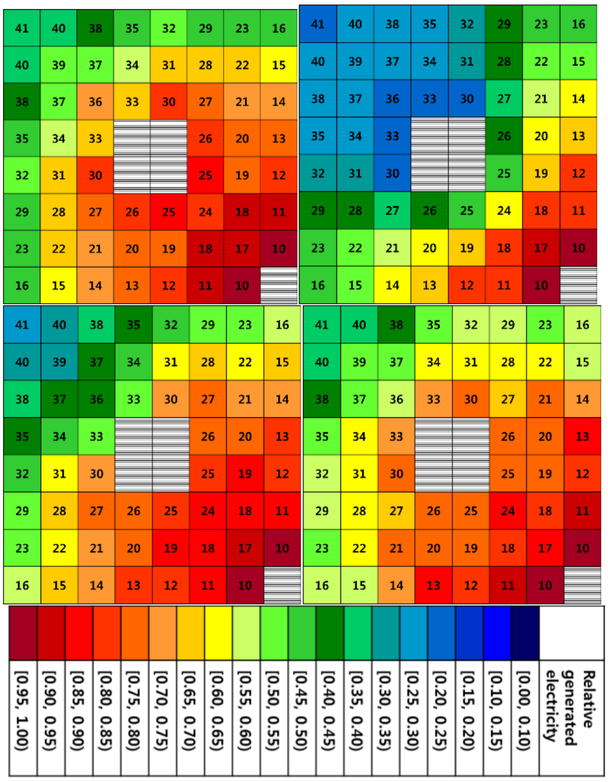

Fig. 4. SPDD feasibility demonstration using method 2 and color legend for relative electricity generation (Left top: reference, Right top: case 1, Left bottom: case 2, Right bottom: case 3).

Table I. Number of unit generation systems which are out of 95% confidence interval. (Total: 59)

	Method 1	Method 2
Case 1	59	12
Case 2	19	1
Case 3	1	0

2.3 Effect of neighboring assemblies on SPDD

Since a number of spent fuel assemblies are stored in a spent fuel storage, the effect of neighboring assemblies on SPDD has to be demonstrated. This research demonstrated the effect of neighboring assemblies on SPDD. Furthermore, the effect of additional shielding was demonstrated.

This research applied reflective boundary condition rather than simulating entire spent fuel assembly for reducing calculation time. SPDD shielding material is stainless steel and thickness is 0.8cm. The shielding also covers the side of a spent fuel assembly 8cm from the top.

Figure 5 and 6 depicts the SPDD results using multi spent fuel assemblies without shielding and with shielding respectively. The effect of neighboring assemblies and shielding can be demonstrated by comparing the results of Figure 4, 5, and 6. Due to neighboring assemblies, the relative generated electricity of fuel pins at the outer part of spent fuel assembly increases significantly compared to the results of single assembly. Results after applying shielding become similar to the result of single assembly. Further research on shielding design have to be studied.

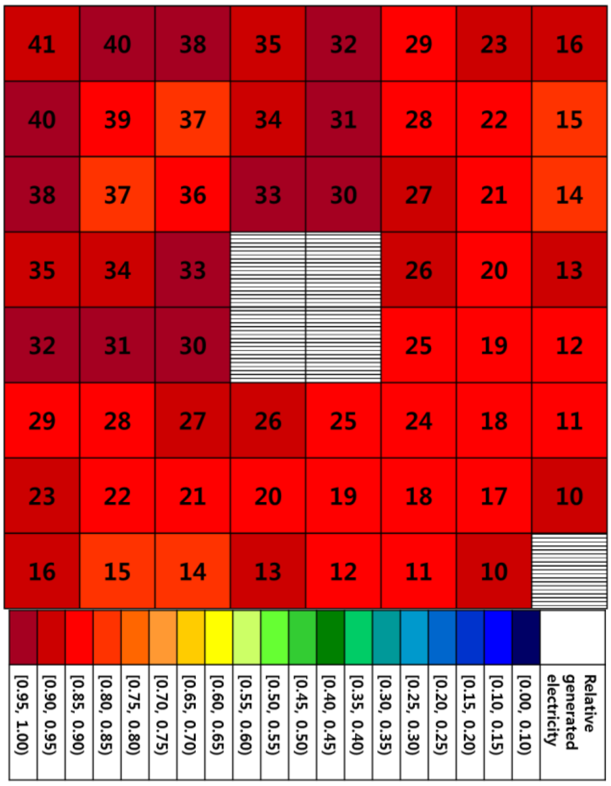

Fig. 5. SPDD performance for a reference assembly using 2 using multi spent fuel assembly environment without shielding.

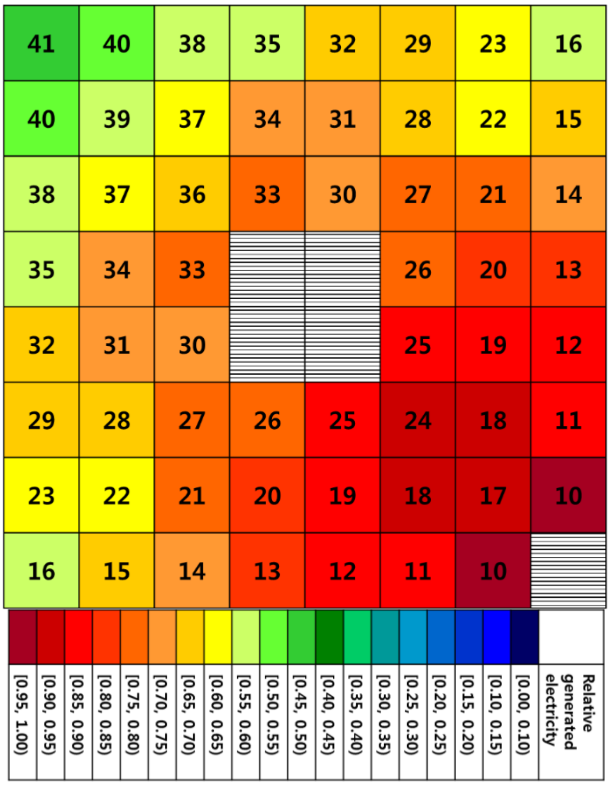

Fig. 6. SPDD performance for a reference assembly using 2 using multi spent fuel assembly environment with stainless steel shielding.

3. Conclusions

This research demonstrated the feasibility of SPDD for partial defect detection and the effect of neighboring spent fuel assembly on SPDD. The results indicated that the SPDD is able to detect even a single fuel pin missing case and the effect of neighboring spent fuel assemblies are significant.

Future work includes SPDD shielding design optimization and further SPDD performance analysis. Further SPDD performance analysis include examination of the low burnup and cooling time limit of SPDD and uncertainty reduction by applying non-conservative evaluating criterion.

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