Transactions of the Korean Nuclear Society Virtual Autumn Meeting
December 17-18

A Study of Performance Specification of $CdWO_4$ Scintillator Based Partial Defect Detector

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1. Introduction

As the amount of spent nuclear fuel increases globally, safeguards for the spent nuclear fuel management become increasingly important. The IAEA requires the detection of partial defects, in order to verify the quantity of nuclear material present before it is permanently disposed or before the fuel rods are “difficult-to-access” [1]. A partial defect is defined as a missing fuel rod when half of the spent fuels in a fuel assembly is replaced by empty dummy rods [2]. A number of studies and experiments have been conducted to identify such partial defect. Most of the existing detector technologies consist of a single detector system with a high detection resolution but has functional limitations. For example, these detectors require the vertical lifting of individual spent fuel assemblies which increases measurement time. Some of the detector technologies have high costs associated with their fabrication, maintenance and operation or they can be applied in only one of the two (wet and dry) spent fuel environments, such as wet only.

For the purpose of low cost and fast measurement time, a $CdWO_4$ scintillator-based partial defect detector (SPDD) was developed in KAIST [3]. The applicability of SPDD to the WH 14x14 and PLUS7 16x16 fuel assemblies was evaluated in previous research. It was also evaluated for the WH 17x17 fuel assembly which has many guide tubes [4]. A series of performance evaluations have shown that this SPDD system is significantly affected by the number of guide tubes in an assembly. However, depending on the burnup, cooling time and initial enrichment of fuel, the amount of fissile plutonium and the intensity of gamma sources will vary significantly. Therefore, the performance evaluation needs to be more quantitative for spent fuels with different operating histories. In this study, the effect of each variable on the detection performance of SPDD is analyzed by identifying the range of those variables.

2. Methods and Results

This section will describe how the detection criteria for the performance evaluation was set; how the generation of test scenarios and simulations proceeded; and what the performance changes were relative to the burnup, cooling time, and initial enrichment.

2.1 Detection performance criteria-Required number of dummy rod(RDR)

The main objective of partial defect detection is verification of the quantity of nuclear material before the spent fuel assemblies are placed in a difficult-to-access environment such as fuel storage casks or fuel transportation casks. Therefore, the performance criteria was set as detection capability with significant quantity of fissile plutonium in a transportation cask. IAEA has designated 1SQ of plutonium as 8kg of fissile plutonium with less than 80% of Pu-238. To verify the range of performance for a WH17x17 fuel assembly, the number of fuel rods required to obtain 1SQ of fissile Pu in a KN-12 cask was calculated in figures 1,2 and 3. Using the ORIGAMI code provided in the SCALE6.2.3, 1SQ of fissile Pu in a KN-12 cask was calculated by varying the burnup, cooling time and initial enrichment [5].

The grade of plutonium is determined from the ratio of Pu-240,. As the ratio increases the spent fuel achieves a high rate of spontaneous fission. If the ratio of Pu-240 decreases, the Pu is getting close to weapon-grade. As the burnup of fuel increases, the required number of dummy rods (RDR) and ratio of Pu-239 is considerably decreased while the ratio of Pu-240 increases. Even though the amount of fissile Pu increases, the quality of plutonium gets worse with increasing burnup of fuel. As the cooling time increases, the RDR converges without significant changes and the ratio of Pu-239 and Pu-240 increase. The increase of initial enrichment of nuclear fuel has little effect on RDR but the ratio of Pu-239 increases significantly, and the ratio of Pu-240 decreases which makes the generated Pu closer to weapon-grade.

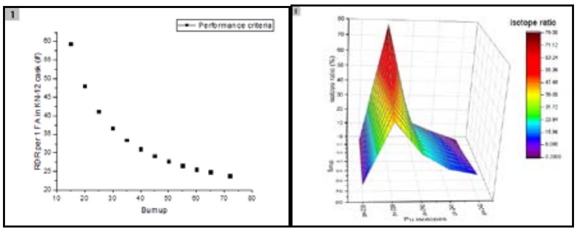

Fig. 1. RDR and Pu isotopes concentration with different burnup

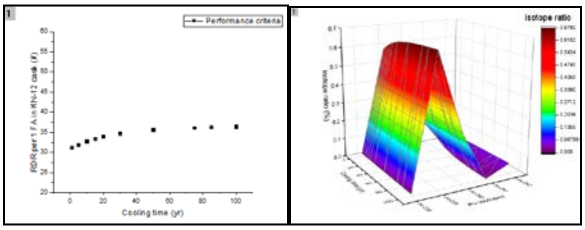

Fig. 2. RDR and Pu isotopes concentration with different cooling time

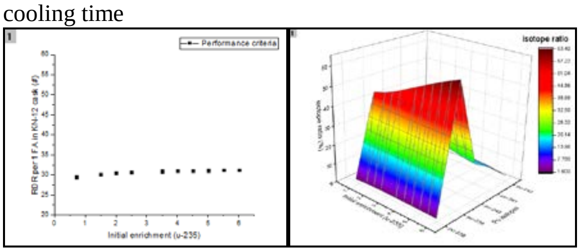

Fig. 3. RDR and Pu isotopes concentration with different initial enrichment

2.2 Test scenarios and simulations of performance verification

The variables to be considered for quantifying the range of spent fuel that the SPDD can be applied to were burnup, cooling time, and initial enrichment. The specific range investigated includes the range of spent fuels generated in current commercial reactors, as shown in table 1. The MCNPX (Monte Carlo N-particle Extended) code was used for the gamma transport simulation [6]. The fuel rods were set as gamma sources while the detectors, inserted in guide tubes, were the target. The number of gamma particles used in the simulations was adjusted to achieve an inherent stochastic relative error of less than 1%. To identify the empty dummy rods, the detection methodology used in previous research was also utilized in this simulation [3]. It compares the estimated reference value obtained with operator declared data to the measured values.

Table. 1. Tested range of each variable

Variable	Range	Control
Initial enrichment	0.72 – 6.0 % of U-235	40GWD/MTU , 0.03y
Total burnup	15 – 72 GWD/MTU	4.5% U-235, 0.03y
Cooling time	1y - 100y	40GWD/MTU, 4.5% U-235

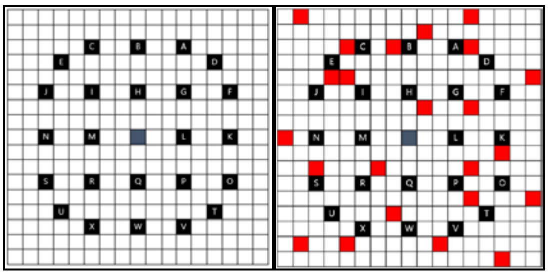

Fig. 4. Left : WH17x17 FA, Right : An example of test scenario with 23 dummy rods(RDR for 72GWD/MTU)

The test scenarios for the performance evaluation were based on a random distribution of dummy rods, i.e., they could be located at any fuel rod, as shown in figure 4. The ratio of dummy rods is based on the RDR for each specific burnup, cooling time and initial enrichment; and each simulation is repeated three times.

2.3 Detection performance with 3 variables-burnup, initial enrichment, cooling time

Table. 2. SPDD performance with different burnup

Total burnup (GWD/MTU)	RDR # (%)	Number of SPDD units which identified DR (# of batch : 3)
15	59 (22.3%)	22 / 24
25	41 (15.5%)	22 / 24
35	33 (12.5%)	16 / 24
45	29 (11.0%)	10 / 24
55	26 (9.8%)	10 / 24
60	25 (9.5%)	8 / 24
65	24 (9.1%)	11 / 24
72	23 (8.7%)	8 / 24

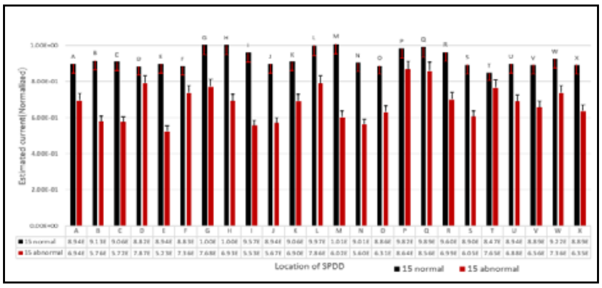

Fig. 5. Estimated current at each SPDD unit, 15GWD/MTU

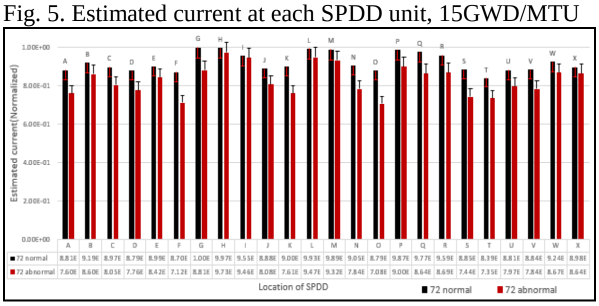

Fig. 6. Estimated current at each SPDD unit, 72GWD/MTU

When the burnup was incrementally increased from 15GWD/MTU to 72GWD/MTU, the SPDD was able to identify the dummy rods, even though the performance criteria increased in difficult from 59(22.3%) dummy rods to 23(8.7%) dummy rods. This study confirmed that the reduction of gamma dose to the detector, due to the increased burnup, did not significantly affect the detection performance of SPDD.

Table. 3. SPDD performance with different cooling time

Cooling time (years)	RDR # (%)	Number of SPDD units which identified

		DR (# of batch : 3)
1	31 (11.7%)	12 / 24
10	32 (12.1%)	11 / 24
20	33 (12.5%)	16 / 24
30	34 (12.9%)	15 / 24
50	35 (13.3%)	15 / 24
75	36 (13.6%)	15 / 24
85	36 (13.6%)	18 / 24
100	36 (13.6%)	18 / 24

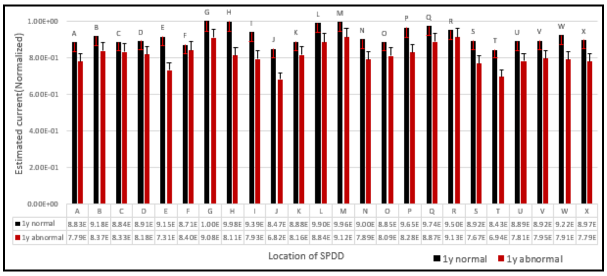

Fig. 7. Estimated current at each SPDD unit, 1yr cooled

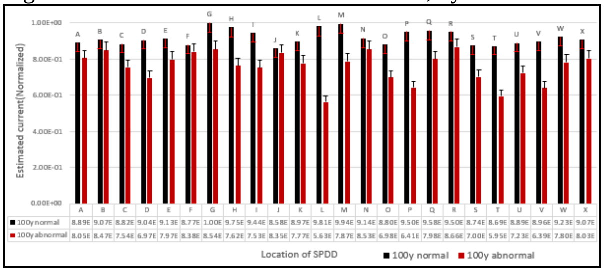

Fig. 8. Estimated current at each SPDD unit, 100yr cooled

The longer spent fuel is cooled in the spent fuel pool, the less gamma emitted from the fuel rods resulting in the more perturbation of the generated current However, as the RDR increased it become easier for the detectors to identify the dummy rods. This study confirmed that changes in gamma intensity and the resulting detection error that occurred between the 1 year to 100 years cooling time, did not affect detection performance of SPDD.

Table. 4. SPDD performance with different initial enrichment

Initial enrichment (wt% of U-235)	RDR # (%)	Number of SPDD units which identified DR (# of batch : 3)
0.72	29 (11.0%)	13 / 24
1.5	30 (11.4%)	14 / 24
2.5	30 (11.4%)	11 / 24
3.5	30 (11.4%)	14 / 24
4.5	31 (11.7%)	12 / 24
4.95	31 (11.7%)	11 / 24
5.5	31 (11.7%)	14 / 24
6.0	31 (11.7%)	13 / 24

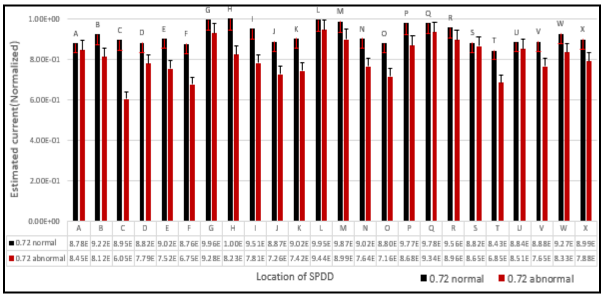

Fig. 9. Estimated current at each SPDD unit, 0.72wt% U-235

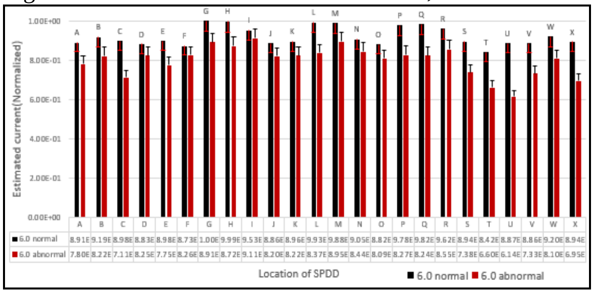

Fig. 10. Estimated current at each SPDD unit, 6.0wt% U-235

When the initial enrichment of nuclear fuel increased, the gamma dose to the SPDD increased and its detection error decreased. It has a positive effect on the detection performance and also the RDR has changed little. Therefore, the SPDD can easily identify dummy rods with an initial enrichment from 0.72 to 6.0 wt% of U-235.

3. Conclusions

To, evaluate SPDD performance an MCNPX gamma transport simulation was used to determine the influence of different burnup, cooling time, and initial enrichment, on the gamma intensity emitted by the spent fuel. The study confirmed that the variation of gamma intensity and resulting detection error were due to changes in each variable, but ultimately have little effect on the detection performance of SPDD. Additionally, the study determined that the SPDD was able to identify the RDR, 1SQ of fissile plutonium which is more difficult than the IAEA performance criteria.

Through this study, we determined that the dummy rod density and the distance between the dummy rod and the detector were the most important features affecting the performance of the SPDD. Therefore, further research must focused on how to overcome the performance limitations resulting from the different number of guide tubes for various types of fuel assemblies. To improve the performance and the potential application of the SPDD system, detectors must not be dependent on the number of guide tubes, instead changing the location of the sensors to areas such as the gap between the spent fuel assembly and its rack should be investigated. Finally, the test simulation data obtained in this study can be utilized as training data in a machine learning algorithm for the potential future application of this technology in an unmanned remote system.

ACKNOWLEDGMENT

This research was supported by National Nuclear R&D Program (Human Resources Program in Energy Technology) through the National Research Foundation of Korea (NRF) by the Ministry of Science, Science and Technology (NRF-2018M2C7A1A02071198).

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