A study of Sensitivity of Partial Defect Detection Capability Using Scintillator-photodiode Detector with 17x17 Spent Fuel Assemblies

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1. Introduction

Nuclear nonproliferation is one of the increasingly important values with the progress of technologies related to the nuclear power generation. Proliferation of nuclear material is conducted by people who has the purpose of abuse such as weaponization and one of the objectives of those people is the spent nuclear fuel. Against the threatening of nuclear proliferation, the global organization in nuclear field, IAEA made several laws, regulations and safeguards which are related to spent nuclear fuel [1]. One of those safeguards is the quantity verification. The IAEA required nations which generate electricity with nuclear power plant to verify the quantity of spent nuclear fuel in the level of bundles but it became strict that the quantity must be verified in the level of pin by pin. When some amount of spent nuclear fuel is stolen, it is called as the partial defect [2]. Some countries already developed the technologies of partial defect detection with targeting large nuclear power plants. However, there is no existing detectors with targeting the small modular reactors. The SMRs and large reactors use similar nuclear fuels in terms of the enrichment of U-235 and burnup rate [3]. It makes both reactors have no difference in the risk of nuclear proliferation in the fuel level. However, the SMRs have higher risk of nuclear proliferation because it can be more widely deployed.

IAEA published technical report about the I&C information of advanced SMRs. This report includes the common issues which makes the existing partial defect detectors hard to be applied to SMRs. Related common features are described in Table 1.

Article	Common issues & characteristics
2.5.1.	SMRs can be deployed where IAEA inspectors are difficult to access.
2.5.3	Due to the compact structure of the SMR, it is difficult to install instruments such as flux mapping detectors.
2.6.1	Due to the hard accessibility, it is required for the installed control systems to operate autonomously with remote intervention capabilities.

Table 1. Common features of SMRs [4]

It is concluded that existing technologies are hard to be applied to SMRs. Therefore, it is necessary to develop a new partial defect detector or to modify and optimize the pre-existing measurement method with targeting the SMR environments. There is a method for detection of partial defect which is called as SPDD, still under development from KAIST in South Korea [5]. Figure 2 shows the design of single leg of SPDD detector. In this research, the SPDD, scintillator based partial defect detector will be modified in accordance with the SMR environment. Currently, the development stage of SPDD is targeting the large nuclear power plants. The performance of SPDD is verified with the Westinghouse 14x14 fuel assembly and PLUS7 16x16 fuel assembly.

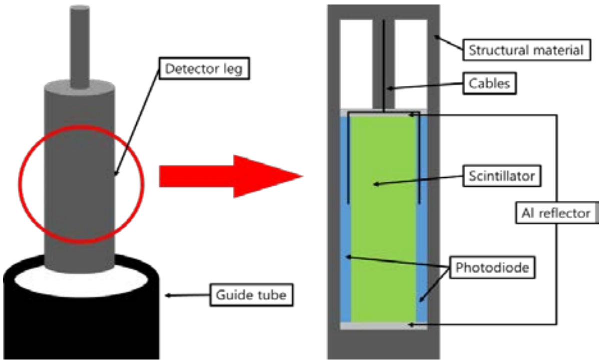

Fig. 1. Design of SPDD detector [5]

2. Methods and Results

As a first step for the purpose of applying this SPDD to the SMR environment, a simulation model of the Westinghouse 17x17 fuel assembly will be built. This fuel assembly is used in SMRs such as SMART which is developed in KAERI and ATOM reactor developed in KAIST. The MCNPX will be used for the simulation and the verification of SPDD performance.

2.1. Detection criterion set up

At first, a detection criterion must be set up to determine whether there is a partial defect in spent nuclear fuel assembly. The SPDD installed in guide tubes measures the gamma-rays emitted from gamma source of spent nuclear assembly by energy unit and it will be simulated with the MCNPX. After that, data from different guide tubes will be compared with each other. The intrinsic error of gamma source will be used as the error of data values for the calculation of confidence interval of each data. Finally, it is stipulated that the defect can be detected when the confidence intervals of the data from each guide tubes do not overlap with each other.

The uncertainty of gamma source is originated from nuclide data and uncertainty of fission product. In this case, it is stipulated that the uncertainty of gamma source is mainly due to the fission product because the uncertainty of nuclide data is negligible. This uncertainty varies with the cooling time of the nuclear fuel. In this research, uncertainty of gamma source cooled for 30 years will be used as previous study. The gamma source estimation uncertainty which is the relative standard error was calculated in the previous study (u_{gamma} = 2.5851 $x10^{-3}$) [5].

In the previous study, it was chosen for the detection criterion that the comparison data from same guide tube between normal and partial defect PWR fuel assembly [5]. It resulted in detection efficiency being too low because it is a very conservative approach. Therefore, in this research, it will be compared with each other that the data from different guide tubes in the single fuel assembly. Figure 2 shows the Westinghouse 17 x 17 fuel assembly and it has 24 guide tubes in an assembly. If the partial defect exists near to A guide tube, confidence intervals of energy data received by A guide tube and U guide tube would be compared with each other.

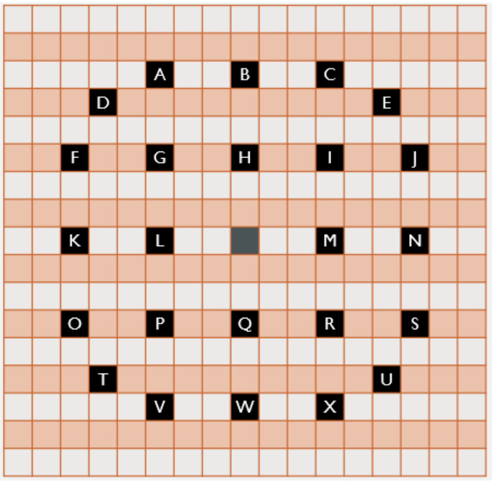

Fig. 2. Guide tubes away from each other in Westinghouse 17x17 fuel assembly

2.2. MCNPX simulation set up

In order to simulate the measurement of the gamma-ray energy by SPDD with MCNPX, a new input file for the Westinghouse 17x17 fuel assembly is required. However, the information of the details about the fuel assembly is not enough to make a new input file. The input file for the Westinghouse 14x14 fuel assembly which is used in the KORI 1 nuclear reactor is written in the previous study. Therefore, it will be modified that the pre-existing input file for the Westinghouse 14x14 fuel assembly to write the target fuel assembly. Figure 3 shows the depiction of modified input file by Visual Editor tool. The number of guide tubes increases from 16 to 24 and it will result in the performance of the SPDD to be more accurate because of the increased number of the data.

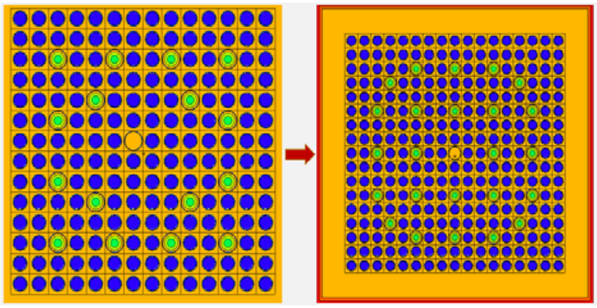
Fig. 3. Depiction of altered input file from 14 x 14 to 17 x 17

Finally, it must be verified that whether the data is satisfied with the detection criterion of SPDD with increasing the number of partial defects to identify the minimum number of defects that can be detected. If the partial defect is located close to the guide tube, it affects the data measured by that guide tube to be decreased significantly. Therefore, it must be verified in two cases that is composed of biased and unbiased distribution of partial defects. Figure 4 and Figure 5 show the biased and unbiased partial defect cases and the location of defects are depicted in red color.

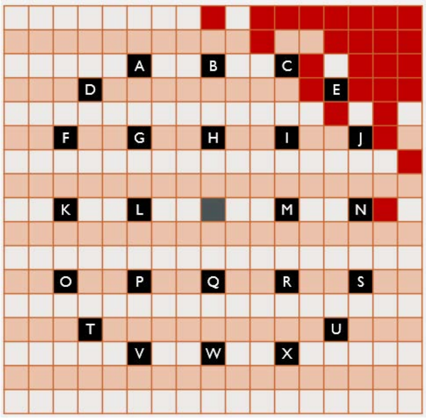

Fig. 4. Biased distribution of partial defects

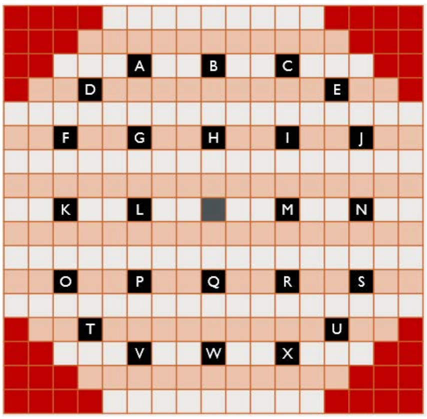

Fig. 5. Unbiased distribution of partial defects

2.3. Minimum measurable number of defects in the case of biased distribution of partial defects

Figure 6 shows the results from MCNPX simulations. In these test cases, the partial defects are biased toward the A and D guide tubes. The data measured at the nearest SPDD were compared with the farthest SPDD from the partial defects with increasing the number of defects. The energy received in the nearest SPDDs at A and D guides tubes decreases as the number of defects increases. On the other hand, the energy received in the farthest SPDDs at U and X guide tubes increases as the number of defects increases.

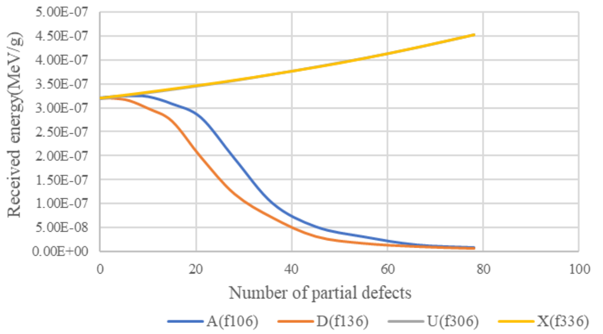

Fig. 6. Received gamma-ray energy in SPDDs at different location with biased distribution of partial defects

The existence of partial defects is confirmed by whether the confidence intervals of measured energy overlap with each other. Table 2 shows the data of confidence intervals of measured energy with the 95 percent of confidence. When the number of partial defects is three, the intervals overlap with each other and not overlap after one more defect is added. Therefore, in the biased partial defect cases, the SPDD can detect the 4 or more defects in the Westinghouse 17x17 fuel assembly.

# of defect	Upper CI of measured energy at D (MeV/g)	Lower CI of measured energy at U (MeV/g)
0	3.21E-07	3.17E-07
1	3.22E-07	3.19E-07
3	3.21E-07	3.21E-07
4	3.20E-07	3.22E-07
6	3.16E-07	3.25E-07
10	3.00E-07	3.30E-07
15	2.73E-07	3.37E-07
21	1.98E-07	3.45E-07
28	1.20E-07	3.55E-07
36	7.00E-08	3.68E-07
45	3.08E-08	3.84E-07
55	1.65E-08	4.02E-07
66	9.76E-09	4.24E-07
78	5.73E-09	4.51E-07

Table. 2. Confidence intervals of measured energy at D and U guide tubes

2.4. Minimum measurable number of defects in the case of biased distribution of partial defects

In the unbiased cases, the defects are distributed symmetrically at the edge of fuel assembly, so a guide tube receives same energy from gamma source with other 3 guide tubes. In other words, the data of received energy in 6 SPDDs from the total SPDDs are enough to be compared with each other. The SPDDs at O, P, Q, T, V and W location will be considered and it is described in Figure 7. Figure 8 shows the change in the received energy by 6 SPDDs as the number of defects increases. The two locations with the greatest difference in measured energy values are P and T guide tubes. The confidence intervals of those two measured data will be calculated with the 95 percent of confidence.

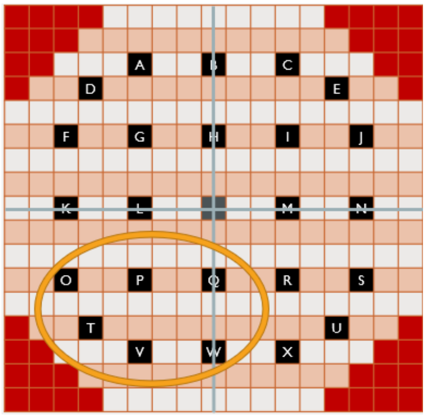

Fig. 7. Locations of 6 different SPDDs

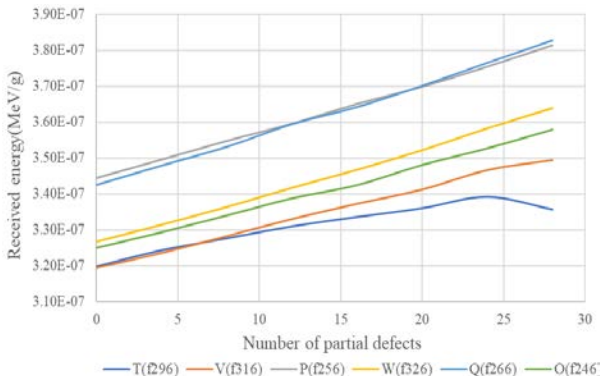

Fig. 8. Received gamma-ray energy in SPDDs at different location with unbiased distribution of partial defects

Table 3 shows the data of confidence intervals of energy measured at P and T guide tubes. Figure 9 shows whether the confidence intervals are overlapping with each other as the number of defects increases but the intervals do not overlap with each other even in normal fuel assembly. Therefore, the gap between the confidence intervals of energy in normal fuel assembly must be a reference value and it is stipulated that there is a defect when the gap between the confidence intervals becomes larger than the reference value. When each single defect is located at the edge of the fuel assembly, the gap between the confidence intervals is lower than the reference value, so it is hard to verify whether there is a partial defect. After the number of defects increase as 8 or more, the gap becomes larger than the reference value. Therefore, in the unbiased cases, the SPDD can detect the 8 or more defects in the Westinghouse 17x17 fuel assembly.

# of defect	Upper CI of measured energy at T(MeV/g)	Lower CI of measured energy at P(MeV/g)
0	3.21E-07	3.43E-07
4	3.26E-07	3.48E-07
8	3.29E-07	3.53E-07
12	3.33E-07	3.58E-07
16	3.35E-07	3.63E-07
20	3.38E-07	3.68E-07
24	3.41E-07	3.74E-07
28	3.37E-07	3.80E-07

Table. 3. Confidence intervals of measured energy at T and P guide tubes

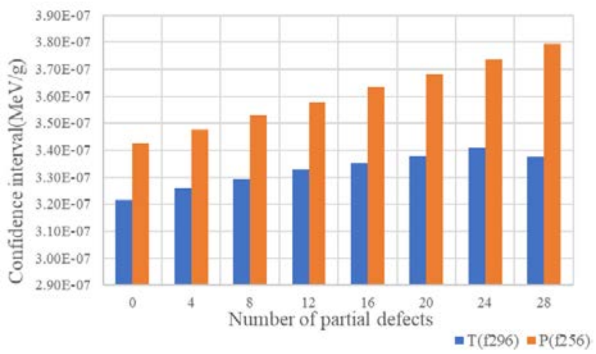

Fig. 9. Gap between the confidence intervals of measured energy at T and P guide tubes

3. Conclusions

This research verified the performance of scintillator-photodiode based detector for the Westinghouse 17 x 17 fuel assembly used in SMRs such as SMART and ATOM reactor. A new detection criterion was attempted to increase the detection efficiency of the detector and it is concluded that 8 or more number of partial defects can be detected with the SPDD. There exist 24 guide tubes in the 17 x 17 fuel assembly and it makes the SPDD be able to detect the defects wherever those defects are located. There are always two or more guide tubes which are located at different distances from the defects in the fuel assembly.

Future studies will include an automation of SPDD detection process through the determination of the number of partial defect combinations within the 17 x 17 fuel assembly and cost-effectiveness analysis through the geometry optimization of the detector. Later, these processes will be proceeded with other types of fuel assembly for the verification of wide applicability of the SPDD.

ACKNOWLEDGMENT

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REFERENCES

[1] International Atomic Energy Agency (IAEA), The structure and content of agreements between the agency and states required in connection with the treaty on the non-proliferation of nuclear weapons, INFCIRC/153 (corrected), 1972.

[2] International Atomic Energy Agency (IAEA), Safeguards techniques and equipment: 2011 edition, IAEA-NVS-3, 2011.

[3] Pannier, Christopher P., and Radek Skoda, Comparison of small modular reactor and large nuclear reactor fuel cost, Energy and Power Engineering, 6, pp. 82-94, 2014.

[4] International Atomic Energy Agency (IAEA), Instrumentation and Control Systems for Advanced Small Modular Reactors, IAEA Nuclear Energy Series, No. NP-T-3.19, pp. 18, 2017.

[5] H. Lee and M. S. Yim, A novel scintillator – photodiode detector to detect partial defects of PWR spent fuel assemblies for nuclear safeguards, Transactions of the Korean Nuclear Society Spring Meeting Jeju, 2018.