NENS Nuclear Energy Environment and Nuclear Security Laboratory

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Examination of the Feasibility of Detecting Partial Defect of Spent Fuel Assembly with Radiation to Electricity Conversion Approach

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Purpose of the Research

- **Objective of safeguards [1]**
  - Timely detection of diversion of significant quantities (SQ) of nuclear material and deterrence of such diversion by the risk of early detection.
    - Detection with timeliness*
    - Detection before diversion of significant quantities* of nuclear material
    - Deterrence of diversion through early detection capability

Notes*

- **Significant quantity [1]**
  - Estimated amount of nuclear material for manufacturing a nuclear explosive device
  - Depending on the type and form of nuclear material
- **Timeliness goal [1]**
  - Proper timeliness for detecting diversion of nuclear material
  - Depending on the type and form of nuclear material

- **Partial defect [2]**

— Gross defect refers to an item or batch that has been falsified to the maximum extent possible, so that all or most of the declared material is missing.

— Partial defect refers to an item or batch that has been falsified to such an extent that some fraction of the declared amount of material is actually present.

— Bias defect refers to an item or batch that has been slightly falsified so that only a small fraction of the declared material is missing.

Purpose of the Research

- **Partial defect detection**
  - Assemblies with partial defect are generated due to leaking fuel rod handling during normal operation.
    - Leaking rods are replaced into dummy fuel rods and the assembly with dummy rods are re-inserted into core [3]
    - Number and management of leaking fuel rods are reported by state-level report
  - Lack of safeguards instruments that can detect partial defects that meet the requirements of IAEA [4]
  - Difficult due to the presence of a large number of spent fuel assemblies,
    - It is almost impossible to verify every spent fuel assembly using the conventional inspection system.
    - Diverting small amount of nuclear material from a single spent fuel assembly can achieve the accumulation of significant quantity of nuclear material.

Purpose of the Research

- **Literature review**
  - Major detectors for spent fuel partial defect detection:
    - Safeguards MOx Python (SMOPY, CEA&COGEMA)
    - Partial Defect Detector (PDET, LLNL)
    - Gamma emission tomography (STUK)
    - Digital Cerenkov Viewing Device (DCVD)

Type of detector	Components	Capabilities	Characteristics	Limitations
SMOPY [5, 6]	- Fission chamber - Gamma spectrometric probe - On-line depletion code	- Distinguish LEU spent fuel assembly from MOX spent fuel assembly - Full characterization of LEU spent fuel assembly - Partial defect detection of LEU spent fuel assembly	- Accurate characterization of spent fuel assemblies	- Fuel movement is required. - It takes time to analyze a spent fuel assembly.
PDET [7-10]	- Thermal neutron counter - Gamma ray counter	- Qualitative analysis - System application inside guide tubes of a spent fuel assembly	- Partial defect detection without assembly movement	- Resolution for less than 10% diversion was not verified. - High price

Table 1-a). Characteristics of partial defect detectors in literature.

Purpose of the Research

- **Literature review**
  - Major detectors for spent fuel partial defect detection

Type of detector	Components	Capabilities	Characteristics	Limitations
Gamma Emission Tomography [5, 11]	- A number of gamma ray detector (similar to CT)	- Two dimensional (2-D) image reconstruction from measured activity profiles	- Real partial defect verification on fuel pin level	- System requires spent fuel assembly movement and rotation (long time).
DCVD [5, 12, 13]	- Blue/UV sensitive camera	- Qualitative analysis - Detection of Cerenkov radiation at directly above an assembly	- Easy, fast, and non-intrusive.	- Spent fuel assemblies out of cooling pool cannot be verified.

Table 1-b). Characteristics of partial defect detectors in literature.

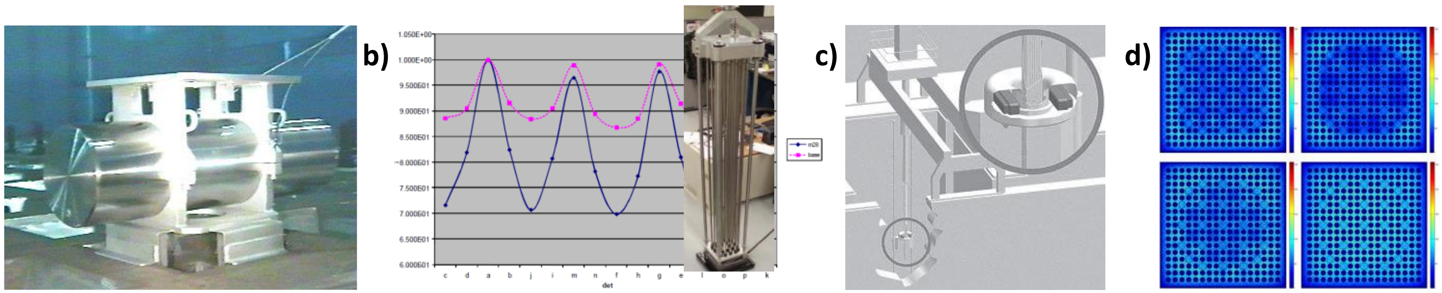
a)


Fig. 1. Design and output of partial defect detectors in literature; a) SMOPY design, b) PDET design and analysis result, c) Gamma emission tomography design, d) DCVD analysis results.

Purpose of the Research

- **Limitations of existing partial defect detectors**
  - Some detectors require long detection time.
  - Some detectors can be applied only to specific environment.
- **Purpose of the research**
  - To develop **"simple and fast"** partial defect detector.
  - Two main design requirements:
    - Short detection time
    - High resolution

Scintillator based Partial Defect Detector (SPDD)

- **Characteristics of SPDD**
  - Resolution is high enough for detecting partial defects.
  - Detection time is short enough to screen every spent fuel assemblies.
    - Detection time ~ 20 sec/assembly
  - SPDD does not require spent fuel movement and additional intrusion.
  - SPDD can be applied to both dry and wet environment.

- **Operating principle of SPDD**
  - SPDD converts spent fuel gamma radiation into electricity using scintillator and photovoltaic cell.
  - Since dummy fuel rods in a defective fuel assembly do not generate gamma radiation, electricity generation near dummy fuel rods decreases compared to other locations.
  - SPDD detects defective fuel assemblies using the generated electricity difference.

Scintillator based Partial Defect Detector (SPDD)

- **SPDD – conceptual design**

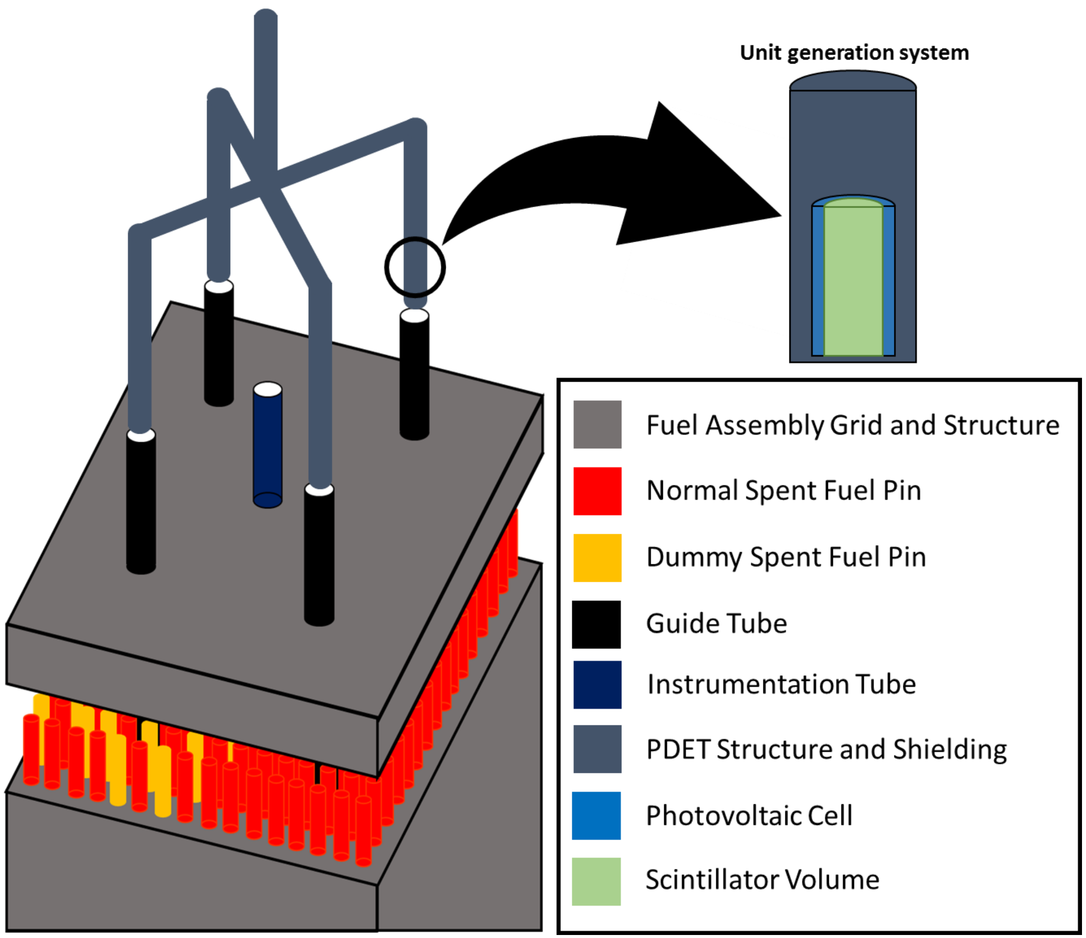


Fig. 2. Conceptual design of a scintillator based partial defect detector (SPDD) applied to a PLUS7 PWR fuel assembly.

Methods for partial defect detection (fuel rod)

1. Four **unit generation systems** (single scintillator-photovoltaic cell) **are inserted into guide tubes** of a fuel assembly.

2. Since spent fuel gamma radiation is attenuated by fuel rods and assembly structure, each unit generation system is mainly irradiated by neighboring fuel pins.

3. Radiation from spent fuel pins is converted into visible photons via a scintillator volume of a unit generation system.

4. Photovoltaic cell generates electricity using the scintillated photons

5. SPDD distinguishes defective assemblies from normal assemblies by comparing the amount of generated electricity between each unit generation system.

6. Calculate relative current generation (R_{unit}), which is current generated by a unit generation system divided into the maximum current generated in the assembly.

$$\left(R_{unit} = \frac{I_{unit}}{I_{max,unit}} \right)$$

7. Compare relative current generation between a normal assembly and defective assembly.

Damage to SPDD in spent fuel storage environment

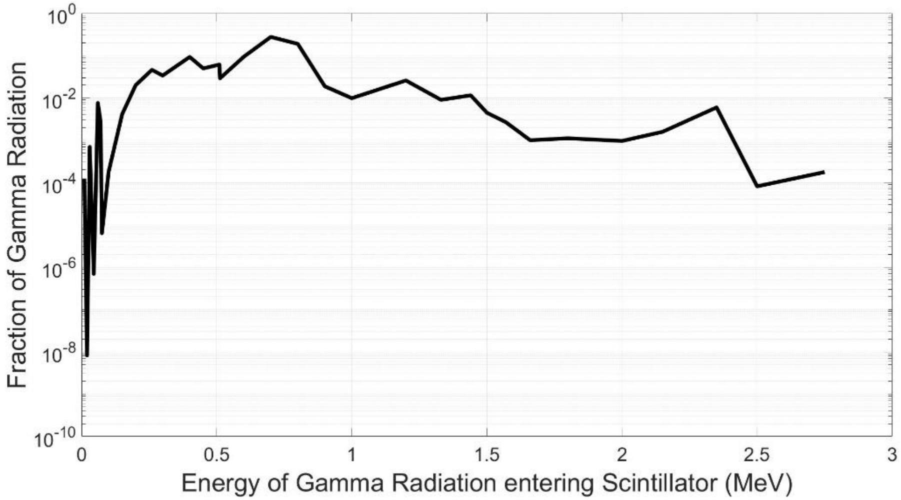
- **Challenges for SPDD application in spent fuel storage environment**
  - Scintillator damage caused by gamma and neutron irradiation
    - Previous studies on scintillator damage mainly focused on decreased PMT signal and absorption coefficient change after irradiation.
    - SPDD irradiation experiment using Cs-137 gamma source.
    - SPDD irradiation experiment using neutron source in KIRAMS
  - Signal to noise ratio in radiation environment
  - Photovoltaic cell damage cause by spent fuel radiation
    - Amorphous silicon (a-Si) photovoltaic cell have extremely high radiation resistance [14].
  - Scintillator damage caused by heat from spent fuel
    - Light output is almost constant between $-40℃$ to $70℃$ with temperature stability $-0.1 \sim -0.3\%/℃$ [15].
  - Photovoltaic cell damage caused by heat from spent fuel
    - J_{SC}, V_{OC} change for a-Si photovoltaic cell between 273K and 523K are less than 20% [16].
  - System application feasibility demonstration
    - Similar approach in the literature (PDET) [7]

Damage to SPDD in spent fuel storage environment

- **Scintillator damage caused by spent fuel gamma and neutron irradiation**
  - Calculate the amount of gamma and neutron irradiation to scintillator in spent fuel storage environment
  - Gamma and neutron irradiation to scintillator were analyzed using a PLUS7 PWR fuel assembly with these characteristics:
    - 47.34GWD/tU discharge burnup
    - 4.0wt% enrichment
    - 1 year cooling time (for conservatism)
  - The OrigenArp and MCNPX code were used to analyze the amount of gamma and neutron irradiation to scintillator using the given spent fuel assembly
- **Signal-to-noise analysis**
  - Perform experiment using a gamma source whose dose rate is similar to spent fuel storage environment

Damage to SPDD in spent fuel storage environment

- **Characteristics of gamma and neutron entering scintillator**



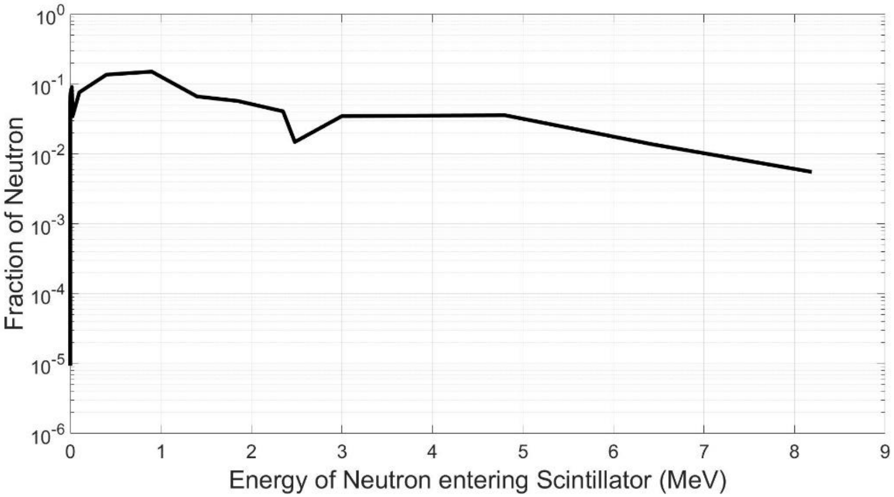


Fig. 3. Energy distribution of gamma (left) and neutron (right) entering scintillator in spent fuel storage environment.

- Gamma dose rate to scintillator volume
  - 146.06Gy/hr
  - Experiment with few kGy dose to a scintillator was performed for conservatism

- Neutron flux to scintillator volume
  - $4.3020 \times 10^7\ \#/\mathrm{cm}^2\mathrm{hr}$
  - Experiment with neutron fluence higher than 10^{10} was performed for conservatism

Damage to SPDD in spent fuel storage environment

- **Experiment on gamma damage to SPDD**
  - Gamma source requirement:
    - Total dose > few 100 Gy, Dose rate > few 10 Gy/hr
  - $CdWO_4$ scintillator
  - Gamma source used
    - Cs-137, 8.51GBq, 65.21Gy/hr
    - Total dose:
      - 130.42 Gy (2 hour irradiation)
      - 456.48 Gy (7 hour irradiation)
      - 1565.1 Gy (24 hour irradiation)
  - **Mean current change < 5% for 1.5kGy**
  - **STDEV increased after irradiation due to scintillator afterglow**

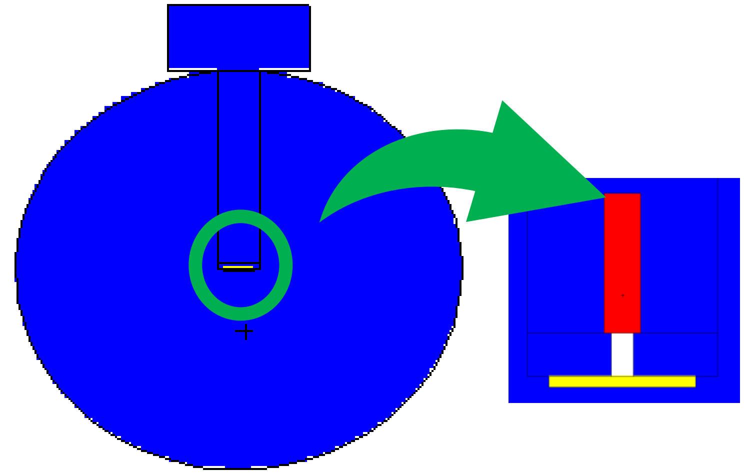


Fig. 4. Gamma irradiation experiment device (Blue: shielding, Red: Cs-137 source, Yellow: Scintillator)

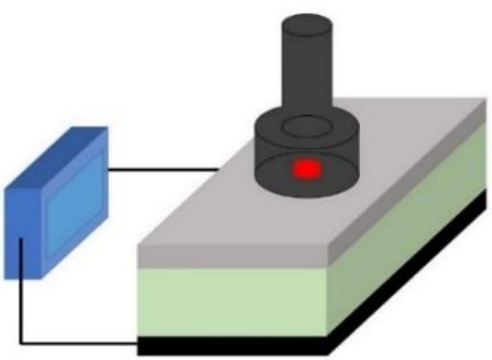


Fig. 5. Conceptual design of experiment device for current detection

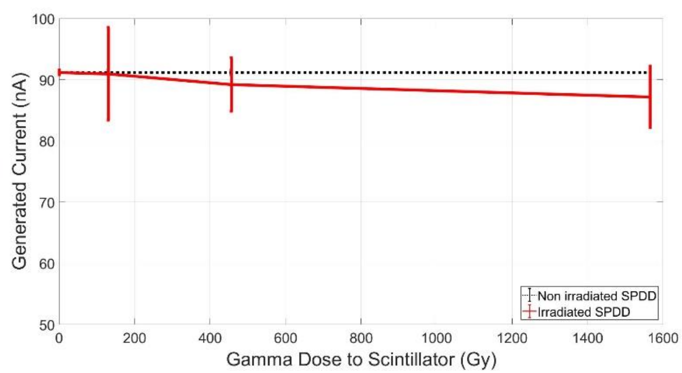


Fig. 6. Current generation before and after gamma irradiation

Table 2. SPDD damage before and after gamma irradiation

Gamma dose (Gy)	130.4	456.5	1565
I_{nonirr} (nA) [STDEV]	91.20 [0.3774]	91.19 [0.3772]	91.22 [0.3988]
I_{irr} (nA) [STDEV]	90.97 [7.547]	89.20 [4.377]	87.19 [4.993]
Error (%)	0.2477	2.188	4.414

Damage to SPDD in spent fuel storage environment

- **Signal-to-noise ratio in gamma environment**

  Experiment

  – Gamma source used
    - 65.21Gy/hr
      – Half of conservative spent fuel gamma dose rate
    - PV cell noise caused by high intensity gamma radiation was detected

  – Compare the amount of generated current between “photovoltaic cell only” and “photovoltaic cell with $CdWO_4$ scintillator”

  – Noise is negligible compared to generated signal.

Table 3. Signal-to-noise detection results

	PV cell – Scintillator	PV cell only
Current (nA)	91.1976	0.07767
STDEV	0.3774	0.6858

Damage to SPDD in spent fuel storage environment

- **Experiment on neutron damage to SPDD**
  - Neutron source requirement:
    - Total fluence > 10^8 neutrons to scintillator
  - Neutron source used to the experiment
    - Fluence > 10^{12} neutrons to $CdWO_4$ scintillator
    - $^9Be(p,n)^9B$ reaction with MC-50 proton cyclotron
    - 20uA, 20MeV proton intensity
    - Neutron intensity, energy distribution was calculated using $\sigma_{\ ^9Be(p,n)\ ^9B}$ and neutron energy distribution in literature [17]
  - **Mean current does not change**
  - **STDEV increased after irradiation due to scintillator afterglow**

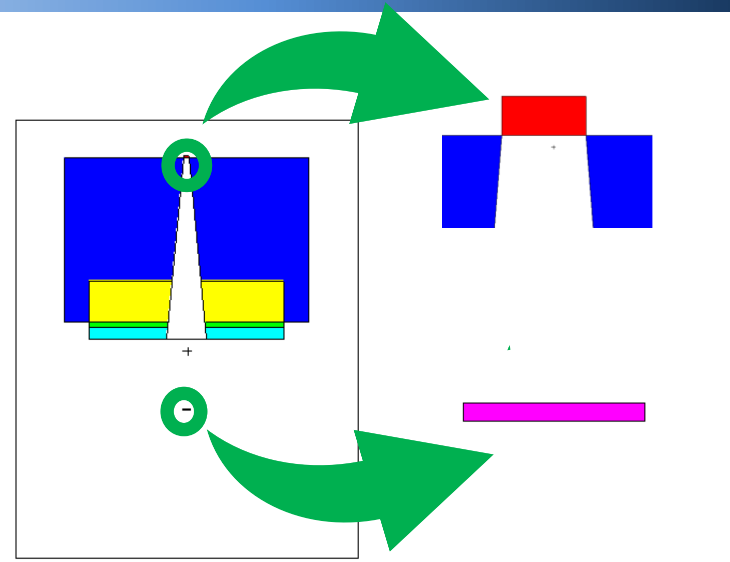


Fig. 7. Neutron irradiation experiment device (Blue: Iron, Yellow: Borated PE, Green: Lead, Cyan: Lead glass, Red: Neutron source, Magenta: Scintillator)

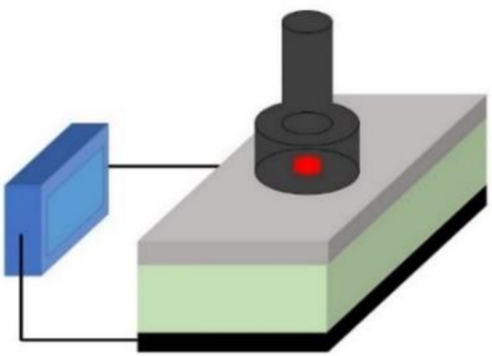


Fig. 8. Conceptual design of experiment device for current detection

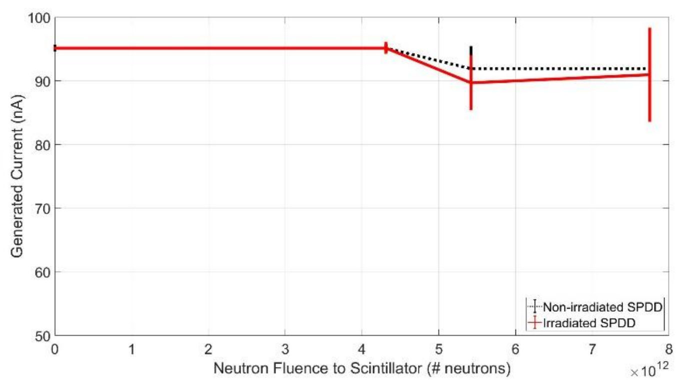


Fig. 9. Current generation before and after neutron irradiation

Table 4. SPDD damage before and after gamma irradiation

N fluence ($\times 10^{12}$)	4.3131	5.4192	7.7477
I_{nonirr} (nA) [STDEV]	95.15 [0.2948]	91.91 [3.354]	91.92 [3.353]
I_{irr} (nA) [STDEV]	95.18 [0.7047]	89.71 [4.080]	90.97 [7.194]
Error (%)	-0.040	2.390	1.020

SPDD performance analysis using computational model

- **Electricity generation analysis using computational model**

Computational model development for analyzing electricity conversion [18]

- Computer model based study as direct use of spent fuel is very difficult.
- The following codes were used: SCALE, OrigenArp, MCNPX.

- CdWO4 and amorphous Si were selected for scintillator and photovoltaic cell.
- The model calculation result was validated using a lab-scale experiment.

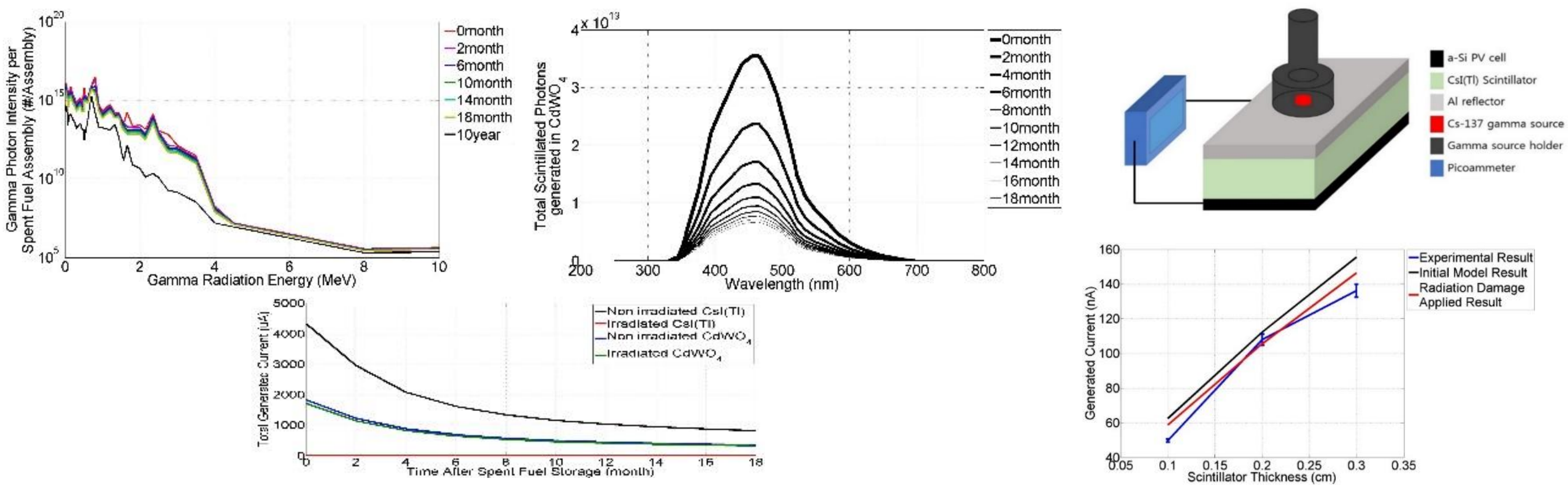


Fig. 10. Scintillator based electricity generation model and results of model validation experiments

SPDD performance analysis using computational model

- **Evaluation of simulation results**
  - Statistical error of MCNPX simulation has to be considered
    - Relative error of MCNPX simulation (RE): $RE = \frac{S_{\bar{x}}}{\bar{x}}$, ($S_{\bar{x}}$: STDEV, $\bar{x}$: mean) [19]
    - Each tally result of all test cases converged ($RE(I_{unit}) < 0.01$)
  - Relative error of relative current generation [20]
    - $R_{unit} = \frac{I_{unit}}{I_{max,unit}}$
    - $RE(R_{unit}) = \sqrt{\{RE(I_{unit})\}^2 + \{RE(I_{max,unit})\}^2}$
    - $STDEV(R_{unit}) = \mathrm{R}_{unit} \times \sqrt{\{RE(I_{unit})\}^2 + \{RE(I_{max,unit})\}^2}$ (1)
  - If the difference of relative current generation at a unit generation system in a target assembly and reference assembly is larger than 2-STDEV of MCNPX simulation and 1.5kGy gamma irradiation experiment, this research defined the target assembly to be a “suspicious assembly”.

SPDD performance analysis using computational model

- **Test case setup for SPDD performance analysis**
  - PLUS7 16x16 PWR fuel assembly, 1/8 symmetry
  - 47.33GWDTU discharge burnup
  - 10 years cooling time
  - Reference assembly and 9 defective assemblies
  - $CdWO_4$ scintillator with a-Si photovoltaic cell
  - Damaged fuel rods are replaced with stainless steel

SPDD performance analysis using computational model

- **Test case fuel assembly gamma source analysis**
  - Pin-wise burnup distribution was calculated using the SCALE code.
    - Every fuel pin is numbered from 10 to 41 (1/8 symmetry)
  - Gamma emitting fission product inventory and gamma intensity of each pin was calculated using the OrigenArp code for given burnup.
  - Gamma emitting fission products were selected if gamma decay heat of the fission product was higher than 0.01% of total gamma decay heat.

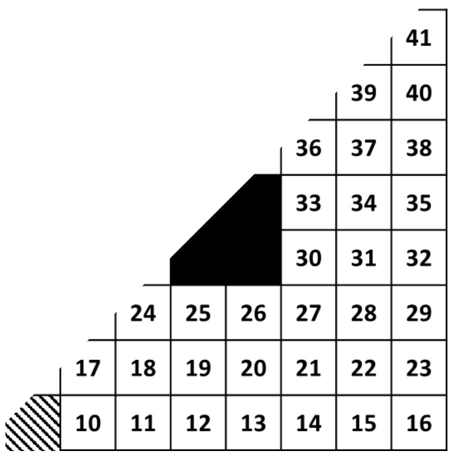


Fig. 11. 1/8 symmetry of PLUS7 PWR assembly

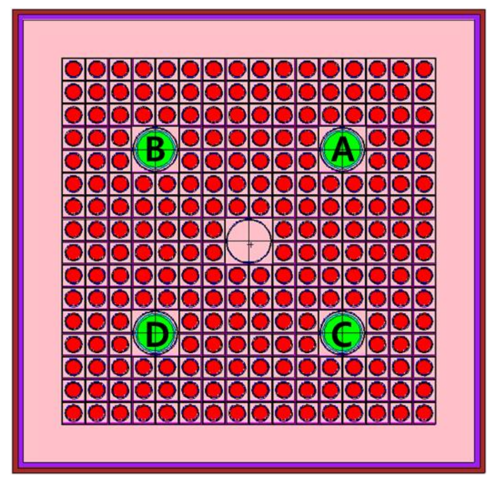


Fig. 12. Location of four unit generation systems (Red: Fuel pin, Green: SPDD unit generation system)

SPDD performance analysis using computational model

- **Test case spent fuel assemblies**

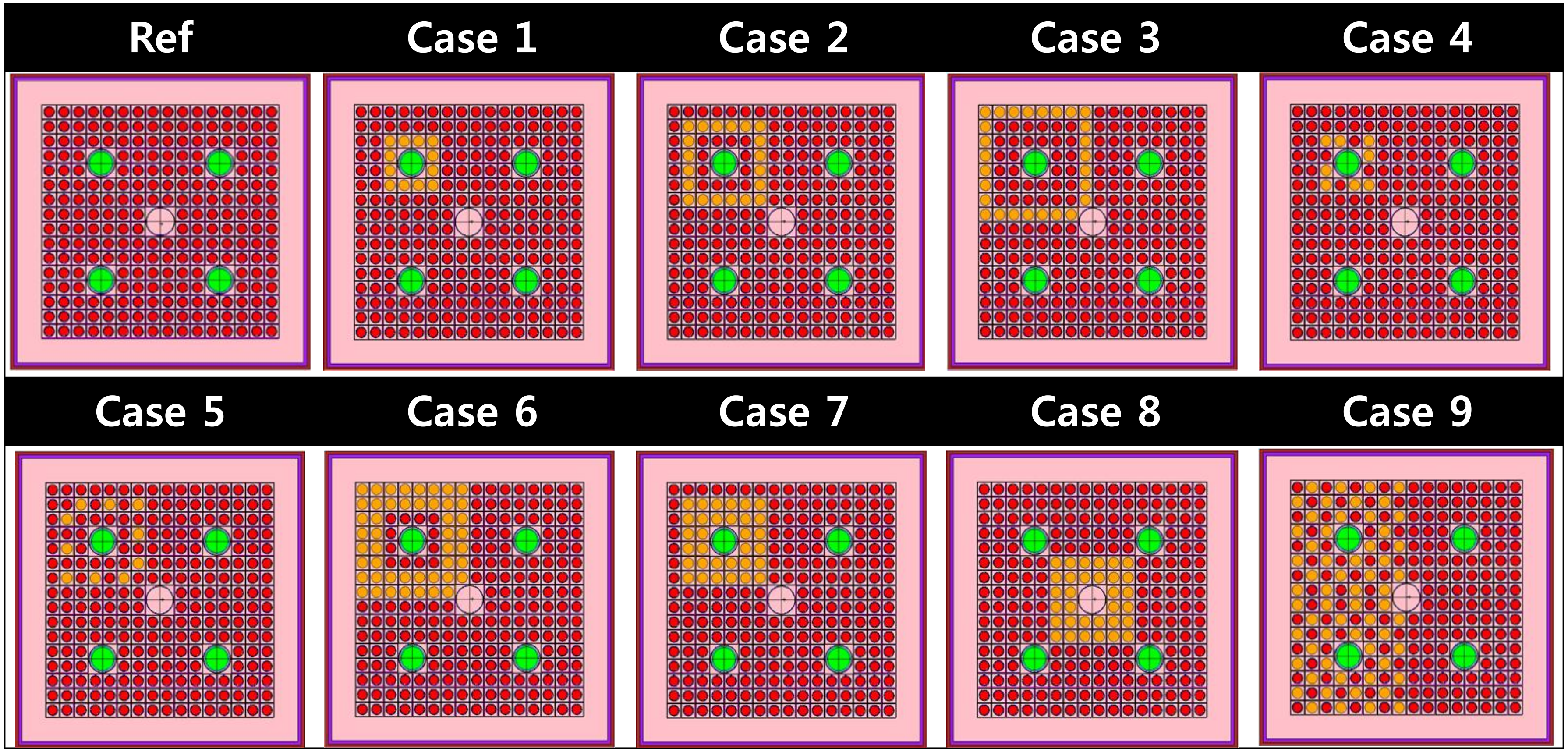


Fig. 13. Reference spent fuel assembly and 9 defective spent fuel assembly cases
(Red: Normal fuel pin, Orange: Dummy fuel pin (stainless steel), Green: SPDD unit generation system)

SPDD performance analysis using computational model

- **Results of SPDD performance analysis**
  - SPDD can distinguish non-symmetric defects
    - Every non-symmetric defective assemblies have relative current generation difference bigger than 2-STDEV of computational model and irradiation experiments
  - Future research is required for symmetric diversion

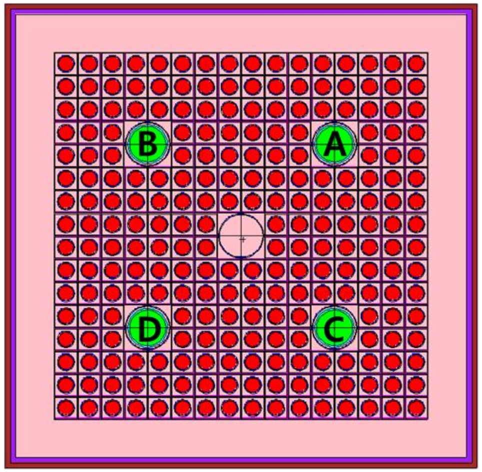


Fig. 14. Location of four unit generation systems

Table 5. Relative current generation of four unit generation systems for a reference assembly and 9 defective assemblies

	Relative Current			
	A	B	C	D
REF	0.9783	0.9872	0.9873	1.0000
CASE1	0.9786	0.6206	0.9878	1.0000
CASE2	0.9875	0.8282	0.9946	1.0000
CASE3	0.9791	0.9069	0.9898	1.0000
CASE4	0.9737	0.7726	0.9791	1.0000
CASE5	0.9802	0.9100	0.9901	1.0000
CASE6	0.9854	0.3721	0.9924	1.0000
CASE7	0.9850	0.7098	1.0000	0.9990
CASE8	1.0000	0.9738	0.9845	0.9539
CASE9	0.9875	0.6591	1.0000	0.6748

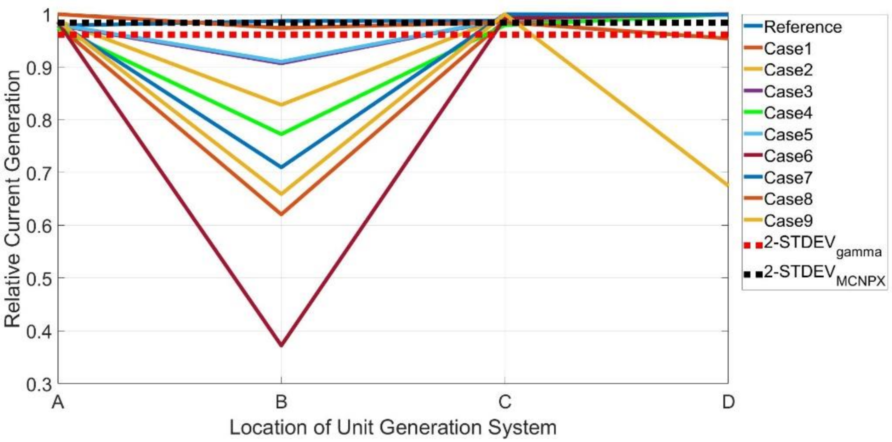


Fig. 15. Relative current generation of four unit generation systems for a reference assembly and 9 defective assemblies (2-STDEV in 1.5kGy gamma irradiation experiment and MCNPX simulation)

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Summary & Conclusions

- The effect of gamma and neutron irradiation on SPDD was examined by experiments
  - Both radiation damage to scintillator and signal-to-noise were negligible.
- The performance of SPDD was verified using a computational model developed in the previous research
  - Results indicate SPDD can distinguish defective assembly from normal assembly for non-symmetric pin diversion.

Future Work

- Economic feasibility have to be demonstrated
- Assemblies with symmetric defect has to be considered
- Define upper cooling time limit and lower burnup limit of a target spent fuel assembly
- Define spatial resolution of SPDD
- Effect of neighboring assembly

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Thank you for your attention!

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