Investigation of Advanced Spent Fuel Verification System in an Encapsulation Plant : Scintillator based Spent Fuel Gross and Partial Defect Detection System

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1. Motivation and Purpose of the Research

◆ Objective of Safeguards (IAEA, INFCIRC/153)[1]

- Timely detection of diversion of significant quantities of nuclear material and deterrence of such diversion by the risk of early detection.

◆ Verifying spent fuel is needed to prevent the diversion of spent fuel

- It includes gross defect detection, partial defect detection.
- If an entire spent fuel assembly or several fuel rods are replaced by dummy material, it becomes gross or partial defect respectively.
- It is a frequent pathway for diverting nuclear material to manufacture a nuclear explosive device.
- Since there are a number of spent fuel assemblies, diverting small amounts of nuclear material from a single spent fuel assembly can result in the accumulation of a significant quantity of nuclear material.

◆ Since conventional verifying methods have some limitations, simple and fast spent fuel verification is needed

- Cannot inspect every spent fuel assembly because of the limited inspection time .
- Cannot inspect spent fuel assembly out of specific area (i.e. spent fuel pool).

◆ Purpose of the research

- Develop a spent fuel defect detection system applied out of spent fuel cooling pool.
- Develop "simple and fast" spent fuel defect detection system for detecting the gross and partial defect of a spent fuel assembly.

2. Methods

2-1 Methods of electricity generation

- ◆ System consists of scintillator and photovoltaic cell
- ◆ Radiation from spent fuel is converted into visible photons via a scintillator.
- ◆ Photovoltaic cell generates electricity using the scintillated photons directly.
- ◆ The generated electricity becomes a signature or signal for a spent fuel rod/assembly.

2-2 Comparison between the method and scintillator detector

Table 1. Comparison of scintillator based electricity generation and scintillator detector.

	Scintillator based defect detector	Scintillator detector
Similarity	- Scintillator converts radiation into electricity. - Visible photons are converted into electrons producing a signal for detecting radiation.	
Difference	- Signals do not need to be amplified because target application is spent fuel environment. - No external high voltage source is needed since the generated electricity itself becomes a signal. - The system only consists of a scintillator and photovoltaic cell, which reduces its price compared to the scintillator detector.	- The main purpose is to detect radiation whose activity is much smaller than spent fuel radiation. - It contains a photomultiplier tube (PMT) and an external high voltage source to amplify the signal generated by scintillated photons.

2-3 Computational model development[2]

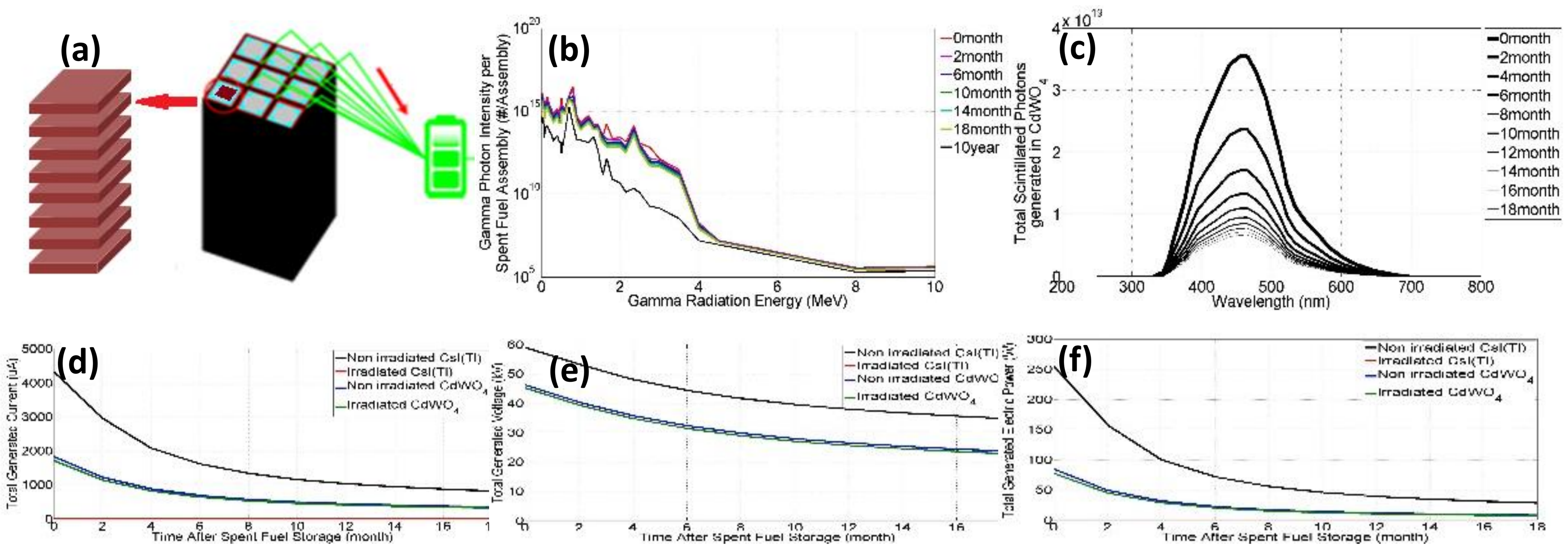

Fig. 1. Computational model description: (a) Conceptual system design geometry, (b) Spent fuel radiation analysis, (c) Scintillated photon analysis, (d) Generated current, (e) Generated voltage, (f) Generated power

2-4 Computational model validation

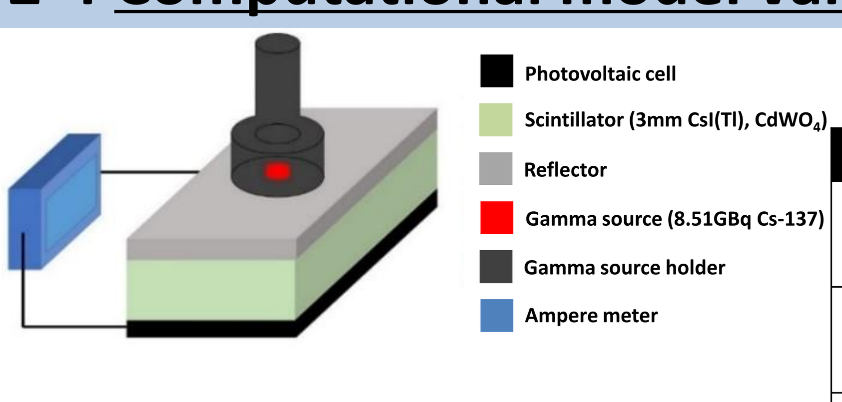

Fig. 2. Geometry of lab scale model validation experiment.

Table 2. Results of model validation experiment.

	CsI(Tl)	$CdWO_4$
Measured Current (nA)	136.2	113.0
Calculated Current (nA)	146.4	111.9
Error (%)	6.959	-0.988

3. Results: Potential applications

3-1 Gross defect detection

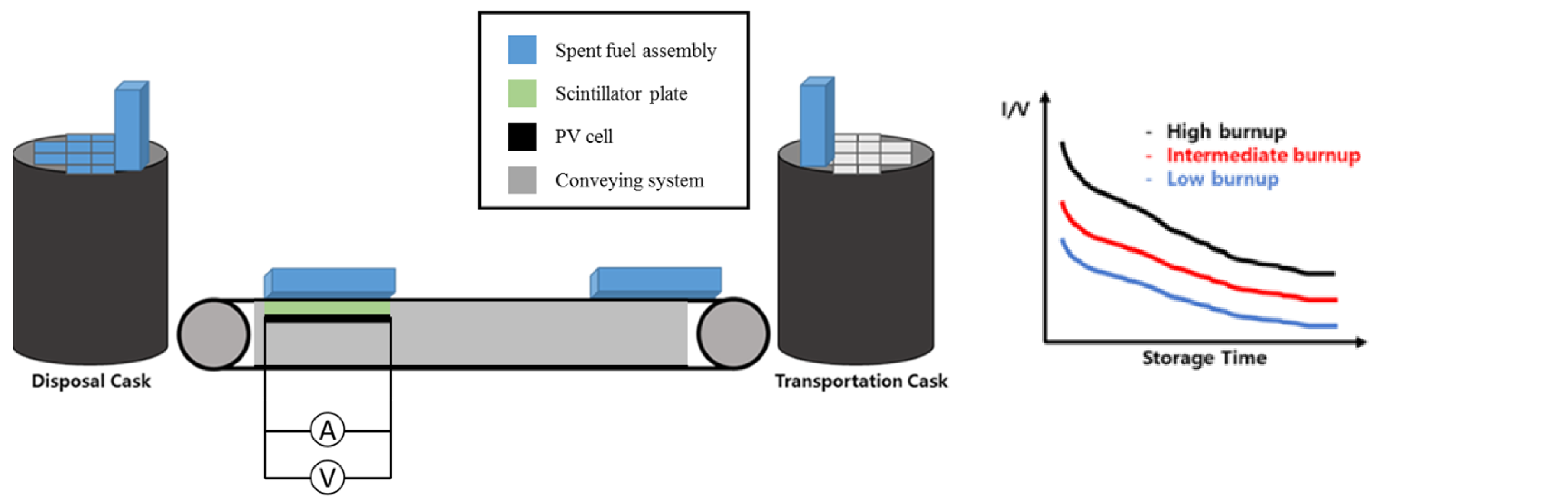

Fig. 3. Conceptual design of gross defect detector

◆ Test case analysis for feasibility demonstration.

- Spent fuel type: Westinghouse 16x16 PWR fuel assembly[3] with 3.5w/o enrichment
- 4 Burnup cases: 34.49, 39.33, 40.54, 47.34 GWd/tU [4]
- 8 Cooling times: 10, 15, 20, 25, 30, 40, 50, 60 year

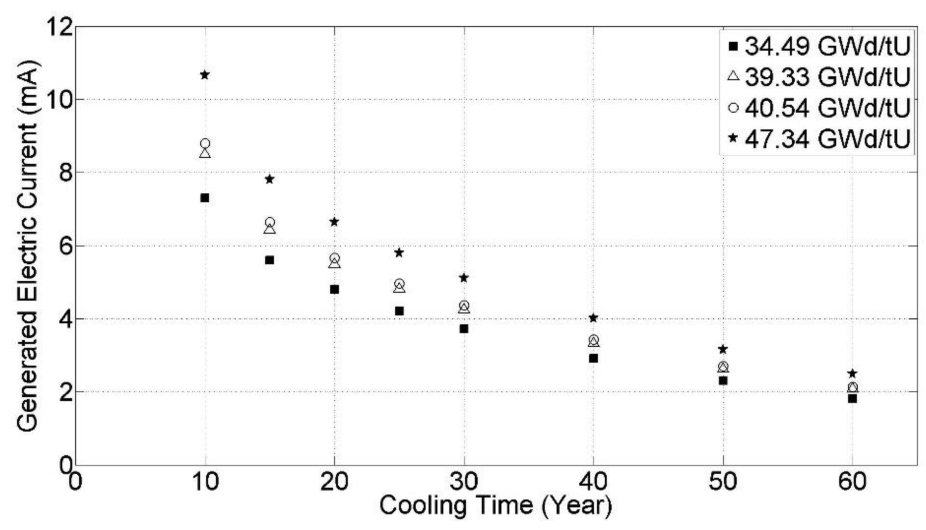

Fig. 4. Generated electric current using test case burnup/cooling time

- The gross defect of a spent fuel assembly can be detected during encapsulating process
- Spent fuel assemblies with significant difference in cooling time can be distinguished.
- The resolution of the burnup has to be improved because the difference in the generated current between 39.33 and 40.54 GWd/tU is too small.

3-2 Partial defect detection

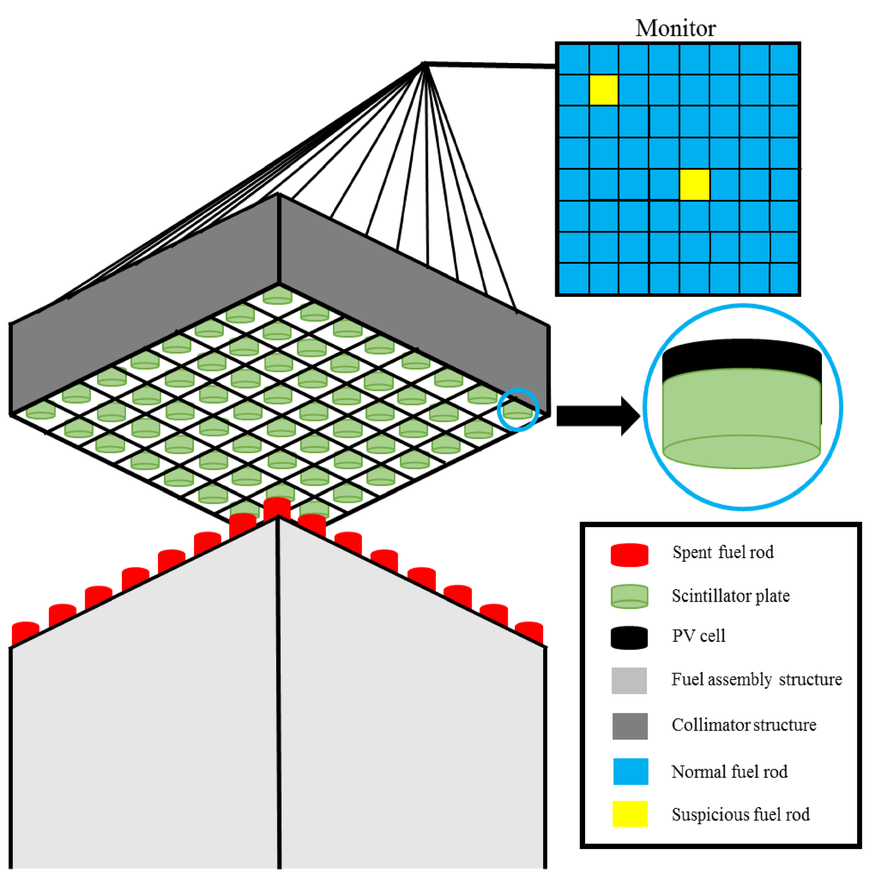

Fig. 5. Conceptual design of partial defect detector

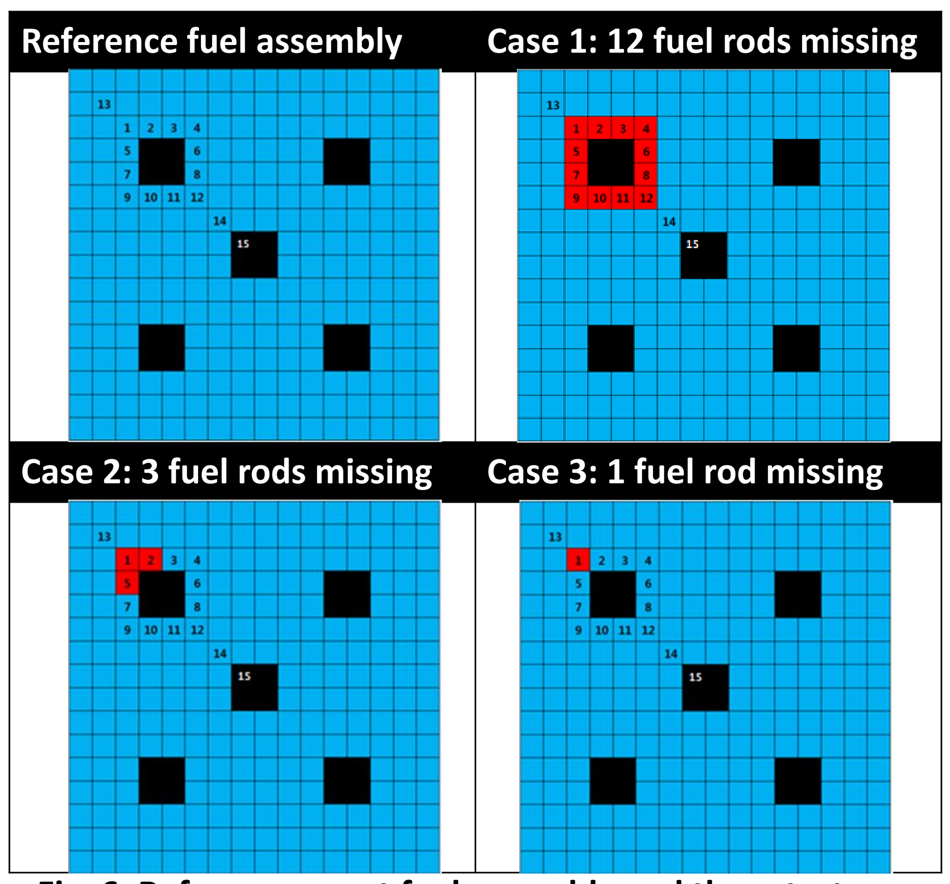

Fig. 6. Reference spent fuel assembly and three test case spent fuel assemblies with different partial defects

◆ Test case analysis for feasibility demonstration

- Reference spent fuel assembly: Westinghouse 16x16 PWR[3]
- Three different test case spent fuel assemblies with different defects
- Case 1: 12 rods missing, Case 2: 3 rods missing, Case 3: 1 rod missing
- 15 reference detecting positions

Table 3. Relative electricity generation of three defect cases compared to the reference (red: location of detect, yellow: location near defect, blue: location far from defect)

Location	Current (nA)				Voltage (mV)				Power (nW)			
	Ref	Case 1	Case 2	Case 3	Ref	Case 1	Case 2	Case 3	Ref	Case 1	Case 2	Case 3
1	1	0.6097	0.7627	0.9418	1	0.6105	0.7633	0.9419	1	0.3722	0.5821	0.8871
2	1	0.5458	0.7824	0.8794	1	0.5467	0.7830	0.8798	1	0.2984	0.6126	0.7737
3	1	0.5496	0.9089	0.9619	1	0.5506	0.9092	0.9621	1	0.3026	0.8263	0.9254
4	1	0.6234	0.9527	0.9819	1	0.6243	0.9529	0.9820	1	0.3892	0.9078	0.9642
5	1	0.5754	0.7959	0.9608	1	0.5498	0.7965	0.9610	1	0.3316	0.6339	0.9233
6	1	0.5768	0.9388	0.9743	1	0.5778	0.9391	0.9744	1	0.3332	0.8816	0.9493
7	1	0.5323	0.8786	0.9710	1	0.5332	0.8789	0.9711	1	0.2838	0.7722	0.9430
8	1	0.6010	0.9367	0.9809	1	0.6020	0.9370	0.9810	1	0.3618	0.8777	0.9623
9	1	0.6779	0.9605	0.9855	1	0.6787	0.9606	0.9855	1	0.4601	0.9227	0.9712
10	1	0.5833	0.9343	0.9730	1	0.5842	0.9345	0.9731	1	0.3407	0.8731	0.9468
11	1	0.5972	0.9365	0.9764	1	0.5982	0.9367	0.9765	1	0.3572	0.8772	0.9535
12	1	0.6705	0.9468	0.9794	1	0.6714	0.9470	0.9795	1	0.4502	0.8966	0.9592
13	1	0.7274	0.8481	0.9757	1	0.7280	0.8485	0.9758	1	0.5296	0.7196	0.9521
14	1	0.8808	0.9872	0.9936	1	0.8812	0.9873	0.9937	1	0.7762	0.9747	0.9873
15	1	0.9680	0.9972	1.0009	1	0.9681	0.9831	1.0009	1	0.9371	0.9944	1.0018

4. Conclusions

◆ Scintillator based gross and partial defect detector

- Feasibility of both systems was demonstrated.
- Results of scintillator based gross defect detector indicated there is enough difference in electricity generation if the burnup/cooling time is different.
- Scintillator based partial defect detector had enough resolution to detect the existence of one fuel rod diversion and roughly estimates the position of a partial defect.
- The system has potential to more quickly detect defects in a spent fuel assembly.
- The system suggested the possibility of adequate inspection without an inspector.

5. References

[1] IAEA, THE STRUCTURE AND CONTENT OF AGREEMENTS BETWEEN THE AGENCY AND STATES REQUIRED IN CONNECTION WITH THE TREATY ON THE NON-PROLIFERATION OF NUCLEAR WEATONS,INFCIRC/153, corrected, IAEA, 1972.
[2] Haneol Lee and Man-Sung Yim, Examination of spent fuel radiation energy conversion for electricity generation, Nuclear Engineering and Design, Vol. 300, pp. 384-392, 2016.
[3] M. L. Boone et al., DEVELOPMENT OF AN ADVANCED 16X16 WESTINGHOUSE TYPE PWR FUEL ASSEMBLY FOR SLOVENIA, 5th International Conference on Nuclear Option in Countries with Small and Medium Electricity Grids, 2004.
[4] "Country Details.", IAEA-PRIS, https://www.iaea.org/PRIS/CountryStatistics/CountryDetails.aspx?current=KR, 03 Oct. 2016.