NENS Nuclear Energy Environment and Nuclear Security Laboratory

KAIST Korea Advanced Institute of Science and Technology

Examination on the Property of Spent Fuel based Electricity Generation System – Scintillator Performance Analysis

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Motivation/Purpose of the research

- **Needs for emergency power source**
  - Some safety systems or functions can be operated with small amounts of electric power

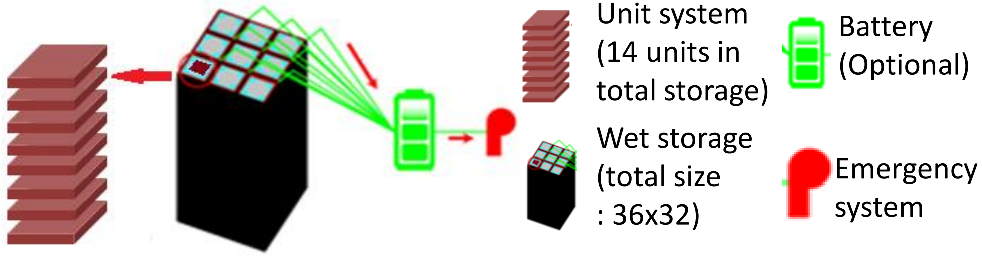
Type of the emergency system	Electric power demand (kW)
Monitoring system inside spent nuclear storage pool	~0.1
Detector system inside nuclear power plant	~10
Spent nuclear fuel storage cooling pump	30
Containment recirculation cooling fan	68
Recirculated cooling water pump	120
Residual heat removal pump	150
Containment water spray pump	161
480V MCC	226
Pressurizer heater	384
Safety injection pump	597

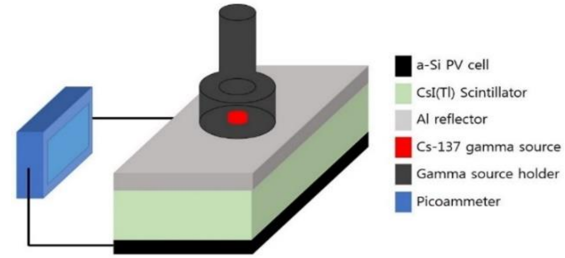
Table 1. Emergency systems operated under severe accident by its electric power demand [1]

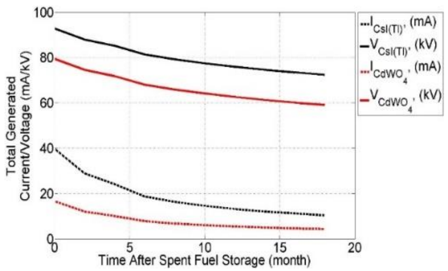
Overview of the Research

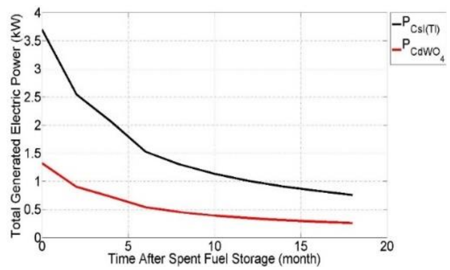
- **Electricity generation system using the radiation from spent fuel**

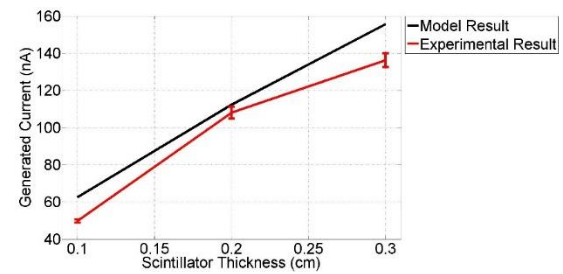
Previous results: Computational model development and model validation by experiment





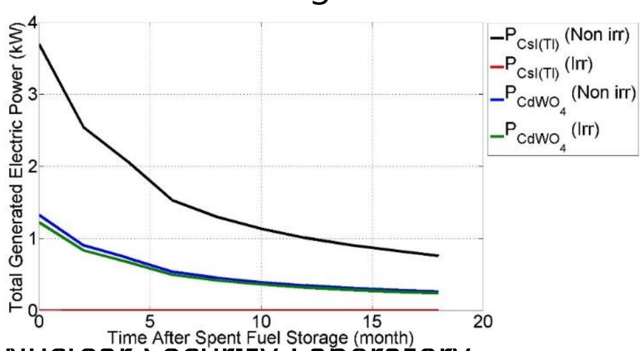


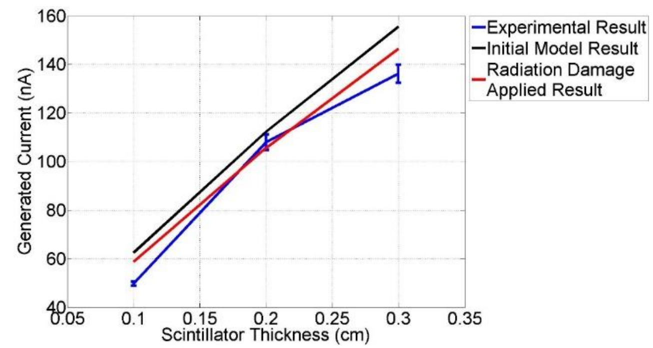




Results of current research: Scintillator performance analysis

- Reduce the computational model error by analyzing
  - The transparency of scintillator
  - Radiation damage on scintillator





Background of Electricity Generation System

- **System Overview**
  - Spent fuel assemblies are stored inside a wet storage.
  - Electricity generation systems are inserted and generate electricity.
  - The generated electricity can be used directly or stored in a battery system.
  - In an emergency situation, the generated electricity is used for emergency purpose.

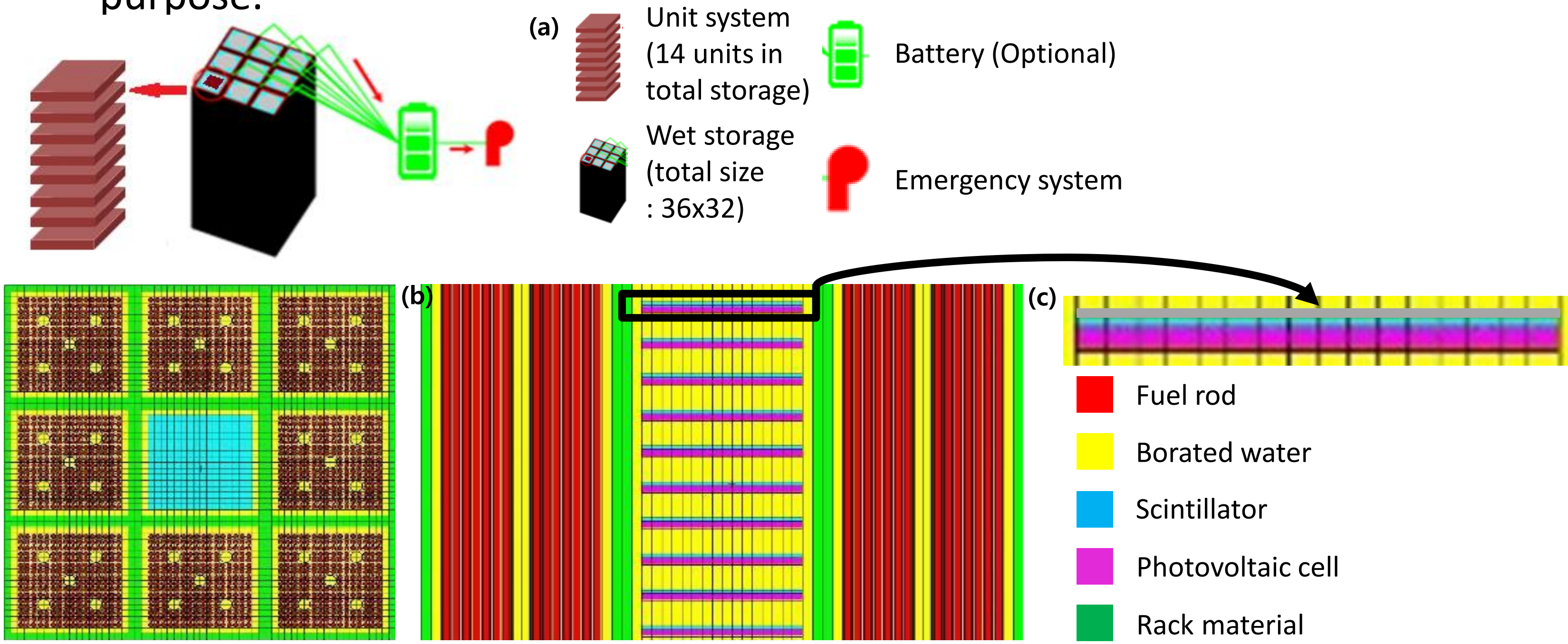


Fig. 1. Overview (a) top view (b) and side view (c) of a unit system design

Background of Electricity Generation System

- **Electricity generation system**
  - Scintillator and PV cell
    - Can generate electricity at spent fuel pool temperature
    - Can generate electricity without an external power
  - Methods to generate electricity
    - High energy gamma/neutron produces visible photons via scintillator
    - PV cell generates electricity using the scintillated photons
  - Materials used in this study
    - Scintillator: Cheap, long output wavelength, and inorganic
      - CsI(Tl): High light yield, relatively low radiation resistance
      - $CdWO_4$: High radiation resistance, relatively low light yield
    - Photovoltaic cell:
      - amorphous-Si: Cheap, High radiation resistance

Background of Electricity Generation System

- **Electricity generation was analyzed using a computational model for the total wet spent fuel storage**
  - Electricity generation system using CsI(Tl) generates more electricity than the system using $CdWO_4$ for **no radiation damage scenario**

	CsI(Tl)		$CdWO_4$	
	0 month	18 month	0 month	18 month
Current (mA)	39.793	10.456	16.628	4.3619
Voltage (kV)	92.883	72.398	79.494	59.127
Power (kW)	3.6961	0.7570	1.3219	0.2579

Table 2. Generated electric current, voltage, and power calculated by the model

- **Direct application**
  - Few 100W ~ kW
- **Store electricity using battery**
  - Ideal charging
  - 8 hour operation
  - CsI(Tl): 1,958kW
  - $CdWO_4$: 809.8kW

  - Model validation using experiment by comparing the results

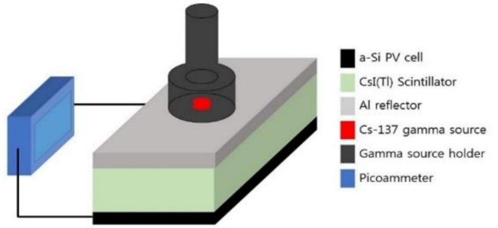


Fig. 2 System geometry of the model validation experiment
Radiation source: 8.51GBq, Cs137
Scintillator: CsI(Tl) 30x50x1, 2, and 3mm

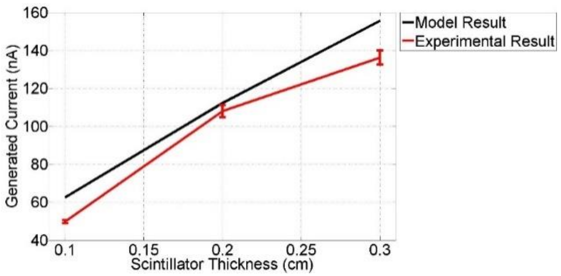


Fig. 3 Model validation experiment result

The overestimation of model caused
- Transparency defect caused by self-absorption of scintillated photons inside a scintillator
- Radiation damage to the system was not considered

Background of Electricity Generation System

- **Purpose of the scintillator performance analysis**
  - Reduce the error of the computational model by applying
  1. Scintillator transparency for scintillated photons
     - Analysis on the transparency of the scintillator material for scintillated photons
  2. Radiation damage on scintillator
     - Analysis on the effect of radiation damage for scintillator

Results

- **Scintillator analysis**

  1. Scintillator transparency for scintillated photons

     - An equation was derived to calculate the transparency of a scintillator for the scintillated photons
       - Figure 4 describes the geometry of the scintillator used in the derivation process

Assumptions

- The scintillated photons are generated uniformly in a scintillator
- The size of the scintillator is large enough. The scintillator can be analyzed using a 1-D model (z-axis)
- The scintillated photons have equivalent yield in +z and –z direction
- The radiation entering surface is blocked by a reflector whose reflectivity is 1
- The reflectivity of CsI(Tl) and $CdWO_4$ is low enough. Photons emitted directly and having one reflection were considered

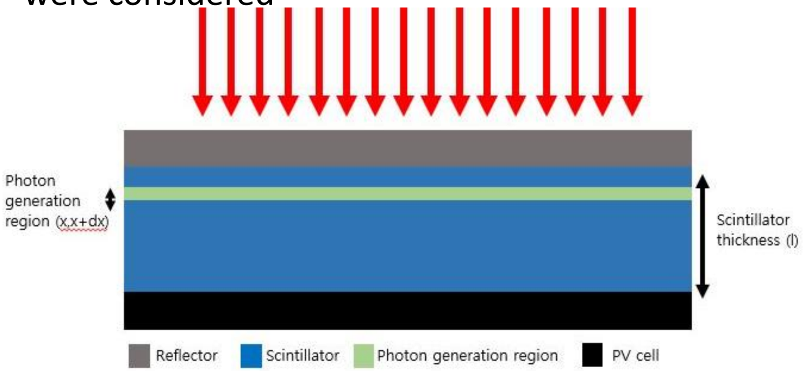


Fig. 4. The geometry of the transparency of a scintillator used in the electricity generation system

Results

- **Scintillator analysis**
  1. Scintillator transparency for scintillated photons
     - An equation was derived to calculate the transparency of a scintillating crystal for the scintillated photons

$$\mathrm{dT_{scint}} = \frac{\mathrm{dT_{up}}}{2} + \frac{dT_{down}}{2}$$

- $d\mathrm{T_{scint}}$: Transparency of scintillated photons generated in the photon generation region ($\mathrm{T_{scint}} = \frac{Photons\ entering\ PV\ cell}{Total\ scintillated\ photons}$)
- $d\mathrm{T_{up}}$: Transparency of scintillated photons having +z direction generated in the photon generation region

$$dT_{up} = \frac{1}{2}\left[(1-R)\frac{dx}{l}\exp(-a(l+x)) + (1-R)R\frac{dx}{l}\exp(-a(3l+x)) + \cdots\right]$$

- dT_{down}: Transparency of scintillated photons having +z direction generated in the photon generation region

$$dT_{down} = \frac{1}{2}\left[(1-R)\frac{dx}{l}\exp\left(-\frac{l-x}{LAL}\right) + (1-R)R\frac{dx}{l}\exp\left(-\frac{3l-x}{LAL}\right) + \cdots\right]$$

$$\mathrm{T_{scint}} = \int_0^l dT_{scint} = \frac{(1-R)}{2a(\lambda)l}[\{1-\exp(-2a(\lambda)l)\} + R\{\exp(-2a(\lambda)l) - \exp(-4a(\lambda)l)\}]$$

$$\boldsymbol{\therefore T_{scint}(\lambda, l) = \frac{(1-R)}{2a(\lambda)l}[\{1-exp(-2a(\lambda)l)\} + R\{exp(-2a(\lambda)l) - exp(-4a(\lambda)l)\}]}$$

$\mathrm{T_{scint}}$: Transparency of scintillated photon $\left(\frac{Photons\ entering\ PV\ cell}{Total\ scintillated\ photons}\right)$

R: Reflectivity of a material $\left(\left(\frac{n-n_{air}}{n+n_{air}}\right)^2, \mathrm{n:\ refractive\ index}\right)$

a(λ): absorption coefficient

λ: Wavelength of scintillated photon

l: Thickness of a scintillating crystal

Results

- **Scintillator analysis**
  1. Scintillator transparency for scintillated photons
     - Results of the transparency analysis for scintillators used in the computational model (3mm scintillator)

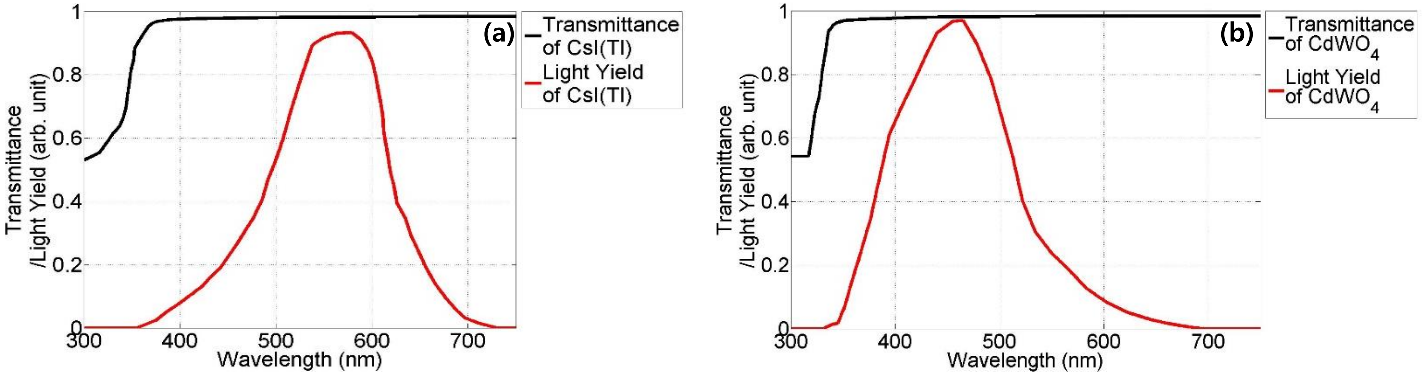


Fig. 5. The transparency of CsI(Tl) (a) and CdWO4 (b) used in the electricity generation system

Results

- **Scintillator analysis**

  2. Radiation damage on scintillator

     - Three main possible mechanisms of scintillator degradation caused by radiation [2, 3]

       1. Scintillation mechanism damage
          » No experimental evidence for this radiation damage [2 - 6]
       2. Radiation induced phosphorescence
          » Severe problem for signal processing in radiation detectors, but not a big problem in energy conversion system [2, 3]
       3. Radiation induced absorption [2, 3, 7]
          » Severe damaging mechanism for energy conversion system
          » Change the absorption coefficient of a scintillator to make the material non-transparent

Results

- **Scintillator analysis**

  2. Radiation damage on scintillator

     - Calculate absorption coefficient change after irradiation using an extrapolation model based on the irradiation experiment results in the literature (Fig. 6) [8, 9]
     - Apply the absorption coefficient change to the scintillator transparency equation to calculate transparency change after spent fuel irradiation
     - Total irradiated dose in spent fuel pool environment: 1E+13Gy
     - $DamageFactor(\lambda, Dose) \equiv \frac{a_{Before\ Irradiation}}{a_{After\ Irradiation}}$

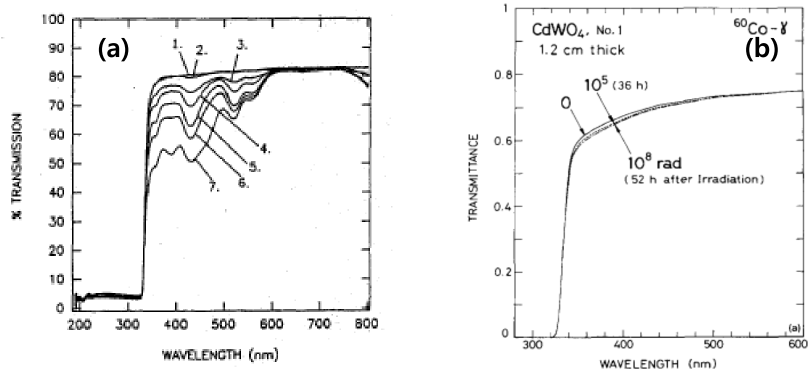


Fig. 6. Irradiation experiment results of CsI(Tl) (a) and CdWO4 (b) in literature (CsI(Tl): 1E+2~4.2E+4Gy, CdWO4: 1E+3~1E+6Gy)

Results

- **Scintillator analysis**

  2. Radiation damage on scintillator

     - Log-Linear model was used for extrapolation model
       - $DamageFactor(\lambda, Dose) = 1 - C(\lambda) \times \log_{10}(Dose)$
     - $C(\lambda)$ was calculated using least square method (LSM) for every wavelength
     - The goodness of fit test for the damage factor extrapolation was performed using R^2 method for some wavelengths [8, 9]

Wavelength (nm)	R^2 for CsI(Tl)	R^2 for $CdWO_4$
350	0.6614	0.9998
400	0.8082	0.9999
450	0.9565	0.9997
500	0.9494	0.9980
550	0.8064	0.9985
600	0.9859	0.9974

Table 3. The results of R^2 goodness of fit test for CsI(Tl) and $CdWO_4$

Results

- **Scintillator analysis**

  2. Radiation damage on scintillator

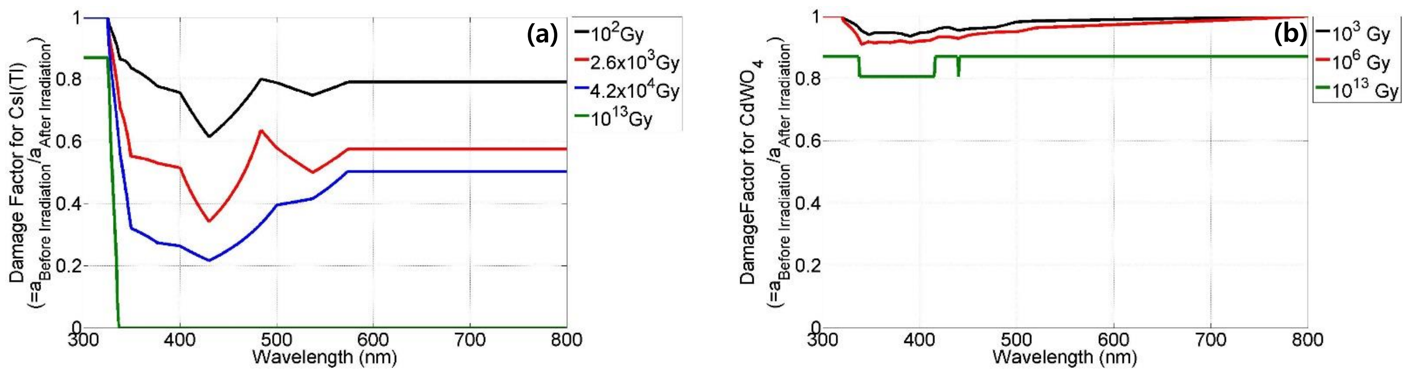


Fig. 7. Results for calculating damage factor of CsI(Tl) (a) and $CdWO_4$ (b) after irradiation

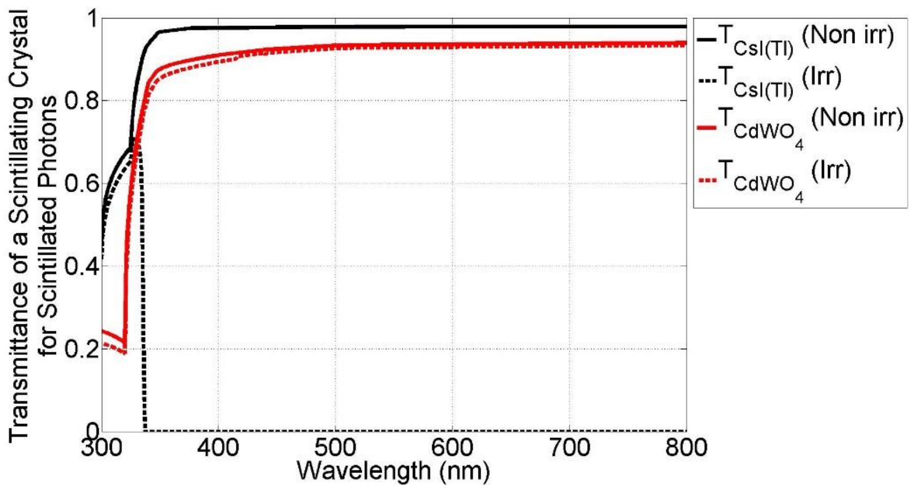


Fig. 8. Transparency change of CsI(Tl) and $CdWO_4$ after spent fuel pool irradiation

Results

- **Generated electricity after applying scintillated photon absorption and radiation damage**

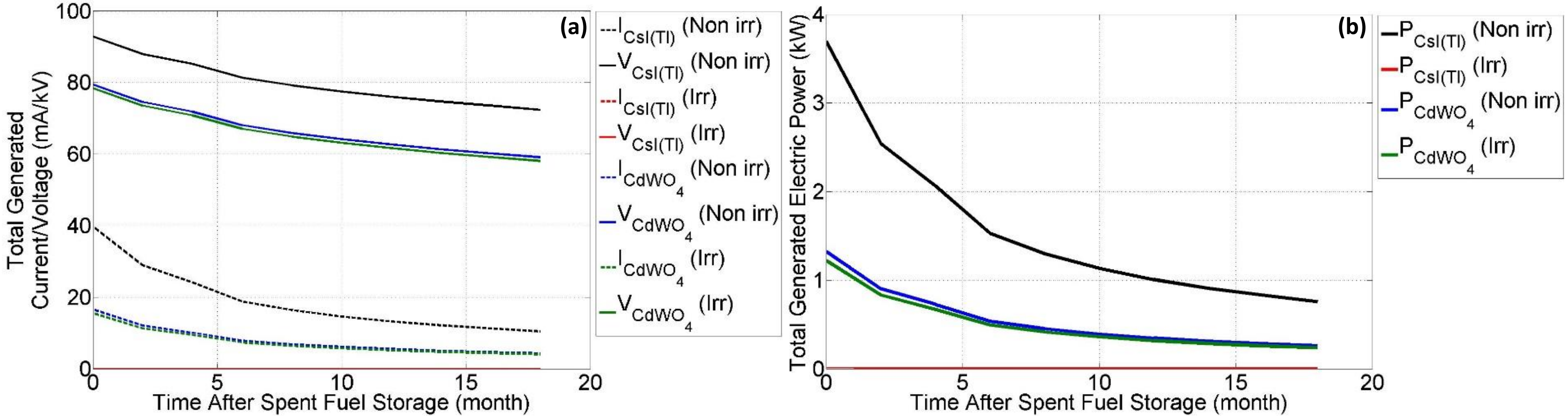


Fig. 9. Total generated electricity before and after applying scintillated photon absorption and radiation damage

Calculated Results	CsI(Tl)				$CdWO_4$			
	0 month		18 month		0 month		18 month	
	Non Irr.	Irr.	Non Irr.	Irr.	Non Irr.	Irr.	Non Irr.	Irr.
Current (mA)	39.79	0.000	10.46	0.000	16.63	15.53	4.362	4.080
Voltage (kV)	92.88	0.000	72.40	0.000	79.49	78.71	59.13	58.12
Power (kW)	3.696	0.000	0.757	0.000	1.322	1.221	0.258	0.237

Table 4. Total generated electricity before and after applying scintillated photon absorption and radiation damage

CsI(Tl) cannot be used for the electricity generation system in spent fuel pool environment and $CdWO_4$ have to be used.

Available electric power

- **Direct: 0.237~1.222 kW**
- **Stored in a battery: 785 kW**

Results

- **Model validation experiment results before and after applying scintillator analysis**

	CsI(Tl) Thickness		
	1mm	2mm	3mm
Measured Current (nA)	49.76	108.0	136.2
Ideal Calculated Current (nA)	62.49	112.3	155.6
Initial Error (%)	**20.37**	**3.829**	**12.47**
Calculated Current (nA)	58.78	105.6	146.4
Error (%)	**15.34**	**-2.304**	**6.959**

Table 6. Model validation experiment result after applying scintillator analysis

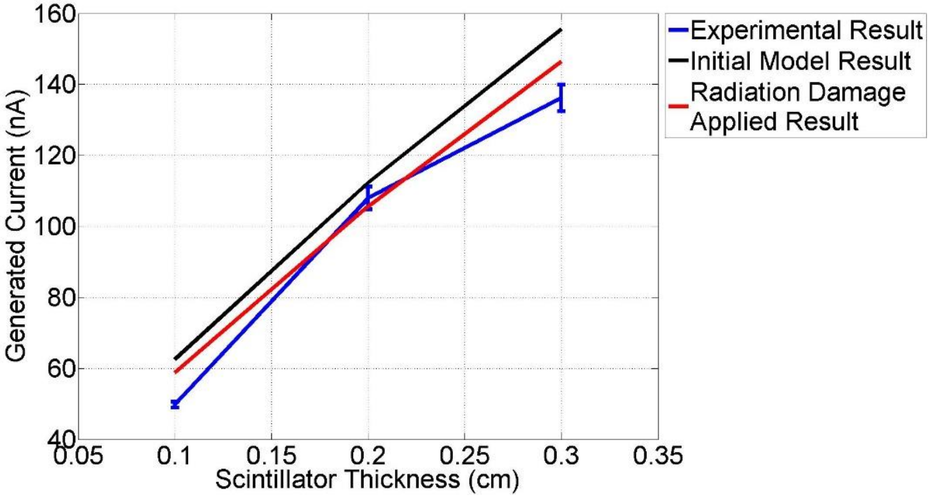


Fig. 10 Model validation experiment result after applying scintillator analysis

Conclusions

- This research analyzed non-ideal scintillator in electricity generation system using spent fuel radiation.
- CsI(Tl) and CdWO4 used in the system was almost transparent for non-irradiated case.
- Radiation damage on scintillator was analyzed using an extrapolation model based on experimental results in the literature.
- CsI(Tl) cannot be used for spent fuel storage pool because of its severe radiation damage. CdWO4 is used as a scintillator material of electricity generation system.
- **Generated electricity using $CdWO_4$ can be used to support emergency system in the severe accident situation.**

Future work

- **Future work**
  - Develop scintillator transparency equation in 3-D to demonstrate the geometry effect of the system
  - Validate the radiation damage model of scintillator by experiments using different gamma sources
  - Apply the 'electricity generation system using the radiation from spent fuel' for different applications which requires less electric power to use direct generated electircity
    - Spent fuel transportation monitoring system
    - Security system of an interim storage
    - Security/monitoring system of a geological disposal site

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Any questions?

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