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Sensitivity Analysis of SPNDs by Neutron Spectrum Using Monte Carlo Method

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1. Introduction

Nuclear power plants(NPP) should determine the amount of nuclear reaction that is related to the number of neutrons within the core [1]. Therefore, measurement of the neutron flux in the core is essential to estimate the reactor power. The technology of in-core detector is very important for securing safety and reliability of NPP. Self-Power Neutron Detectors (SPNDs) are widely used in-core detector. SPNDs are used not only as real-time neutron flux monitoring in research reactors but also as neutron detectors in the commercial reactors [2].

The concept of detector sensitivity is used by SPNDs to measure the current generated by electrons and convert them into neutron flux. A theoretical model for predicting sensitivity was proposed by Warren in 1972 [3]. Sensitivity is affected by various factors. Therefore, the sensitivity of the detector is important not only in determining the life of the detector but also in the control and safety of the reactor through accurate neutron measurement.

In this paper, the sensitivity behavior of SPNDs due to the difference in spectrum between pressurized water reactor(PWR) and HANARO are evaluated using the Monte Carlo method. Space charge effect, beta escape probability, and the sensitivity by the prompt electrons were calculated using the MCNP6 code, and the McCARD code was used for the calculation of the sensitivity by the delayed electrons. This study will be important for predicting the characteristics and behavior of SPNDs tested in HANARO when this is loaded on PWR.

2. SPNDs Sensitivity Calculation Model

The total sensitivity of SPNDs is calculated by the sensitivity of the prompt electrons due to the (n,γ,β) reaction and the delayed electrons due to the (n,β) reaction. The total sensitivity is given by

$$S_t = S_p + S_d \tag{1}$$

where the S_p and S_d are the sensitivity by prompt and delayed electrons. Unit of the sensitivity is C·cm^2.

2.1. Sensitivity by prompt electrons

The emitter material absorbs neutrons from the outside and becomes excited. It emits gamma rays to return to the ground state. At this time, the emitted gamma rays generate prompt electrons by the interaction with the materials in the emitter region. The sensitivity by prompt electrons was calculated as in Eq (2).

$$S_p = \frac{eT_p}{\phi_{emitter}} \tag{2}$$

where e is the electronic charge, T_p is the number of prompt electrons measured in the collector region, and $\phi_{emitter}$ is the average flux in the emitter area. T_p is calculated using the MCNP6 code.

2.2. Sensitivity by delayed electrons

The emitter material is excited by the neutrons and emits beta rays by beta decay to return to a stable state. It does not respond immediately because it is affected by the half-life of the nuclide. In addition, the emitter region is divided into 10 rings because the probability of escaping the emitter region is different depending on the generated position. Sensitivity due to delayed electrons is as follows.

$$S_d = \frac{eT_d}{\phi_{emitter}} \tag{4}$$

where number of electrons per second is given by

$$T_d = C \sum_{all\ ring} \varepsilon_i \Sigma_a \phi_i V_i \tag{5}$$

where ε_i is the beta escape probability, Σ_a is macroscopic absorption cross section, ϕ_i is a ring-specific neutron flux, V_i is the emitter volume, and the all ring is an area of 10 subdivisions to consider the beta escape probability. In case of a material with a very short half-life of the emitter nuclide, the half-life is ignored and the neutron absorption rate is assumed to be equal to the reaction rate of the electrons produced by the beta decay. However, since the half-life period cannot be ignored, it is possible to estimate the amount of electrons produced through the additional compensation factor. In this 1 was used as the compensation factor, C, because only short life nuclides were used.

2.3. Space charge effect

The space charge effect is a phenomenon that current flow is disturbed because of the electric potential generated by the charge existing around the object. Therefore, the concept of critical distance (r_o) and minimum energy (E_{min}) is applied to compensate for the space charge effect in the Monte Carlo code [4]. Collectors measure electrons passing critical distance with energy above minimum energy. E_{min} is given by

$$E_{\min} = \exp\{6.6 - [34.662 - 10.48 \times \ln(\bar{r}\rho)]^{1/2}\} \quad (6)$$

$$\bar{r} = \frac{(r_i - r_e)}{(1-k)}\left(\left[\frac{1-k^2}{2\ln(1/k)}\right]^{1/2} \times E\left\{k\left[\frac{2\ln(1/k)}{1-k^2}\right]^{1/2}\right\} - k \right. \quad (7)$$

where $\bar{r}$ is the average track length from emitter surface to critical distance, and ρ is density of insulator r_i and r_e is the outer radius of the insulator and emitter. k is the ratio of the emitter to insulator radius. E (erg) is complete elliptic integral of the second kind. And critical distance is as following Eq:

$$r_o = r_i\left[\frac{1-k^2}{2\ln(1/k)}\right] \quad (7)$$

A more detailed description is given in reference 3.

2.4. Beta escape probability

Beta escape probability(ε) is the probability that electrons generated in the emitter region will be measured by the collector. This is largely influenced by the location of the beta particles in the emitter region. ε will be expressed as

$$\varepsilon = \int_0^{E_\beta} B(E_\beta)\varepsilon(E_\beta, r)dE_\beta \quad (8)$$

where $B(E_\beta)$ is beta electron energy spectrum, and $\varepsilon(E_\beta, r)$ is the probability of beta electrons departing from position r [3].

2.5. Neutron energy spectrum

This section produces neutron energy spectrum for sensitivity calculations for HANARO and commercial PWR.

Fig. 1 is a topview of the HANRO entire core. In order to produce the neutron energy spectrum, the irradiation hole to be loaded with the SPNDs capsule was set as the tally area. The PWR used a 16x16 fuel assembly. The instrumentation tube region at the center of the fuel assembly was set as a tally region for calculating the neutron energy spectrum of PWR.

Fig. 3 graphically shows the neutron energy spectrum of HANARO and commercial PWR. HANARO's thermal neutron spectrum peak is higher than PWR. On the other hand, the neutron energy spectrum of PWR has higher in the fast neutron spectrum. This difference of spectrum can affect the behavior of the sensitivity.

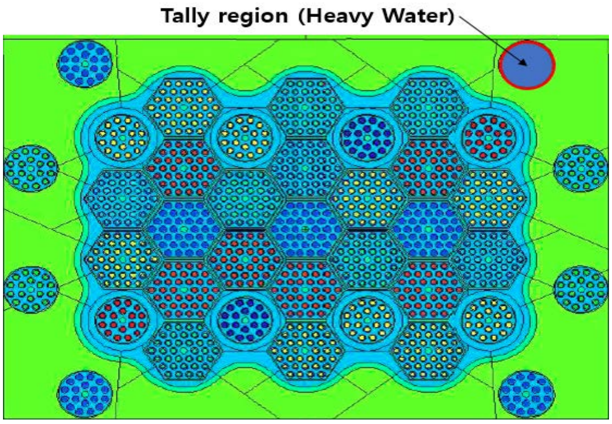

Fig. 1. Configuration of irradiation hole in HANARO

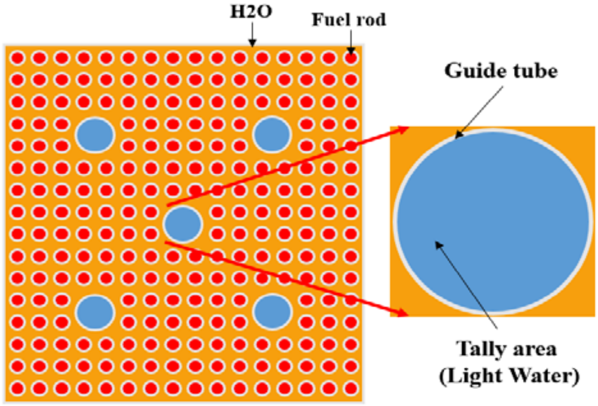

Fig. 2. Configuration of single fuel assembly of PWR

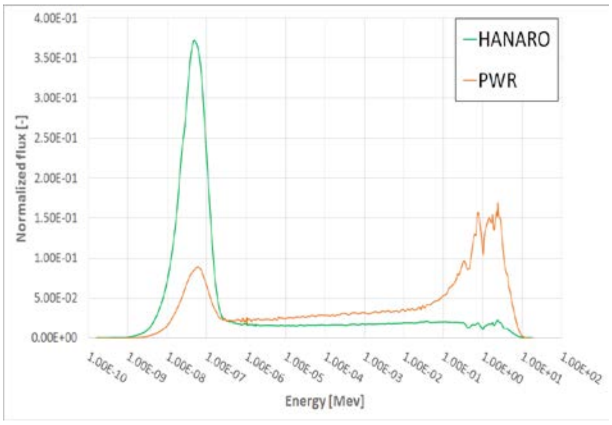

Fig. 3. Calculated spectrum

2.6 Calculation model

SPNDs consists of an emitter, an insulator and a collector. Cobalt, vanadium and rhodium were used as the emitter, aluminum oxide was used for the insulator, and Inconel 600 was used for the collector. Outside the collector, there is a 1cm thick light or heavy water, and the initial source with the neutron energy spectrum in the region is distributed. Fig. 4 is a radial view of the model used for the sensitivity calculation. The emitter region is subdivided into 10 rings. The reason is to apply different beta escape probability to each emitter position. The specification of the SPNDs is summarized in Table I.

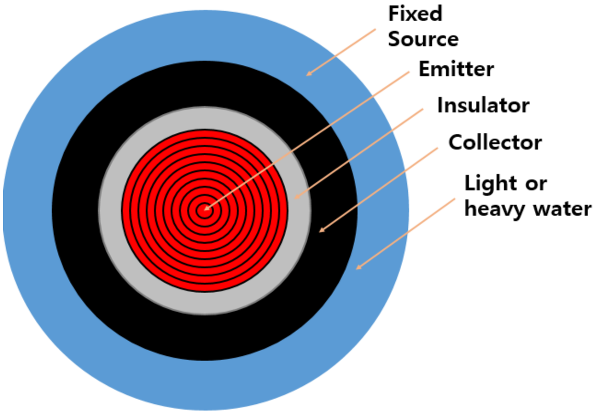

Fig. 4. Configuration of SPNDs calculation model

Table 1: SPNDs specification and initial nuclide

SPNDs	Initial Nuclide	ρ (g/cm^2)	R$_e$* (mm)	R$_c$** (mm)
Vanadium	^{50}V, ^{51}V	6.10	0.700	1.415
Cobalt	^{59}Co	8.90	1.000	2.000
Rhodium	^{103}Rh	12.41	0.230	0.790

* R$_e$: Radius of the emitter, **R$_c$: Radius of the collect

3. Result

In this section, the SPNDs relative sensitivity was calculated depending on the HANARO spectrum and commercial PWR spectrum. The relative sensitivity is the ratio of the sensitivity of each burnup step to the initial sensitivity. McCARD and MCNP6 code were used for the relative sensitivity calculation. The conditions of the calculation of total charge is time period with 10 years. Compared with vanadium, the long-half-life nuclides, rhodium and cobalt burn out within a short period of time and disappear. In particular, since the average burning rate of Rh^{103} is 9.17%/years, 10 years in which rhodium is mostly consumed is used as calculation time.

3.1 Vanadium SPND

Vanadium generates 99% of electrons via delayed beta emission reactions and 1% of electrons via prompt gamma reactions. Therefore, the relative sensitivity is affected not only by the delayed electrons generated by ^{51}V but also by the prompt electrons generated by the ^{52}V [5].

Fig. 5 shows the relative sensitivity of vanadium SPNDs depending on the HANARO spectrum and PWR spectrum. The total charge of vanadium SPNDs calculated using the HANARO spectrum is about 30.8C, and the total charge calculated using the PWR spectrum is 10C. The reason for the difference in total charge measured over 10 years is that the neutron absorption cross section of vanadium differs depending on the spectrum. In addition, the relative sensitivity change rate has a similar tendency in the two spectrum.

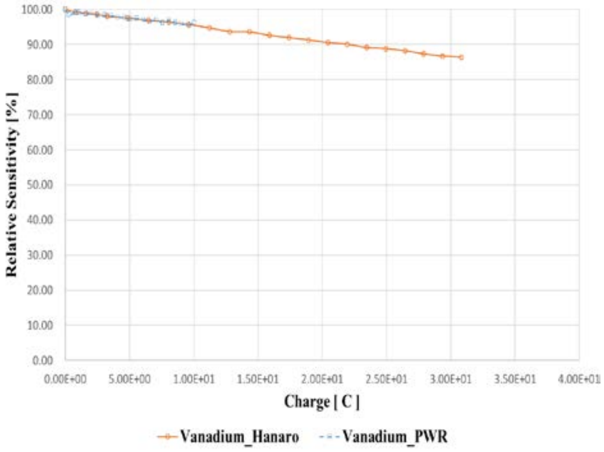

Fig. 5. Comparison of relative sensitivity of vanadium SPNDs

3.2 Cobalt SPND

Cobalt SPNDs is a prompt detector, unlike rhodium and vanadium SPNDs. Therefore, it has the advantage of a quick reaction but the signal is small and interpretation is difficult [6].

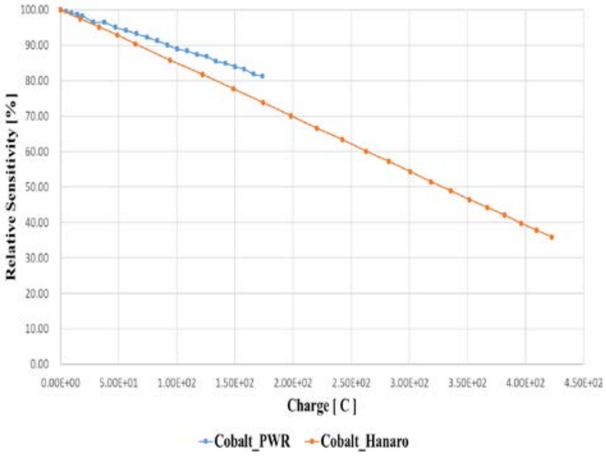

Fig. 6. Comparison of relative sensitivity of cobalt SPNDs

Fig. 6 shows the relative sensitivity of the Cobalt SPNDs to HANARO spectrum and PWR spectrum. A larger amount of charge was measured in cobalt SPNDs than in vanadium SPNDs because the charge is proportional to the neutron absorption cross-section of the emitter nuclide. Unlike vanadium, the relative sensitivity change rate behaves differently in the two spectrum.

3.3 Rhodium SPND

Rhodium SPNDs is a delayed detector that generates very large signals. The reason for the large signal is that the neutron absorption cross section of rhodium is very large than another SPNDs. Therefore, although rhodium SPND has the advantage of generating a very large signal, the replacement cycle of the instrument is very short [6].

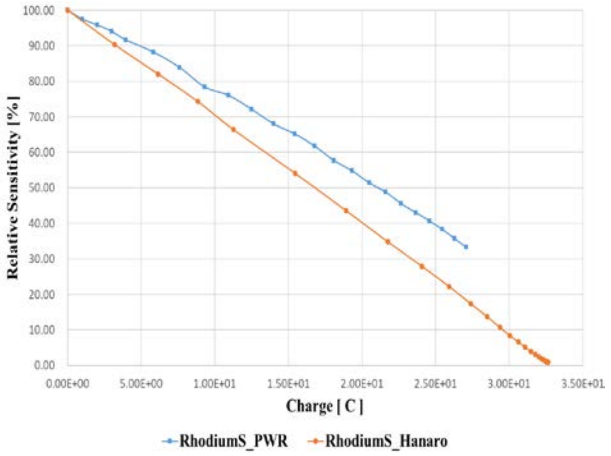

Fig. 7. Comparison of relative sensitivity of rhodium SPNDs

Fig. 7 shows the relative sensitivity of rhodium SPNDs with HANARO spectrum and PWR spectrum, which is similar to that of the result of cobalt SPNDs. Rhodium SPNDs burn completely within a very short period because rhodium has a larger neutron absorption cross section than other emitter nuclide. Relative sensitivity trends of rhodium SPNDs are also different depending on HANARO spectrum and PWR spectrum.

3. Conclusion

Through Monte Carlo Method, the relative sensitivity depending on the neutron energy spectrum of vanadium, cobalt and rhodium SPNDs were calculated. The neutron energy spectrum was calculated by simulating the irradiation area of HANARO and the center instrument-ation tube of the 16x16 fuel assembly. SPNDs uses a single model for computational convenience. In addition, the calculated neutron energy spectrum is used as an initial source of MCNP6 and McCARD codes for the sensitivity calculation of SPNDs. In order to consider the space charge effect in the relative sensitivity calculation, the minimum energy and critical distance were applied and the beta escape probability of the generation position of the beta was considered. The total sensitivity of SPNDs is calculated for 10 years.

The relative sensitivity is calculated using the HANARO spectrum and PWR spectrum. Based on the results of the relative sensitivity calculation, the total amount of charge measured in the collector area was compared with the tendency of relative sensitivity-charge during irradiation time. The total charge is larger in the HANARO spectrum than in the PWR spectrum in Vanadium, Cobalt and Rhodium SPNDs. This is the because the HANARO spectrum has a larger neutron absorption cross-section in the thermal neutron region than the PWR spectrum. In addition, the relative sensitivity of all SPNDs tends to be gentler in the HANARO spectrum. Total sensitivities are affected by the electrons generated by the prompt gamma and the delayed beta. Relative sensitivities due to delayed beta were a similar trend in HANARO spectrum and PWR spectrum. However, the relative sensitivity of HANARO spectrum tended to be more gentle compared to the PWR spectrum. Therefore, the tendency of total relative sensitivity due to the two spectra is affected by the difference in relative sensitivities due to the immediate gamma.

As a result, the neutron energy spectrum affects the signal strength of SPNDs and detector life. Therefore, proper compensation is required to apply SPNDs tested at HANARO to commercial PWRs.

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