Feasibility Study of Silver as Emitter of In-core Neutron Detector

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1. Introduction

Historically, rhodium self-powered neutron detectors (SPNDs) have been used in nuclear reactors for in-core monitoring in Korea. The rhodium SPND provides strong detector signals so that they can be easily detected, but there is an issue the rhodium emitter needs to be replaced frequently because of its fast depletion. As an alternative, the vanadium SPND was designed and evaluated by Lee et al. [1], but it also has an issue the detector signal level is too low. In this work, another material, silver, was introduced as emitter material of in-core detectors because its neutron absorption cross section is bigger than that of vanadium and smaller than rhodium. The feasibility of silver was investigated in comparison with the rhodium and vanadium detectors. The SPND model was designed using a Monte Carlo code MCNP6 and ORIGEN-S in SCALE code package [2,3].

2. Detector Model Description

A self-powered neutron detector model designed by Lee et al. using MCNP6 was adopted in this study [1]. The SPND configuration is shown in Figure 1 and the detector geometry is listed in Table I. The details of the calculational models will be described in the following sections.

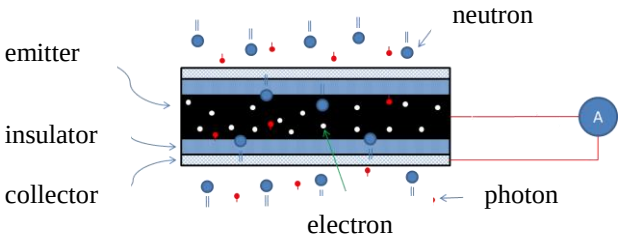

Fig. 1. Configuration of self-powered neutron detector.

Table I. Detector Geometry

Geometry	Length [cm]
Emitter radius	0.0565
Insulator radius	0.0508
Collector radius	0.1295
Detector height	Infinity (reflective)

2.1 Detector Sensitivity

The sensitivity is defined as a sum of the beta decay sensitivity and the photon reaction sensitivity as follows:

$$S = \frac{I}{\phi_{outer}} = \frac{I_\gamma + I_\beta}{\phi_{outer}}, \quad (1)$$

where I_γ is the electric current from photon reaction, I_β is the electric current by the beta decay, and ϕ_{outer} is the neutron flux at the outer boundary of the emitter.

Figures 2 and 3 show the sensitivity and the relative sensitivity of rhodium, vanadium, and silver up to ten-year operations in the core. The relative sensitivity indicates the normalized sensitivity to that of 0th year being 100%.

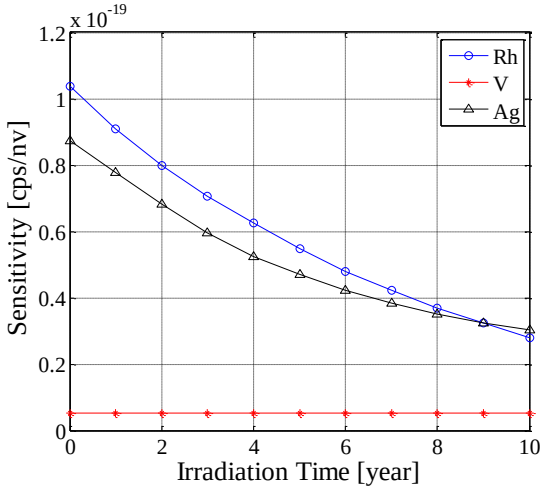

Fig. 2. Sensitivity of Rh, V, and Ag emitters.

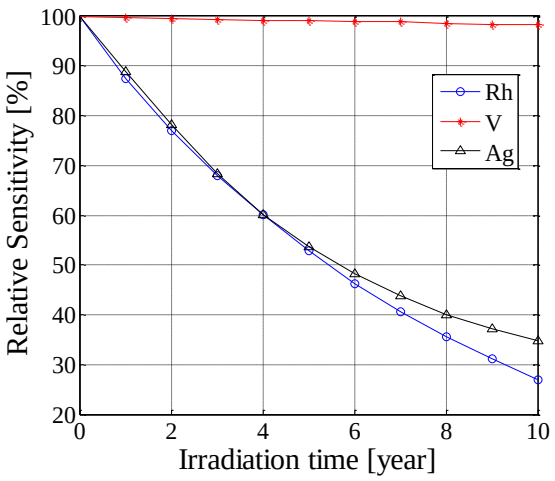

Fig. 3. Relative sensitivity of Rh, V, and Ag emitters.

2.2 Beta Decay Electron Sensitivity Model

The MCNP6 SPND model considers both electron escape probability and space charge effect as follows:

$$I_\beta = eA \times \sum_i \varepsilon_i \times D \times R_{a,i}, \qquad (2)$$

where e is the electric charge, 1.602×10^{-19} C, A is the emitter cross section, ε is the electron escape probability, i is the emitter ring index, D is the ratio between beta decay and neutron absorption rate, and $R_{a,i}$ is the neutron absorption reaction rate of the i-th ring. For the rhodium and vanadium detectors, D represents one.

2.3 Absorption Reaction Rate

The absorption rate is calculated with pin geometry as in Figure 4. Since the SPND is positioned in an assembly, the initial source should be located far from the outer radius of the pin. The initial neutron source energy should be the same as the energy spectrum of the pressurized water reactor assembly. The emitter region is divided into ten tally rings. As a result of the Monte Carlo simulation, the absorption rate and flux for each divided ring are tallied.

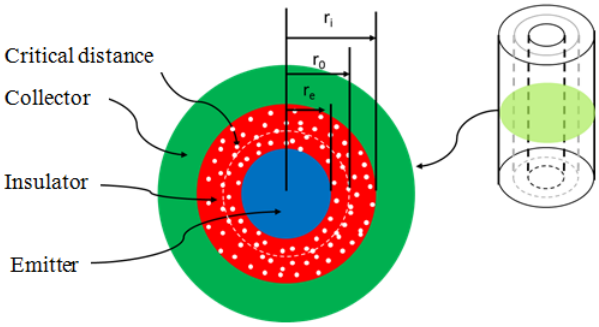

Fig. 4. Top view of self-powered neutron detector.

2.4 Electron Escape Probability

The electron escape probability varies according to the location of electrons in the emitter [4]. The electron at the center of the emitter has the lowest escape probability [5]. From the Monte Carlo simulations, the electron escape probability is calculated for each tally ring. Figure 5 shows the subdivisions of the emitter.

The space charge effect is considered by the critical distance and an energy cut-off option of the MCNP6. The electrons passing the critical distance can be reflected to inside back or absorbed before reaching the emitter surface, which are difficult to be simulated by MCNP6. Therefore, the electrons tallied at the critical distance in the MCNP6 are regarded as the electrons contributing to the detector signals.

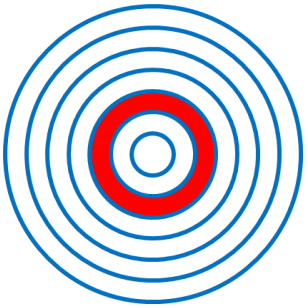

Fig. 5. Configuration of emitter tally region and initial source distribution in the 3rd tally cell.

2.5 Photon Reaction Sensitivity Model

Electrons can be emitted from not only beta decay but also photon reactions. The electric current from photon reactions are as follows:

$$I_\gamma = eA \times T_{photon}, \qquad (3)$$

where T_{photon} is the total amount of electrons detected from photon reactions, which is tallied by the absorption reaction rate tally function of the MCNP6 simulations.

2.6 Depletion Calculation Model

The depletion model is designed by ORIGEN-S in SCALE code package and calculated according to Lee et al. [1]. It is assumed that the SPND is used for 10 years. Since the neutron flux should provide irradiate the emitter of the detector, the average flux is calculated for a general assembly in a nuclear power plant. The detailed depletion specifications are listed in Table II.

Table II. Depletion Specifications

Fuel assembly type	CE 16x16
Enrichment [wt%]	4.0
Power density [W/g]	36.86
Power/fuel assembly [MW/basis]	15.9
Average flux [$cm^{-2} \cdot sec^{-1}$]	4.1×10^{13}

The PLUS7 16x16 assembly is used and the initial uranium enrichment is 4.0 wt%. The power density is 36.86 W/g and the total mass of the uranium is assumed as 431,362 kg.

3. Detector Lifetime Evaluation Model

The lifetime is determined as the point whose relative sensitivity error exceeds a criterion, ε, in Eq. (4).

$$L = \frac{\varepsilon + y_0}{1 - a_{\max}}, \qquad (4)$$

where L is the lifetime, ε is the criterion, y_0 is the relative sensitivity at 0^{th} year, and a_{max} is the maximum slope so that a certain c exists satisfying Eq. (5). In other words, c is the topmost point in Figure 6.

$$0 < \exists c \le L;\ a_{\max} = \frac{c + \varepsilon - y_0}{c - 0} = 1 + \frac{\varepsilon - y_0}{c}. \qquad (5)$$

Figure 6 shows how to determine the lifetime. First, draw a line whose slope is a negative. Second, increase the slope until a topmost point appears so that all points on the line satisfy the criterion within a certain range, for example, until 7^{th} year in Figure 6. Then, the point exceeding the criterion appears as the 8^{th} year. Third, interpolate between two points, 7^{th} year and 8^{th} year, and then the lifetime is determined as 7.35 years.

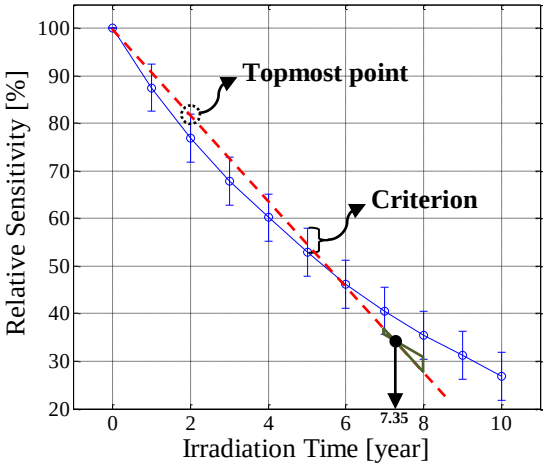

Fig. 6. Detector lifetime estimation using relative sensitivity criterion.

4. Results

Table III summarizes the lifetimes determined by the method in section 3 with the material density. Here, 2% was used as the criterion.

Table III. Material Density and Lifetime

Material	Density [g/cm^3]	Lifetime [year]
Rhodium	12.40	3.92
Vanadium	6.10	> 10
Silver	10.49	4.70

It was demonstrated that the lifetime of silver SPND is longer than that of rhodium SPND by 0.78 years. As mentioned in section 1, the rhodium has a disadvantage of the short lifetime, whereas the vanadium has a disadvantage of the weak signal. On the other hand, silver shows a longer lifetime than rhodium, and stronger detector signals, the magnitude of sensitivity in Figure 1, than vanadium.

5. Conclusions

A silver self-powered neutron detector (SPND) was introduced in this paper, and the feasibility of silver as an emitter material of in-core detectors was investigated. The comparisons with rhodium and vanadium emitters demonstrate that silver has 0.78 years longer lifetime than rhodium and 10 times stronger signal than vanadium. Since a cycle length is generally 1.5 years, silver can be used for three cycles whereas rhodium should be replaced after two cycles. Therefore, silver is a viable candidate for SPND emitter material from the lifetime and signal-magnitude perspectives.

For the future work, material properties of the silver, such as the durability, corrosiveness, and conductivity, will be investigated. Also, detailed economics analysis of silver will be performed on the cycle length of a core.

Acknowledgments

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