Sensitivity Calculation of Vanadium Self-Powered Neutron Detector

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1. Introduction

Self-powered neutron detector (SPND) is being widely used to monitor the reactor core of the nuclear power plants. The SPND contains a neutron-sensitive metallic emitter surrounded by a ceramic insulator. Currently, the rhodium SPND has been used in many nuclear power plants. The lifetime of rhodium is too short (about 3~5 years) to operate the nuclear power plant economically. The vanadium (V) SPND is also primarily sensitive to neutrons like rhodium, but is a somewhat slower reaction time as that of a rhodium SPND. The benefit of vanadium over rhodium is its low depletion rate, which is a factor of 7 times less than that of rhodium. For this reason, a vanadium SPND has been being developed to replace the rhodium SPND which is used in OPR1000. [1]

Some Monte Carlo simulations were accomplished to calculate the initial sensitivity of vanadium emitter material and alumina (Al_2O_3) insulator with a cylindrical geometry. An MCNP-X code was used to simulate some factors (neutron self shielding factor and electron escape probability from the emitter) necessary to calculate the sensitivity of vanadium detector. The simulation results were compared with some theoretical and experimental values. [2] The method presented here can be used to analyze the optimum design of the vanadium SPND.

2. Methods and Results

In this section some models used to calculate the detector sensitivity are described. The simulation model includes a calculation of neutron self shielding factor and electron escape probability.

2.1 Specification of Vanadium Detector

A vanadium SPND consists of three parts (emitter, insulator and collector) which can be arranged as coaxial cylinders. The emitter is the neutron sensitive vanadium wire which is a piece of cylindrical wire. The insulator has to retain a high electrical resistivity even when it is continuously exposed to intense radiation fields.

Table 1: Material & Spec. of Vanadium SPND

Part of SPND	Material	Density (g/cm^3)	Length (cm)	Radius (cm)
Emitter	V-52	6.1	40	0.0565
Insulator	Al_2O_3	1.9	40	0.1015
Sheath	Inconel-600	8.44	40	0.1295

2.2 Current and Sensitivity Equation

The sensitivity is defined as the ratio of the detector current to flux; that is,

$$S = I / \Phi \tag{1}$$

The current of vanadium detector is proportional to the volume of emitter (V), neutron capture rate (C_p) and beta escape probability (ε), and also can be calculated from the following equation;

$$I = eV\varepsilon Cp \tag{2}$$

where e is 1.602×10^{-19} A-sec/electron.

The neutron capture rate per unit volume is given by

$$\int_0^{E_{max}} \Sigma(En)\phi(En)f(En)dEn \tag{3}$$

where
En : incident neutron energy
$\Sigma(En)$: macroscopic neutron capture cross section
$\phi(En)$: neutron flux per unit energy
f(En) : neutron self-shielding factor

The above equations mean that once neutron self-shielding factor and beta escape probability be calculated for thermal neutron energy, one could get the signal current of the concerning emitter. To compare with the reference data [2], the simulations were performed at thermal energy (2200m/sec) region.

2.3 Calculation of Neutron Self-shielding Factor

Neutron self-shielding factors inside a vanadium emitter are calculated by using MCNP-X code. A vanadium SPND is positioned at a center of instrument tube and surrounded by a cylindrical neutron source. The detector part cuts three segments (layers) from verticals, i.e., the height of the first and third layer is 20cm, the height of the second layer is 40cm which is a practical detector height of the existing rhodium SPND used in OPR1000. The emitter and insulator parts are respectively divided by 20 and 16 segments (cells) from the radial axis.

Neutron self-shielding factors for vanadium emitter can be calculated simply from the following equation given by Weinberg and Wigner. [3]

$$f(2200m/\sec) = 1 - \frac{4}{3}\Sigma(2200m/\sec) \times r_e \quad (4)$$

Table 2: Calculation Result of Self-Shielding Factor

This work	Weinberg & Wigner	Warren
0.97439	0.9724	0.9733 (interpolated value)

2.4 Calculation of Electron Escape Probability

A beta particle generated inside a vanadium emitter undergoes continuous Coulomb interaction with atoms in various parts of SPNDs. Its track may be more or less straight initially but becomes zigzag later as it loses its energy before it completely stops. The final stopping position in SPND will be one of three parts of the SPND.

The beta escape probability is considered as the probability of beta particles to pass over the critical point (r_o) in insulator radially before stopping.

$$r_o = r_i \left[\frac{1-k^2}{2\ln(1/k)} \right]^{1/2} \quad (5)$$

where r_o is measured from center of the emitter (0.0779cm), r_i is outer radius of the insulator (0.1015cm), and $k = r_e/r_i$ (0.55665)

The beta escape probability certainly is a function of critical distance (r_o) and the following energy spectrum of beta particle.

$$B(E') = \frac{105}{16}\frac{1}{(E_\beta)^{7/2}}(E_\beta - E')^2\sqrt{E'} \quad (6)$$

$$\int_0^{E_\beta} B(E')dE' = 1 \quad (7)$$

where E_β is the maximum energy of electron for vanadium emitter (2.47MeV).

Because of the complication of calculating the beta escape probability of the vanadium emitter numerically, MCNP-X code was performed to calculate it using the equation (5) through (7). The emitter and insulator parts are respectively divided by 20 and 17 segments (cells) radially. Also to compare with the reference data, the beta escape probability at thermal energy (2200m/sec) region was used.

Table 3: Calculation Result of Beta Escape Probability

This work	Warren
0.52778	0.56828 (interpolated value)

3. Conclusions

Some MCNP models to calculate the neutron self-shielding factor and beta escape probability for thermal neutron energy were proposed. The calculation values are more or less similar to the referenced value.

Using these models, the initial sensitivity of vanadium detector for both thermal neutron energy and epithermal neutron energy can be calculated. And considering the manufacturing concerns of the detector, one can search the optimum geometry of emitter and insulator by adjusting the critical distance (r_o) and k value.

REFERENCES

[1] Kyoon Ho Cha, "Long-lived Hybrid Incore Detector for Core Monitoring and Protection", KNS Fall Meeting, October 2010.
[2] H. D. Warren, "Calculation Model for Self-Powered Neutron Detector", Nuclear Science and Engineering: 48, 331-342, 1972
[3] A. M. Weinberg and E. P. Wigner, "The Physical Theory of Neutron Chain Reactors", p707, The University of Chicago Press, Chicago, 1958