Sensitivity Analysis of Vanadium Self-Powered Neutron Detector under Varied Geometries of Emitter and Insulator

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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. Especially, the rhodium SPND has been being used in the in-core detector system of OPR1000 due to the good characteristics of neutron interaction. The capture cross section of rhodium (Rh) is so large that the detector sensitivity of it is excellent to use to detect the neutron behaviors in the core. Unfortunately, because of the capture cross section, the life time of rhodium is relatively short (3~5 years) than the life time of vanadium (~10 years).

The vanadium (V) detector has been being used in the Pressurized Heavy Water Reactor like Wolsung Nuclear Power Plant. Therefore, if the vanadium detector can be used in the OPR1000, it will be very helpful for the plant owner to manage the plant economically.

2. Methods

2.1 Current and Sensitivity

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), self-shielding factor (*f*) and beta escape probability (ε), and can be calculated from the following equation;

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

The neutron capture rate per unit volume is given by

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

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

- 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 neutron energy, one could get the signal current of the detector.

Table1 shows that the sensitivity of vanadium is less than the sensitivity of rhodium. Therefore, for the purpose of using the vanadium detector in the OPR1000, it needs to improve the neutron sensitivity of vanadium.

Table 1: Thermal Neutron Sensitivities per Unit Length for Rhodium and Vanadium Emitters [1]

Emitter Material	Emitter Diameter (cm)	Self-Shielding Factor (*f*)	Escape Efficiency (ε)	Sensitivity (10^{-22}amp/ (nv cm))
Rhodium	0.0508	0.730	0.623	16.10
Vanadium	0.0508	0.988	0.768	0.87

2.2 Space-Charge Effects

To calculate the sensitivity it is important to consider the space-charge effects in the insulator region. Being separated by an insulator between emitter and collector, the insulator acts as a reservoir for electron. This is called as space-charge effects. [2] Emitting from the emitter, some electrons find themselves at thermal equilibrium within the insulator. Because of the charge traps and insulator's energy band structure, electrons spend a finite time within the insulator before exiting at an emitter. This permits the buildup of space charge.

When the space-charge electric field becomes strong enough, there is only one potential peak in the insulator for the electron to exit to the collector. Electrons from emitter that lose all their kinetic energies before crossing the potential peak are repelled to the emitter. Thus, only those electrons crossing the potential peak actually contribute current in a detector.

Assuming that the insulator contains a uniformly distributed static space charge of electrons, the solution to Poisson's equation within the insulator region is then

$$V(r) = A\left[-\left(\frac{r}{r_i}\right)^2 + \frac{\ln(r/r_e) + k^2\ln(r_i/r)}{\ln(1/k)}\right] \tag{4}$$

where

- A : proportionality constant, related to radiation intensity and kind of insulator
- r : radial distance from the center of the emitter to a point within the insulator
- r_e : radius of the emitter
- r_i : outer radius of the insulator
- k : r_e / r_i

Equation (4) is obtained by applying the boundary conditions that $V(r_e)= V(r_i)=0$ in the normal operating condition of the self-powered detector. The electric field is given by

$$E(r)=\frac{2A}{r_i}\left\{\frac{r}{r_i}-\left[\frac{1-k^2}{2\ln(1/k)}\right]\frac{r_i}{r}\right\} \tag{5}$$

The potential has a peak value, and the electric field has a zero value and a change in direction at the radial point as given by

$$r_o=r_i\left[\frac{1-k^2}{2\ln(1/k)}\right]^{1/2} \tag{6}$$

where r_o is measured from center of the emitter .

2.3 Simulations and Results

The emitter is divided by 20 segments (cells) from the radial axis. The simulation models include some calculations of neutron self shielding factor and electron escape probability by varying the geometry of emitter and insulator to contemplate the space-charge effects.

MCNP5 was used to simulate two factors (neutron self shielding factor and electron escape probability from the emitter) necessary to calculate the sensitivity of vanadium detector. To find the optimal geometry of the vanadium detector, the simulations were performed by varying the diameter of emitter and insulator. This means the change of k-value (r_e / r_i).

Figures 1 and 2 shows the results of the calculations for the self-shielding factor and beta escape efficiency.

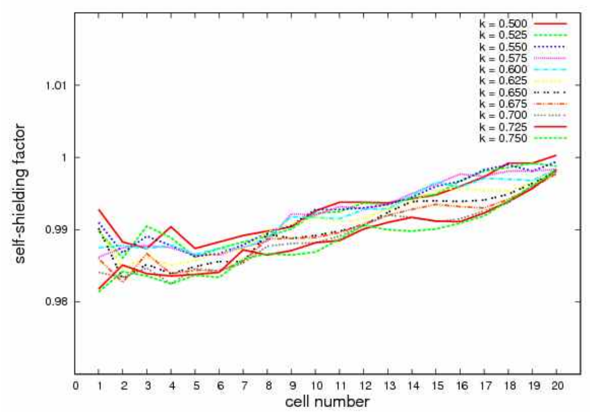

Fig 1: Self-shielding Factor for various k-value of Vanadium Emitter

Some peak values in cell 1 of Fig 1 may come from the shape difference in geometry of cell 1 and other cells. Whereas some electrons of center cell (cell 1) are accumulated in its own cell, some electrons of other cells may be distributed both inner and outer cells.

Table 2 shows the thermal neutron sensitivities per unit length of vanadium detector calculated by using the results of the simulations according to the above equations.

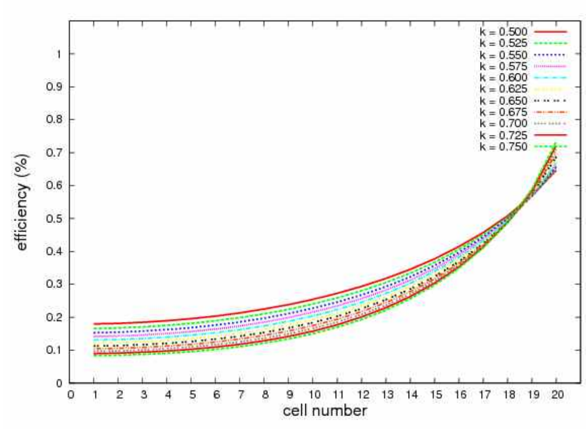

Fig 2: Beta Escape Efficiency for various k-value of Vanadium Emitter

Table 2: Thermal Neutron Sensitivities per Unit Length of Vanadium Emitter by Varying k-value

k-value	0.5	0.55	0.6	0.65	0.7	0.75
Emitter Diameter (cm)	0.10160	0.11176	0.12192	0.13208	0.14224	0.15240
Insulator Thickness (cm)	0.0508	0.0457	0.0406	0.0356	0.0305	0.0254
Sensitivity (10^{-22}amp/ (nv cm))	1.89	2.19	2.51	2.85	3.22	3.62

For the vanadium detector to be used in the OPR1000, the insulator wall thickness should not be minimized to a certain degree. In general, the insulator wall thickness may range from 0.025 to 0.05cm.

3. Conclusions

Some MCNP simulations to calculate the neutron self-shielding factor and beta escape probability by varying the *k* value were achieved. And the sensitivities of vanadium detector are calculated to find the optimal geometries of emitter and insulator by reflecting the space-charge effects.

Whenever minimizing the insulator wall thickness to a certain degree, one might expect that the diameter of vanadium emitter can be maximized to increase the neutron sensitivity regardless of considering the space-charge effects

REFERENCES

[1] H. D. Warren, "Calculation Model for Self-Powered Neutron Detector", Nuclear Science and Engineering: 48, 331-342, 1972.

[2] H. D. Warren and N.H Shah, "Neutron and Gamma-Ray Effects on Self-Powered In-Core Radiation Detectors", Nuclear Science and Engineering: 54, 395-415, 1974