Proceedings of the Korean Nuclear Society Spring Meeting
Kwangju, Korea, May 1997

A Study on the Sensitivity of Self-Powered Neutron Detectors(SPNDs) and a new Proposal

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Abstract

Self-Powered Neutron Detectors(SPNDs) are currently used to estimate the power generation distribution and fuel burn-up in several nuclear power reactors in Korea. In this paper, Monte Carlo simulation is accomplished to calculate the escape probability of beta particle as a function of their birth position for the typical geometry of rhodium-based SPNDs. Also, a simple numerical method calculates the initial generation rate of beta particles and the change of generation rate due to rhodium burn-up. Using the simulation and the numerical method, the burn-up profile of rhodium density and the neutron sensitivity are calculated as a function of burn-up time in the reactor. The sensitivity of the SPNDs decreases non-linearly due to the high absorption cross-section and the non-uniform burn-up of rhodium in the emitter rod. In addition, for improvement of some properties of rhodium-based SPNDs which are currently used, this paper presents a new material. The method used here can be applied to the analysis of other types of SPNDs and will be useful in the optimum design of new SPNDs for long term usage.

1. Introduction

SPNDs are a fixed-type in-core detector to measure the neutron flux distribution directly inside the reactor core. Though SPNDs supply the most valuable information about the in-core neutron flux distribution, the measured signals are not used for the real-time reactor operation yet because the measurement uncertainty is not negligible and more importantly the response time is quite long. Another problem is the reduction of the neutron sensitivity due to the rapid burn-up of rhodium because of its high neutron absorption cross-section. The purpose of this paper is to estimate the change of the sensitivity of typical rhodium-based neutron detectors as a function of burn-up and to present new type of SPNDs which is able to be used at future reactor.

2. Calculation of sensitivity

2. 1 Current and sensitivity equation

If we assume that SPNDs have a cylindrical geometry and the signal current is contributed only by thermal neutrons (practically 93%), the signal current can be expressed by the following equation

$$I = q \times \int_V dV \left[\sigma \times N_{Rh}(r) \times \phi(r) \times \int_{E\beta} p(E_\beta) \times \varepsilon(E_\beta, r) dE_\beta \right] \qquad \text{Eq. (1)}$$

where I is the signal current of SPNDs due thermal neutrons, V is the volume of the Rh rod (= $\pi R^2 L$), L is the length of Rh rod (typically 30 cm), R is the radius of Rh rod (= 0.0254 cm), E_β is the energy of the beta particle emitted by the decay of Rh^{103}, $\varepsilon(E_\beta,r)$ is the escape probability of beta particles of energy E_β generated at the position r, $p(E_\beta)$ is the normalized beta energy distribution, σ is the thermal neutron absorption cross section of rhodium ($\approx$ 150 barn) ,$N_{Rh}(r)$ is the rhodium number density at r in SPNDs, and $\phi_{th}(r)$ is the thermal neutron flux at r in SPNDs.

The sensitivity of SPNDs is generally defined as

$$S \equiv \frac{I}{\phi_0 \times L} = 2\pi \times q \times \sigma \times \int_0^R N_{Rh}(r) \times f_n(r) \times \int_{E\beta} p(E_\beta) \times \varepsilon(E_\beta, r) \times rdr \qquad \text{Eq. (2)}$$

where S is the sensitivity of SPNDs [A/nv-cm], ϕ_0 is the thermal neutron flux in the vicinity of SPNDs location. As the rhodium burn-up, the rhodium density decreases and the sensitivity drops from the initial sensitivity of the fresh SPNDs. if we normalize the position variable and the rhodium density with the radius of the emitter and initial value respectively, then the sensitivity can be simply expressed into a integral two terms in product; a time-dependent term of the beta particle generation rate and a time-independent term of the beta escape probability, i.e.

$$S(t) = S_0 \times \int_0^1 g_\beta(r,t) \times \varepsilon_\beta(r) \times rdr \qquad \text{Eq. (3)}$$

2.2 Calculation of the beta generation rate, $g_\beta(r,t)$

In order to estimate the time- and position-dependent beta generation rate, it is necessary to calculate the time-dependent neutron flux distribution inside the rhodium emitter of SPNDs, i.e. Since the neutron absorption cross-section of Rh^{102} is very high(~150 barn) compared to its scattering cross-section (~5 barn), the diffusion approximation is not applicable. Weinberg and Wigner has calculated the neutron flux distribution in an infinitely long cylinder of various strong absorbers immersed in an infinite volume of a constant thermal neutron flux using a transport theory[1]. However, those transport-based lengthy programming is not necessary if we consider the specific geometry of Rh emitter rod, of which radius is so small that the scattering event is never important.

Therefore we have calculated the time-dependent Rh depletion and neutron flux distribution using the following simple theory based on several reasonable approximations; (1) the rhodium emitter is a pure absorber, (2) the effect of thin insulating layer and collector sheath on the neutron flux in the rhodium emitter is negligible due to their low absorption and high scattering cross-section. Due to the reciprocal theorem of neutron transport, the local neutron flux in a pure absorber surrounded by an infinite neutron field of unit density is the same as that the escape probability out of the absorber from an isotropic point source of neutron in that position[2][3]. For a fresh Rh-based SPNDs, the neutron flux distribution inside the rhodium emitter at time(t=0) can be calculated by

$$\phi(r,0) = \frac{1}{4\pi} \times \int_{Surface} \phi_0 \times \exp[-\Sigma \times x] \times d\Omega(r) \qquad \text{Eq. (4)}$$

where x is the path length of a thermal neutron from a local position r to the surface of the cylindrical rhodium emitter located in the direction of Ω. Σ is a product of the initial rhodium density and the macroscopic absorption cross section($\Sigma = N_0 \times \sigma$) where N_0 is uniform initially in the emitter. This integration is difficult to estimate analytically but easy to calculate numerically. Fig. 1 Shows the normalized distribution of neutron flux for a fresh Rh-based SPNDs.

As seen in the figure, since the initial burn-up rate near surface is high, depletion of Rh becomes non-uniform. The depletion equation for rhodium is given by

$$\frac{dN_{Rh}(r,t)}{dt} = -\sigma \times \phi(r,t) \times N_{Rh}(r,t) \qquad \text{Eq. (5)}$$

2.3 Calculation of the escape proability, $\varepsilon_\beta(r)$

A beta particle generated inside a rhodium emitter with a finite energy undergoes continuous Coulomb interaction with atoms in various parts of SPNDs. Its track may be more or less straight initially but becomes zig zag later as it loses its energy before it completely stops. The final stopping position in SPNDs will be one of three regions; the emitter rod itself, the collector sheath, or the thin insulating layer between them. Stopping of beta particles in the thin insulating layer accumulates space charges in the insulator and starts to build a static electric field and potential. After a certain time, the accumulated charge must be saturated due to the finite values of electric capacitance of SPNDs and the electric resistance of the insulating material. This built-in field expels the beta particles which is in the insulator either forward into the collector sheath or backward into the emitter rod. Fig. 2 shows a schematic diagram of those two events and the electric field distribution around the critical thickness which is determined by the saturated charge build-up profile. Warren has calculated the critical thickness for various size of emitter radius and for various insulator materials [4].

Therefore the beta escape probability is considered as the probability of beta particles to pass over the critical thickness of the insulator before stopping. It certainly is a function of the birth position and the initial energy of beta particle. Since it is much more complicated to calculate numerically than the calculation of thermal neutron flux inside the rhodium emitter rod, we have used the MCNP4A code in order to calculate the beta escape probability.

3. Results and Discussion

The beta generation rate is numerically calculated using a simple Euler algorithm for time and finite discrete method for the space[5]. The input parameters used for the calculation are summarized in the Table 1. Fig. 3 shows the calculated Rh density distribution at different burn-up time. As the burn-up progress, the rhodium density decreases and its spatial distribution becomes non-uniform. In addition, the time dependent generation rate is calculated. It is decreases because the rhodium number density is diminished due to burn-up. Fig. 4 shows the time dependent generation rate from the initial time to 5 years. The position-dependent escape probability is calculated using the Monte Carlo Neutron and Particles Transport (MCNP) code[6].

Fig. 5 shows the position-dependent beta escape probability in the Rh-based SPNDs and it is strongly dependent upon the position of the beta creation in emitter. Fig. 6 shows the change of the sensitivity normalized to its initial value as a function of burn-up time and the initial value of the sensitivity is compared with other's estimated and experimental value as shown in Table 2 . Our calculation yields a little under-estimated value of the initial sensitivity because the density of the insulator(Al_2O_3) might be different from other's, but our value is almost the same value of SPNDs used in the YGN 3. From these results, Our calculation model is good for calculating the initial sensitivity and for estimating the change of the sensitivity and rhodium density due to burn-up.

4. Proposal silver-based SPND

SPNDs which are used in the present commercial power plants have some disadvantage that be unable to use the long term and the response time is slow. The long term usage and fast response time is beneficial in many aspects when operating nuclear power plant. From the radiological health handbook and other isotope table, the Ag^{110} is chosen as a best candidate to make better SPNDs. Fig. 7 shows the normalized silver density distribution as a function of the burn-up time. The change of the silver density due to burn-up is low and almost uniform compared to that of the rhodium because of the low absorption cross section and low density. As shown in the fig. 8 and fig. 9, the generation rate is low but the escape probability is high so the total initial sensitivity is increased. From these results, silver is proposed to use as an emitter which be able to be used for long term.

5. Conclusion

In this work, we established a simple method to calculate the position-dependent escape probability in beta emitting rod (Rh) of SPNDs and the change of the sensitivity due to burn-up. The calculation value is similar to the measured value of YGN 3 SPNDs. As the neutron flux increases, the sensitivity change shows a non-linear decrease during burn-up.

It is necessary to choose the low absorption cross section material for the long term usage. Ag^{109} is chosen as a best candidate because the Ag^{109} has the lower absorption cross section, the faster response time and lower density than rhodium. Also it is easy to make a thin sliver wire. In this paper, the sensitivity of new silver based SPND is calculated using the method developed. From the results, the reduction of the sensitivity in silver is smaller than that of rhodium for same burn-up.

References

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Table 1 Input parameters for calculation of the beta generation rate

Thermal neutron flux	2×10^{12} #/cm^{2}sec
Burn-up time	5 year
Abs c.x of Rh	150 barn
Radius of Rh emitter	0.0253 cm
Initial Rh density	12.3 g/cm^2

Table 2 Comparison of the sensitivity

	This work	Warren	Goldstein	YGN 3	YGN 4
S(0)	0.97	1.21	1.51	0.965 0.980	0.958 0.971

*S has a unit of 10^{-21}Amp/nv-cm.

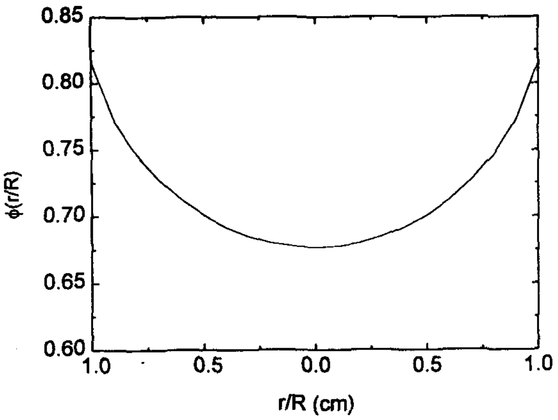

Fig. 1 Normalized distribution of neutron flux for a fresh Rh-based SPNDs

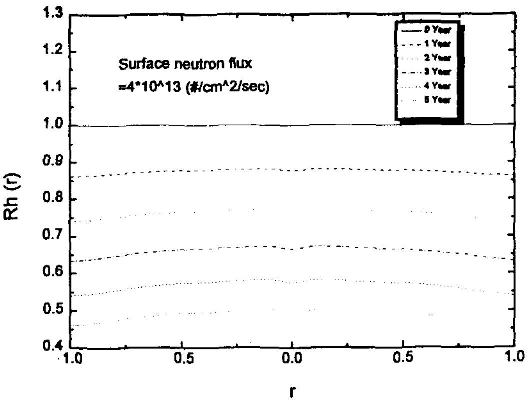

Fig. 3 Normalized rhodium density distribution as a function of burn-up time

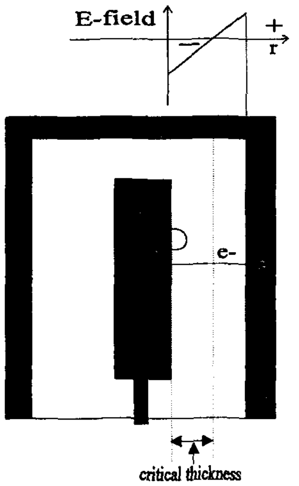

Fig. 2 Schematics for explaining critical thickness of insulation

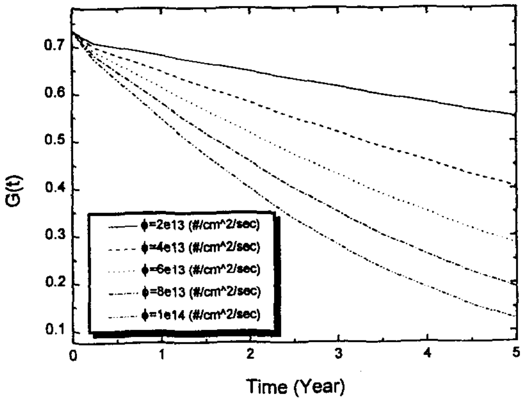

Fig. 4 The change of generation rate as a function of burn-up in Rh-based SPNDs

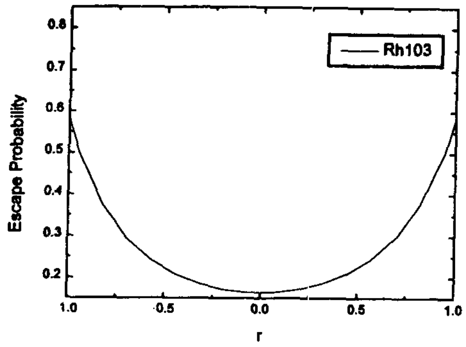

Fig. 5 Energy averaged escape probability as function of radial birth position in Rh-based SPNDs

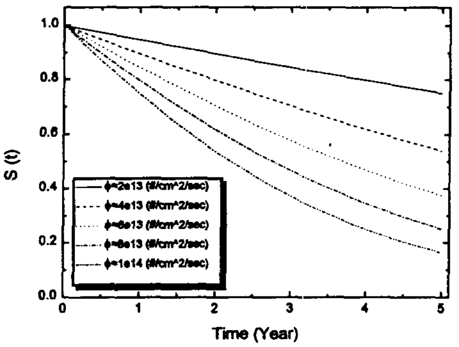

Fig.6 Normalized sensitivity as a function of burn-up time in Rh-based SPNDs

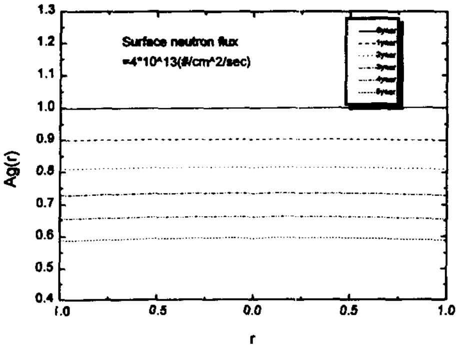

Fig. 7 Normalized silver density distribution as a function of burn-up time

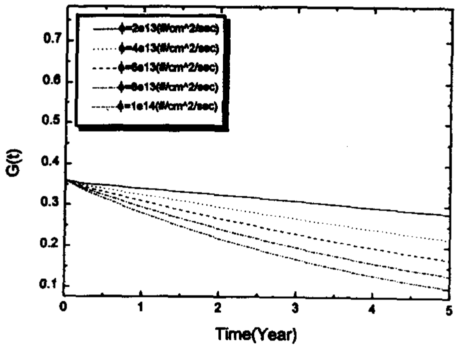

Fig. 8 The change of generation rate as a function of burn-up in silver emitter

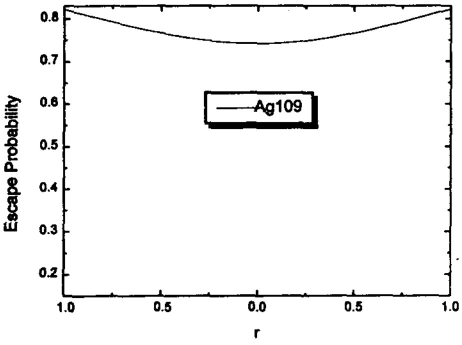

Fig. 9 Energy averaged escape probability as a function of radial birth position in silver emitter