Proceedings of the Korean Nuclear Society Spring Meeting
Pohang, Korea, May 1999

A Study on the Signal Processing of the Sensitivity Depletion Laws for Rhodium Self-Powered Neutron Detectors (SPNDs)

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ABSTRACT

This work on the signal processing of the sensitivity depletion laws for rhodium self-powered neutron detectors (SPNDs) is performed to improve the uncertainty of the sensitivity depletion laws used in ABB-CE reactors employing rhodium SPND and to develop a calculational tool for providing the sensitivity depletion laws to interpret the signal of the newly designed rhodium SPND into the local neutron flux. The calculational tool for a time dependent neutron flux distribution in the rhodium emitter during depletion and for a time dependent beta escape probability that a beta generated in the emitter escapes into the collector was developed. These programs provide the sensitivity depletion laws and show the reduction of the uncertainty by about 1.0 % less than that of the method employed by ABB-CE in interpreting the signal into the local neutron flux. The reduction in the uncertainty by 1.0 % in interpreting the signal into the local neutron flux reduces the uncertainty by 1.0 % or more in interpreting the signal into the local power and lengthens the lifetime of the rhodium SPND by about 10.0 % or more.

1. INTRODUCTION

A rhodium self-powered neutron detector (SPND) is a high level neutron sensing device operated on the mechanism of neutron activation of the rhodium-103 emitter material. The neutrons incident on the rhodium emitter are converted to the high energy electrons which spontaneously migrate between insulated electrodes often termed emitter and collector. The net flow of electrons is usually from the emitter (a wire of rhodium or other material). When the emitter is electrically connected to the collector through a resistor, a counter current flows to maintain charge equilibrium. The net rate of electron migration through the insulation is equal to the counter current and is directly proportional to the rate at which radiation impinges upon the device. The in-core instrumentation provides the operator with the on-line three-dimensional nuclear power distribution.

The objective of this work is to calculate the behavior of the depletion laws for the rhodium self-powered neutron detectors (SPNDs) and lengthen the lifetime of Rhodium SPNDs. The RHODIUM program was developed to calculate the burnup dependent neutron flux distribution within the rhodium emitter using the discrete ordinates neutron transport method during depletion of the rhodium emitter. For the burnup dependent average beta escape probability, non-uniform beta generation is accounted for and a numerical approach based on the neutron transport and probabilistic method is employed. The BETAESC program was developed to calculate the electron escape probability from inside the emitter to the surface of the emitter using the track length probability technique.

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2. ANALYSIS MODEL

2.1 Sensitivity Depletion Law

The basic equation governing current-sensitivity produced by a Rh SPND is given as follows:

$$I = e\,\overline{P_\beta}\,\overline{N}\int_{Rh}\int \sigma\,\Phi\,dE\ dV, \tag{1}$$

where at any time

e = electron charge

$\overline{P_\beta}$ = average beta escape probability,

$\overline{N}$ = average rhodium number density,

σ = rhodium neutron capture cross section,

V = volume of rhodium,

Φ = neutron flux in the rhodium.

In the useful approach reported by Handschuh[1] and by Warren[2], the sensitivity depletion law based on the ratio of the signal of an old detector to that of a new detector is

$$\left(\frac{S}{S_o}\right)_S = \frac{I^B}{I^F} = \frac{e\,\overline{P^B_\beta}\,\overline{N_B}\int_B\int\sigma\,\Phi\,dE\,dV}{e\,\overline{P^F_\beta}\,\overline{N_F}\int_F\int\sigma\,\Phi\,dE\,dV}, \tag{2}$$

where the superscripts B and F indicate the partially-burned detector and fresh detector, respectively.

Then, the sensitivity depletion law based on signals becomes

$$\left(\frac{S}{S_o}\right)_S = \left(1-\frac{Q}{Q_\infty}\right)\cdot\frac{\overline{P^B_\beta}}{\overline{P^F_\beta}}\cdot\frac{\int_B\int\sigma\,\Phi\,dE\,dV}{\int_F\int\sigma\,\Phi\,dE\,dV}, \tag{3}$$

where the self-shielding ratio is $SF = \dfrac{\int_B\int\sigma\,\Phi\,dE\,dV}{\int_F\int\sigma\,\Phi\,dE\,dV}$.

Estimates of the ratio of the double integrals with remaining rhodium number density have been evaluated with the RHODIUM neutron transport program for a typical 0.0457 cm (18 mil) detector. The sensitivity depletion law based on signals has a downward curvature as shown in Figures 2 and 3. This can be fit reasonably well with an equation of the form:

$$\left(\frac{S}{S_o}\right)_S = \left(1-\frac{Q}{Q_\infty}\right)^\alpha, \tag{4}$$

where α is 0.825 for 0.0457 cm diameter rhodium emitter.

2.2. Beta Escape Probability[2]

The beta particle (or electron) escape efficiency is given by

$$\varepsilon = \int_0^{E_\beta}\left(\frac{-dE}{dx}\right)_E^{-1} dE \ \times \int_E^{E_\beta}\left(N\,[\,R(E')-R(E)\,]\right) B(E')dE'. \tag{5}$$

B(E')dE' is thus the probability that an electron will be ejected from a nucleus with energy between E' and E'+dE'. E_β is the maximum energy of a beta decay. $N(\ell)$ is the probability per unit track length that a track of length ℓ to the surface exists within the emitter. The track length ℓ = R(E')-R(E) is the difference in ranges of electrons of energies E' and E within the emitter material. $\left(\frac{-dE}{dx}\right)_E^{-1}$ is the reciprocal of the specific energy loss of electrons within the emitter material evaluated at energy E. Of all the beta particles produced by neutron capture, ε is the fraction that appears at the emitter's surface. However, the appearance of an electron at the emitter's surface does not necessarily mean that it is a current contributing electron. It must have energy greater than EMIN to contribute to the current. The continuous spectrum of beta generation is used in this BETAESC program. Beta generation is isotropic and straightly migrates inside the emitter. The range versus energy of a beta uses the data provided by Reference 4. The tracking of a beta is performed at the discrete grid points inside the emitter.

2.3 Development of the 1-D S_N Equation (4),(5)

This section provides the development of a one-dimensional, one-group, discrete-ordinates, diamond-differenced form of the burnup-dependent neutron transport equation in a cylindrical geometry.

The burnup-dependent homogeneous neutron transport equation in one space dimension is :

$$\nabla \cdot \Omega\, \phi(r, \Omega, t_i) + \sigma(r, t_i)\, \phi(r, \Omega, t_i) = S(r, t_i)\ , \tag{6}$$

where $\phi(r, \Omega, t_i)$ is the particle flux (particle number density times the particle speed) defined such that $\phi(r, \Omega, t_i)\ dr\, d\Omega$ is the flux of particles, in the volume element dr about r at burnup step t_i with directions of motion in the solid angle element $d\Omega$ about Ω . The macroscopic total cross section is σ. All of the quantities may be spatially dependent. The discrete-ordinates approximation to Equation (6) can then be written:

$$\mu_m \frac{\partial (r\psi_m)}{\partial r} + \left(\frac{\alpha_{m+\frac{1}{2}}}{w_m} \right] \psi_{m+\frac{1}{2}}(r, t_i) - \left(\frac{\alpha_{m-\frac{1}{2}}}{w_m} \right] \psi_{m-\frac{1}{2}}(r, t_i) + r\sigma\psi_m(r, t_i) = 0\ , \tag{7}$$

where the $\alpha_{m-\frac{1}{2}}$ and $\alpha_{m+\frac{1}{2}}$ are angular coupling coefficients. These coefficients satisfy the recursion relation $\alpha_{m+\frac{1}{2}} - \alpha_{m-\frac{1}{2}} = -\ w_m \mu_m$ with the requirement that the first $(\alpha_{\frac{1}{2}})$ and last $(\alpha_{M+\frac{1}{2}})$ coefficients on each ξ-level must vanish.

3. RESULTS AND DISCUSSIONS

The RHODIUM program is intended to calculate the burnup dependent radial neutron flux distribution for the non-uniform rhodium atom density because rhodium atom density becomes non-uniform as it depletes. The benchmark calculation between the RHODIUM program and the ANISN code is shown in Figure 1. The results estimated by ABB-CE(1) show that the average beta escape probability slightly increases as it depletes and ABB-CE assumes that the average beta escape probability is constant because the uncertainty of the calculations computed by the ROCS and MC codes is equivalent to the evaluated variation of the average beta escape probability. The burnup dependent average beta escape probability shall decrease as it depletes because the betas are generated deeper as it depletes. But the average beta escape probability calculated by ABB-CE tends to slightly increase as it depletes due to the calculational uncertainty. This is contradicted to the physical nature of the beta travel in the rhodium emitter. The results of the BETAESC program shows the slight decrease of an average beta escape probability in accordance with the depletion as shown in Figures 4 and 5. The BETAESC program calculates the average beta escape probability of 44.0 % for the typical 0.0457 cm diameter of fresh rhodium emitter and concludes that it is reduced to 42.5 % in the depletion of 80 %.

The initial sensitivity-current is calculated from Equation (1) and the initial sensitivity-current increases as the diameter of the Rh emitter increases. The behaviour of the sensitivity depletion laws of Equation (2) as the neutron flux varies is the same during the burnout of the Rhodium emitter as shown in Figure 2. This means that the sensitivity depletion laws of Equation (4) is independent of the reactor core neutron flux variation. The behaviour of the sensitivity depletion laws versus the diameter of rhodium emitter is different during the burnup of rhodium emitter as shown in Figure 3. This means that different geometry has different sensitivity depletion laws. The sensitivity depletion laws of Equation (4) is required to interpret the signal into the neutron flux in the reactor core.

The RHODIUM and BETAESC programs are sufficient to implement the signal processing algorithm into the on-line computer system of the reactor. Recently, it was attempted to reduce the loading density of the rhodium detector and lengthen the discharge burnup of the rhodium detector. As shown in Figures 4 and 5, the average beta escape probability changes about 1.5 % through the residence time in the reactor core. Because ABB-CE assumed the average beta escape probability constant, this change of 1.5 % will contribute to the uncertainty in power level interpretation. This error will also propagate to the uncertainty in the total peaking factor. In case that the uncertainty in the total power peaking factor can be reduced to the order of 1.0 %, the life of a rhodium detector can be lengthened by about 10 % of the existing detector life(2). Also, the diameter of the rhodium emitter is increased to lengthen the life of a detector as shown in Figure 3.

4. CONCLUSIONS AND RECOMMENDATIONS

The RHODIUM program utilizes the existing numerical model of the neutron transport, but the RHODIUM program is essentially a new program for the special purpose having the capability to calculate the burnup dependent neutron flux distribution and rhodium atom density during depletion. The BETAESC program has a capability to simulate the burnup dependent average electron escape probability. The RHODIUM and BETAESC programs can establish the improved sensitivity depletion laws in designing the rhodium self-powered neutron detector different from the existing SPND in diameter. The RHODIUM and BETAESC programs may reduce the uncertainty in the average beta escape probability and then lengthen the life time by 10 % for rhodium SPND. We believe that the algorithm of the RHODIUM and BETAESC programs can be also utilized for the signal interpretation of prompt-response platinum detector with further studies on the platinum emitter.

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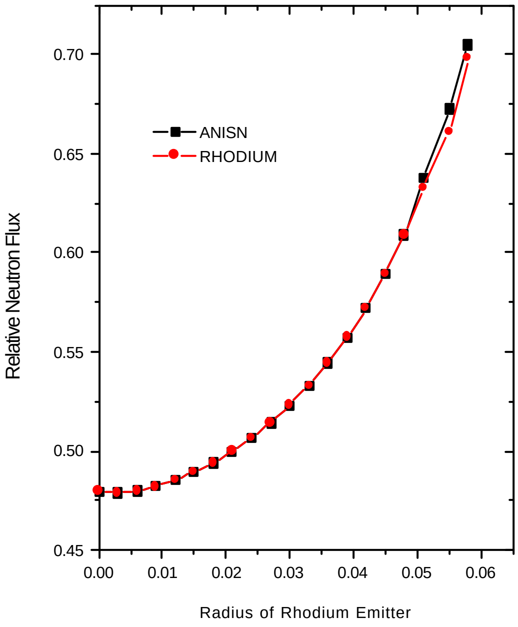


Figure 1. Radial Neuron Flux Distributions Between RHODIUM and ANISN Results

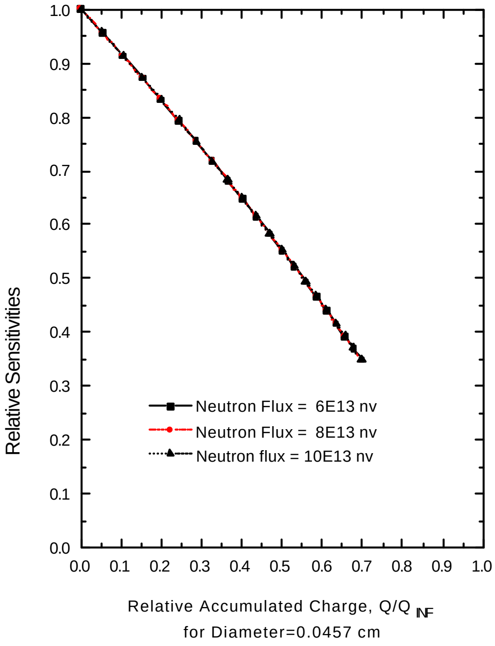


Figure 2. Relative Sensitivity vs Relative Accumulated Charge for Different Neutron Flux Levels with Diameter, 0.0457 cm

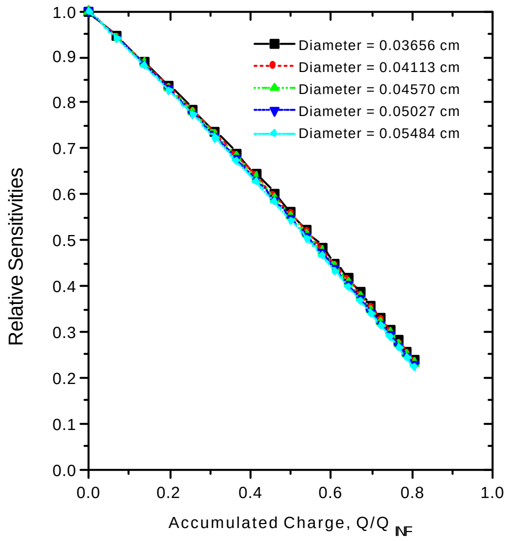


Figure 3. Relative Sensitivity vs Relative Accumulated Charge for Different Diameters

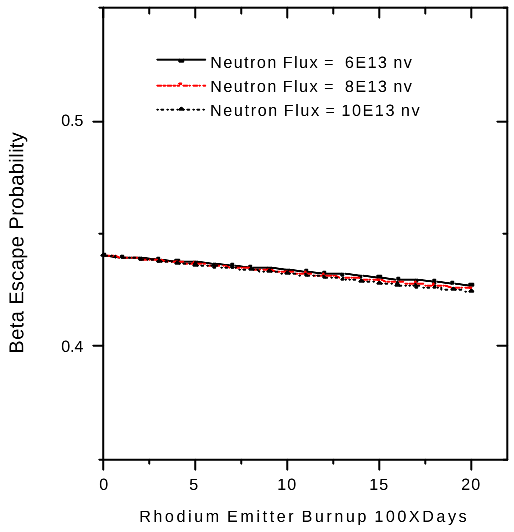
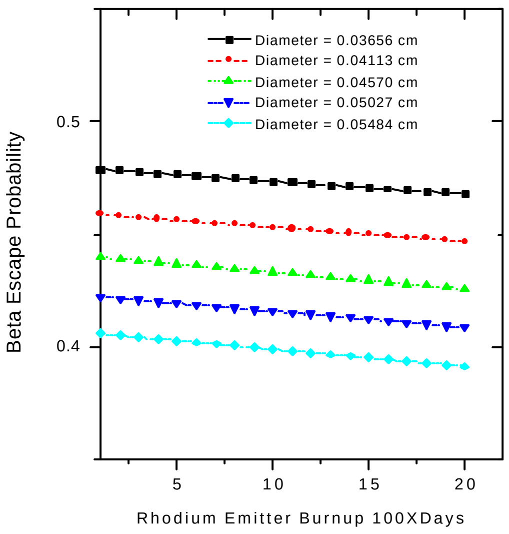
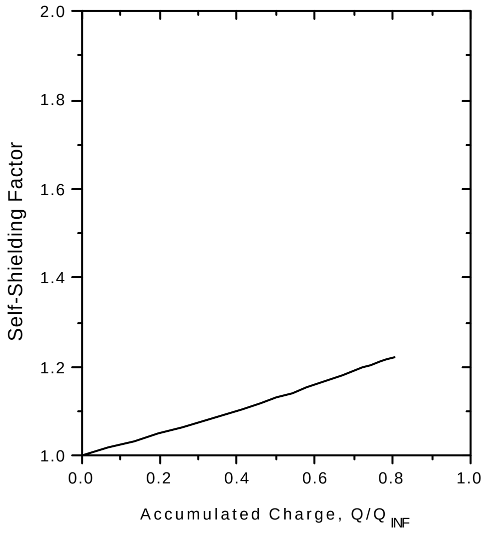


Figure 4. Beta Escape Probability vs Rhodium Emitter with Diameter =0.0457 cm Rhodium Emitter Burnup (days) for Different Neutron Flux Levels





Flux Level

Figure 5. Beta Escape Probability vs Rhodium Emitter Burnup (days) for Different Diameters at the Condition of Neutron Flux Level, $8*10^{13}$ nv

Figure 6. Ratio of Self-Shielding Factor (SF) of Burned to Fresh Detector RHODIUM Calculations