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Investigation of the Sensitivity Depletion Laws for Rhodium Self-Powered Neutron Detectors (SPNDs)

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Abstract

An investigation of the sensitivity depletion laws for rhodium SPNDs was performed to reduce the uncertainty of the sensitivity depletion laws used in Combustion Engineering (CE) reactors and to develop calculational tools that provide the sensitivity depletion laws to interpret the signal of the newly designed rhodium SPND into the local neutron flux. The calculational tools developed in this work are computer programs for a time-dependent neutron flux distribution in the rhodium emitter during depletion and for a time-dependent beta escape probability that a beta particle generated in the emitter escapes into the collector. These programs provide the sensitivity depletion laws and show the reduction of the uncertainty by about 1 % compared to that of the method employed by CE in interpreting the signal into the local neutron flux. A reduction in the uncertainty by 1 % in interpreting the signal into the local neutron flux reduces the uncertainty by about 1 % in interpreting the signal into the local power and lengthens the lifetime of the rhodium SPND by about 10 % or more.

Key Words : SPND, sensitivity depletion laws, beta escape probability, rhodium detector lifetime

1. Introduction

In-core instrumentation provides the operator with the on-line 3-dimensional nuclear power distribution. The objective of this work is to calculate the behavior of the depletion laws for the rhodium SPND and lengthen the lifetime of rhodium SPND. The published neutron transport computer programs do not generally have the capability of atom depletion self-simulation, and thus the program is restarted by manually updating the input data in each depletion step. The RHODIUM program was developed to calculate the burnup-dependent neutron flux distribution within the rhodium emitter using the discrete ordinate neutron transport method during depletion of the rhodium emitter.

The variations of beta escape probability versus depletion are small and the calculation model is very complicated. The depletion behavior of the beta escape probability was experimentally estimated by CE[1] and the initial average beta

escape probability based on uniform electron generation was reported by Warren[2]. The calculation model for the depletion behavior of the beta escape probability was not reported. Therefore, CE treats the beta escape probability as constant during the depletion of the rhodium SPND by assuming the uncertainties are small. This treatment contributes to the uncertainties of the instrumentation. In this work, for the burnup-dependent average beta escape probability, non-uniform beta electron 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. The sensitivities vary during burnup of the rhodium SPND. The initial sensitivities are obtained from the experimental data. It may be difficult to predict the full range of sensitivities associated with the depletion of the emitter in the phase of the development and operation of rhodium SPND. Therefore, a calculation model to interpret the behavior of the sensitivities for the rhodium emitter is required. From experimental and operational experience, it is known that the neutron flux distribution and the electron escape probability to the surface of the rhodium emitter are dependent on the depletion of the emitter. The electric field in the insulator region and the electron generation probability with energy E and the electron energy loss per unit length travel are independent of the depletion of the rhodium emitter.

These programs mentioned above provide the sensitivity depletion laws and evaluate the uncertainty of the method employed by CE in interpreting the signal into the local neutron flux. By applying the newly established sensitivity depletion laws, the reduction of the uncertainty in interpreting the signal into the local neutron flux and the extension of the life of the Rh detector are evaluated.

2. Analytical Methods

2.1. Operation Principles and Emitter Interactions of Rh SPND

A rhodium SPND is a high level neutron sensing device operating on the mechanism of neutron activation of rhodium-103 emitter material. The neutrons incident on the rhodium emitter are converted to high energy electrons which spontaneously migrate between insulated electrodes often termed the 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 as shown in Fig. 1, a counter current flows to maintain the 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

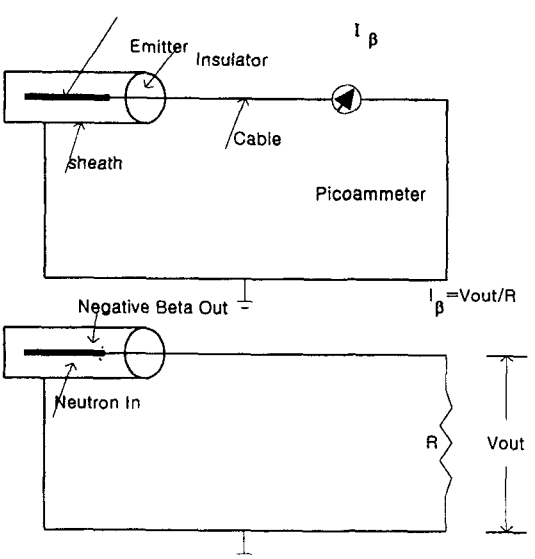

Fig. 1. Configuration of SPND

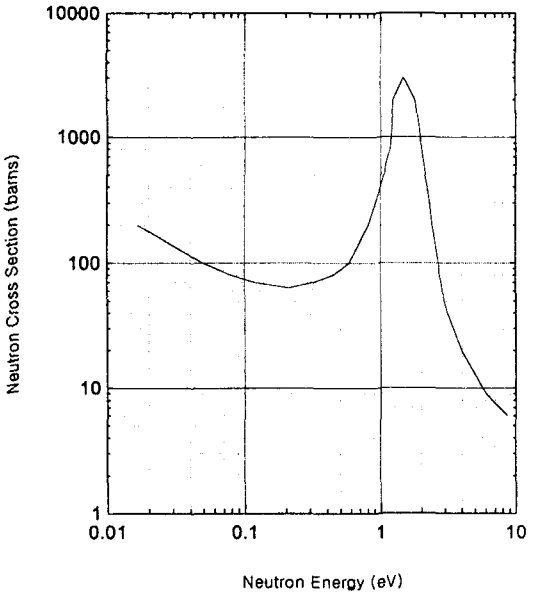

Fig. 2. Rh^{103} Capture Cross Section vs. Neutron Energy

impinges upon the device.

Three major interactions, by which incident radiation is converted to energetic electrons, are the (n,β), (n,γ,e), and (γ,e) interactions. External electrons from other internal components of the reactor, impinging on the emitter and collector, also contribute to the overall output current. Rhodium (^{103}Rh) is selected as the emitter material for its large thermal neutron capture cross section (150 barns (1 barn=10^{-24} cm^2)) and for the relatively short half-life (42 seconds) of its principal capture product isotope (^{104}Rh) which generates about 87 % of the total signal. A metastable capture product isotope (^{104m}Rh) which generates about 7 % of the total signal occurs about 8 % of the time. It decays with a 264-second half-life. The processes by the above two neutron captures result in a change in the relative sensitivity of the detector to the neutron flux with time due to rhodium depletion. The overall efficiency for the (n,β) reaction is high, usually one electron per capture with a typical escape probability of 40 %. Detailed calculation is the major topic of this work, which is presented in section 2.3. In the current signal processing of the rhodium detector, it is assumed that the gamma rays are incumbersome for a rhodium emitter.[3]

The energy-dependent neutron capture cross section for Rh^{103} is shown in Fig. 2. Rhodium has a thermal neutron capture cross section (σ_o) of about 150 barns. The effective neutron capture cross section (σ_{eff}) corrected for the neutron spectrum and temperature in the reactor core is 135 barns for 0.0457 cm diameter rhodium emitter.

Consider an atom on the surface of the wire. It sees the full neutron flux which is incident from the outside. Some of this flux is absorbed by those atoms at or near the surface. Atoms in the center of the wire do not see the full neutron flux because the number of neutrons decreases due to absorption near the surface. This emitter-diameter-dependent effect is called self-shielding. A burnup-dependent effective thermal neutron self-shielding ratio (SSR) is defined in Eq. (1) as follows;

$$SSR = \frac{\iint_B \sigma \Phi \, dEdV}{\iint_F \sigma \Phi \, dEdV} \quad (1)$$

where σ = rhodium neutron capture cross section
V = volume of rhodium
Φ = neutron flux in the rhodium.
B = partially-burned detector, and
F = fresh detector.

The burnup-dependent effective thermal neutron self-shielding ratio for a 0.0457 cm diameter rhodium emitter is presented in Fig. 3. Self-shielding also affects the burn-up rate of emitter atoms because those in the center are depleted less compared with those near the surface.

Another variable to consider is the beta escape probability, i.e., the probability of a beta particle contributing to the detector current. To illustrate

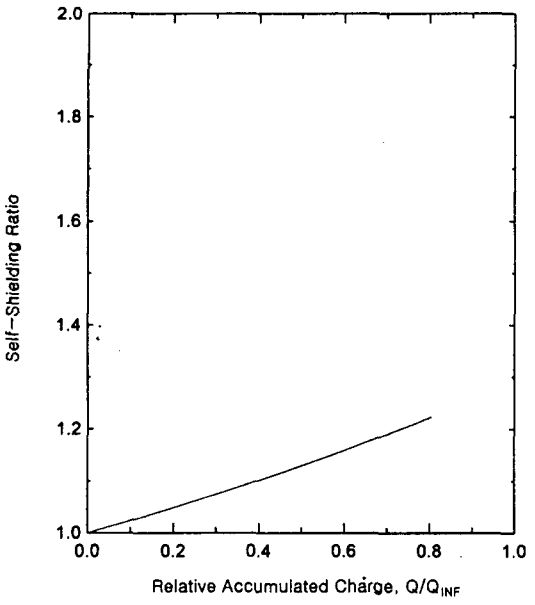

Fig. 3. Ratio of the Self-Shielding of Burned to Fresh Detector Calculated by RHODIUM Program

this, assume an atom at the emitter' s surface has just emitted a beta particle. The emission is isotropic; that is, it occurs equally in all directions. If the emission is in a direction away from the emitter, the beta particle is likely to penetrate the insulation and contribute to the current. Since the beta particle energy is very high, it may also pass through the emitter and insulator, and appear on the opposite side of the detector. At low angles, the beta particle has a very long path through the emitter and insulator, and is likely to be absorbed by them. Therefore, beta particles which are emitted along low angle paths may not contribute to the detector signal. The beta escape probability is dependent upon the detector geometry.

The components of the detector signal consist of two parts, i.e., the emitter signal and background signal. The term "background" is used for the sum of all the generated signals not related to interactions in the rhodium emitter. The easiest way to overcome background is to have a large signal to background ratio. For 0.158 cm diameter SPNDs with a 0.0457 cm diameter rhodium emitter, the background signal represents about 2-3% of the total initial detector signal.

2.2. Sensitivity Depletion Law

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

$$I = \varepsilon P_\beta N \int_{Rh} \int \sigma \Phi \, dE dV \tag{2}$$

where at any time

- ε = electron charge
- P_β = average beta escape probability
- N = average rhodium number density
- σ = rhodium neutron capture cross section
- V = volume of rhodium, and
- Φ = neutron flux in the rhodium.

In the CE approach, the sensitivity depletion law is used to give the sensitivity of the depleted detector based on the activation rate. The sensitivity based on rhodium activation is defined as the signal to activation ratio, i.e.,

$$S_A = \frac{I}{\frac{1}{V}\int_{Rh} \int \sigma \Phi \, dE dV} \tag{3}$$

Combining Eqs. (2) and (3),

$$S_A = \varepsilon P_\beta N V \tag{4}$$

which has a near linear characteristic on N because of a small variation of P_β during depletion. CE assumed that P_β is constant with depletion at least to about 66 % depletion.[1] Because the accumulated charge (Q) would be inversely proportional to N, a sensitivity depletion law would show a near linear characteristic. The sensitivity depletion law based on rhodium activation is expressed in terms of the total

theoretical charge Q_{INF} and the initial sensitivity S_o as follows:

$$\left(\frac{S}{So}\right)_A = P \times \left(1 - \frac{Q}{Q_{INF}}\right) \quad (5)$$

where average beta escape probability change ratio is

$$P = \frac{P_\beta^B}{P_\beta^F} \quad (6)$$

In the alternative useful approach reported by Dechand et al.[1], the sensitivity depletion law based on the ratio of the signal of an old detector to that of a new detector is

$$\left(\frac{S}{S_0}\right)_S = \frac{I^B}{I^F} = \frac{\varepsilon P_\beta^B N_B \int_B \int \sigma\Phi \, dEdV}{\varepsilon P_\beta^F N_F \int_F \int \sigma\Phi \, dEdV} \quad (7)$$

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

This sensitivity depletion law based on signals has also a linear characteristic on the rhodium atom density N. The neutron self-shielding effects between a fresh and partially-burned detector are represented by the ratio of the double integrals in Eq. (7) and the calculation results of that equation are shown in Figs. 4 and 5. Because the accumulated charge (Q) would be inversely proportional to N, the sensitivity depletion law based on the signals becomes as follows:

$$\left(\frac{S}{S_0}\right)_S = \left(1 - \frac{Q}{Q_{INF}}\right) \times \frac{P_\beta^B}{P_\beta^F} \times \frac{\int_B \int \sigma\Phi \, dEdV}{\int_F \int \sigma\Phi \, dEdV} \quad (8)$$

If the self-shielding ratio (Eq. (1)) and the average beta escape probability change ratio (Eq. (6)) are constant during the burnup of a rhodium emitter, the two depletion laws are exactly the same. However, the two ratios are not constant because of spectral, resonance, and self-shielding effects. The self-shielding ratio versus burnup given by Eq. (1) is in fact nearly linear in behavior as shown in

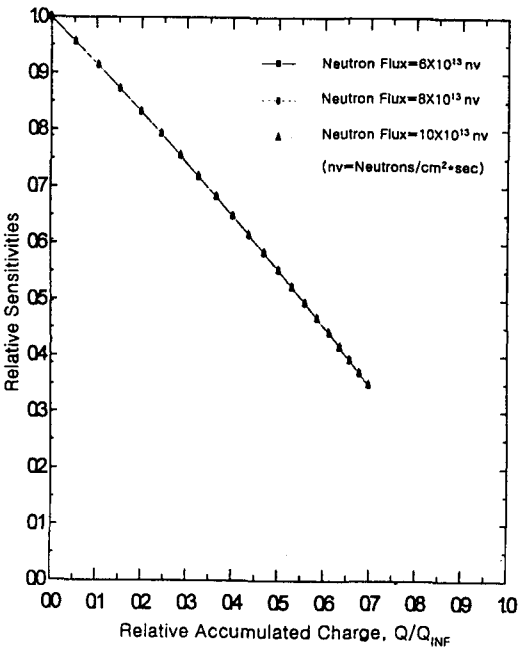

Fig. 4. Relative Sensitivites vs. Relative Accumulated Charge for Different Neutron Flux Levels with a Diameter of 0.0457cm

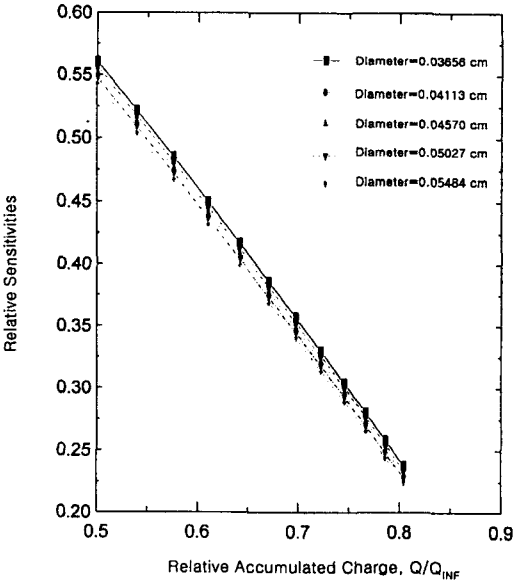

Fig. 5. Relative Sensitivites vs. Relative Accumulated Charge for Different Different Diameters with Neutron Flux Level of 8× 10^{13} Neutrons/cm^2 • sec

Fig. 3. Estimates of the ratio of the double integrals with the remaining rhodium number density have been evaluated with the RHODIUM neutron transport program for a typical 0.0457 cm (0.018″) detector. The sensitivity depletion law based on activation (Eq. (4)) is nearby linear, while the one based on the signals (Eq. (7)) has a downward curvature as shown in Figs. 4 and 5. The latter can be fitted well with following equation:

$$\left(\frac{S}{S_0}\right)_S = \left(1 - \frac{Q}{Q_{INF}}\right)^{\alpha} \tag{9}$$

where α is 0.825 for a 0.0457cm diameter rhodium emitter. Either Eq. (7) or (9) is acceptable as long as it is used in a consistent fashion with the properly defined power to signal or activation factor.

2.3. Beta Escape Probability

The probability that an electron of energy E′ arrives at the emitter's surface with residual energy E is found from track length probability functions. To arrive at the surface with energy E, the electron must have travelled a specific track of length l, losing energy during the process. The probability of arrival at the surface with energy between E and E+dE is equal to the probability that the electron travels to the surface with a track length between l and $l+dl$. This probability is given by NP(l)dl where NP(l) 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 the electrons of energies E′ and E within the emitter material. Now $dl = -dR(E)$ and

$$dR(E) = -\left(-\frac{dE}{dx}\right)_E^{-1} dE \tag{10}$$

where Eq. (10) is the reciprocal of the specific energy loss of electrons within the emitter material evaluated at energy E. Thus, the probability that a source electron of energy E′ arrives at the emitter's surface with energy between E and E+dE is given by

$$NP(l)dl = NP\left(R[E'] - R[E]\right) \times \left(-\frac{dE}{dx}\right)_E^{-1} dE. \tag{11}$$

The restrictions on its use are that the track generations must be uniform throughout the volume and that the tracks must be straight. Use of the NP function here requires the assumption that the beta decay electrons travel straight lines to the surface.

Therefore, the incident neutron flux in the cylinder must be assumed to be isotropic. Although electrons do not always travel in straight lines when slowing down in material, the symmetry of the cylinder should reduce the errors introduced by large-angle electron scatterings. The integration over residual surface energy E has the upper limit E_β and the lower limit EMIN. E_β is the maximum electron energy in the beta decay. EMIN is the average minimum energy that an emitter surface electron must contribute to the current sensitivity of the SPND. The beta decay energy spectrum at the emitter's surface is inherent to Eq. (11) in the form of

$$C(E) = \left(-\frac{dE}{dx}\right)_E^{-1} dE \int_E^{E_\beta} \left[NP\left(R[E'] - R[E]\right)\right] B(E')dE' \tag{12}$$

where C(E) is the number of electrons of energy E per unit volume, energy and time appearing at the emitter's surface for a given neutron capture rate and B(E) is the probability of continuous beta generation.[4] When as a function of E, C(E) displays a beta energy spectrum distorted by the loss of electron energy within the emitter. The beta particle (or electron) escape efficiency is also inherent to Eq. (12) and is given by

$$P_S = \int_0^{E_\beta} C(E)\,dE = \int_0^{E_\beta} \left(-\frac{dE}{dx}\right)_E^{-1} dE \int_E^{E_\beta} \left[NP\left(R\left[E'\right] - R\left[E\right]\right)\right] B(E')\,dE' \quad (13)$$

Of all the beta particles produced by a neutron capture, P_s 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 the electron contributes to the current of a detector. It must have energy greater than EMIN to contribute to the signal. Electrons with energy less than EMIN are excluded by the lower limit on the right hand side integral of Eq. (13). The calculation of EMIN defined as the minimum beta energy to overcome the electric potential field in the insulator of the detector is provided in the Ref. 2. EMIN for the Al_2O_3 insulator of 0.0457cm diameter rhodium emitter is 0.36 MeV as shown in Ref. 2. This EMIN value is used in this beta escape probability calculation.

Beta generation at a position is proportional to the neutron absorption at that position. The continuous energy spectrum of beta generation are described in Ref. 2 and the track length probability function are required to calculate the average electron escape probability. But the analytic solution does not exist for the non-uniform depletion of rhodium atom, while the track length probability function described in Eq. (11) has an analytic solution but complicated for the uniform probability of electron generation. Then to solve this problem, the hypothetical flights of electron in the emitter are introduced. The BETAESC algorithm computes the electron escape probability in the emitter based on whether the generated electron contributes to the current of a detector or not. An electron migrates in the rhodium emitter and contributes to the current if the distance from the location of electron generation to the surface of the emitter is shorter than the range of an electron having the energy (E-EMIN). Therefore it is possible to track all discrete flights in the emitter if the time-dependent neutron flux and rhodium atom density are calculated. Since the electric field in the insulator is independent of the burnup, EMIN is assumed to be constant during depletion of a rhodium emitter. Beta generation is isotropic and straightly migrates inside the emitter. The migration range of a beta is provided in Ref. 4. The tracking of a beta is performed at the discrete grid point inside the emitter at each time step of depletion of a rhodium emitter.

2.4. Neutron Transport Method and Rhodium Depletion

This section provides the development of one-dimensional, one-group, discrete ordinates, and diamond-differenced form of the time-dependent Boltzmann transport equation in a cylindrical geometry.[5, 6] The time- dependent Boltzmann transport equation in one space dimension and quasi-static form is

$$\Omega \cdot \nabla \varphi(\vec{r}, \Omega, t) + \Sigma(\vec{r}, t)\varphi(\vec{r}, \Omega, t) = 0 \quad (14)$$

where $\varphi(\vec{r}, \Omega, t)$ is the particle flux (particle number density times the particle velocity) defined such that $\varphi(\vec{r}, \Omega, t)d\vec{r}\,d\Omega\,dt$ is the flux of particles, in the volume element $d\vec{r}$ about $\vec{r}$ and in the time dt about t with directions of motion in the solid angle element $d\Omega$ about Ω. The macroscopic total cross section is Σ. Eq. (14) is subject to appropriate (inhomogeneous) boundary condition at the enclosure of the emitter. All of the quantities may be spatially dependent. The discrete ordinates approximation to Eq. (14) can then be written as

$$\mu_m \frac{\partial(r\varphi_m)}{\partial r} + \left(\frac{\alpha_{m+\frac{1}{2}}}{\omega_m}\right)\varphi_{m+\frac{1}{2}}(r,t) - \left(\frac{\alpha_{m-\frac{1}{2}}}{\omega_m}\right)\varphi_{m-\frac{1}{2}}(r,t) + r\sigma\varphi_m(r,t) = 0 \quad (15)$$

where the $\alpha_{m+\frac{1}{2}}$ and $\alpha_{m+\frac{1}{2}}$ are the angular co-upling coefficients. These coefficients satisfy the recursion relation

$$\alpha_{m+\frac{1}{2}} - \alpha_{m-\frac{1}{2}} = -\omega_m \mu_m \qquad (16)$$

where μ_m is the discrete ordinates and ω_m is the quadrature weights with the requirement that the first $\alpha_{M+\frac{1}{2}}$ and last $\alpha_{M+\frac{1}{2}}$ coefficients on each ξ-level on the z-axis of discrete ordinate direct cosine sets must vanish. The discrete ordinates approximation is employed to calculate the angular neutron flux at point $\vec{r}$ and time t since Eq. (14) is spatially non-uniform and a time-dependent function. At the next time step, Eq. (17) is solved to calculate the atom density. If $N(\vec{r}, t)$ is the atom density of rhodium at point $\vec{r}$ and time t, its depletion is determined by the equation as follows:

$$\frac{dN(\vec{r},t)}{dt} = N(\vec{r},t)\sigma\Phi(\vec{r},t) \qquad (17)$$

where σ is the microscopic total cross section ,

Φ is the neutron flux at point $\vec{r}$ and time t, and an appropriate initial condition is given for$(\vec{r}, t)$. The discrete ordinates approximation for rhodium emitter of Eq. (15) and the calculation of rhodium depletion by Eq. (17) is incorporated into the RHODIUM program.

3. Results and Discussions

The RHODIUM program is intended to calculate the radial neutron flux distribution for the non-uniform rhodium atom density because the rhodium atom density becomes non-uniform as it depletes. The benchmark calculation between the RHODIUM program and ANISN code is shown in Fig. 6. The two programs' results for the neutron flux distribution inside the rhodium emitter are almost the same.

The average beta escape probability can be determined from Eq. (2) as

$$P_\beta = \frac{I}{N\varepsilon \int_V \int_E \sigma\Phi \, dE dV} \qquad (18)$$

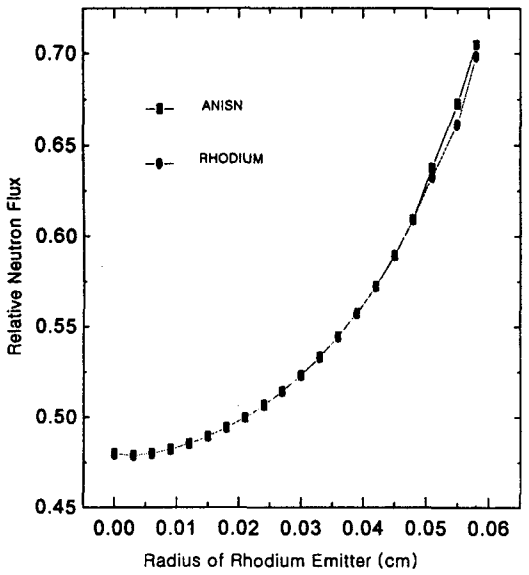

Fig. 6. Radial Neutron Flux Distributions Calculated by RHODIUM and ANISN

CE evaluated the average beta escape probability using the measured current and the calculations computed by the ROCS and MC code [7]. The results estimated by CE show that the average beta escape probability slightly increases as the rhodium depletes but CE assumes that the average beta escape probability is constant because the uncertainty computed by the ROCS and MC code is equivalent to the evaluated variation of the average beta escape probability. If the denominator is properly calculated or the neutron self-shielding/non-uniform rhodium atom density are considered, the results will be more accurate. The early study on sensitivity depletion laws is not sufficient from the view point of the neutron self-shielding/non-uniform rhodium atom

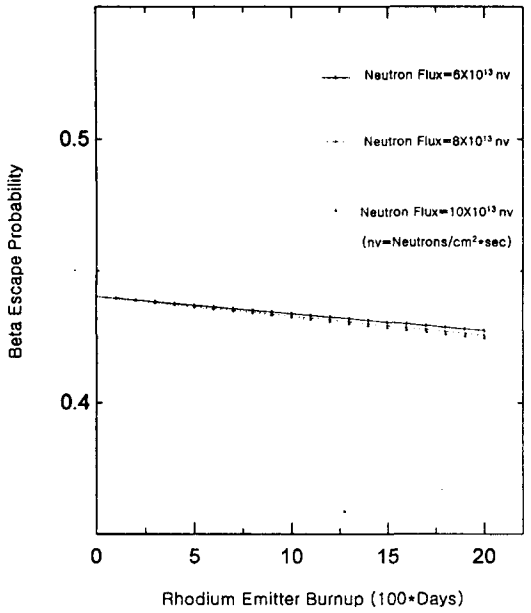

Fig. 7. Beta Escape Probability vs. Rhodium Emitter (Diameter=0.0457cm) Burnup (Days) for Different Neutron Flux Levels

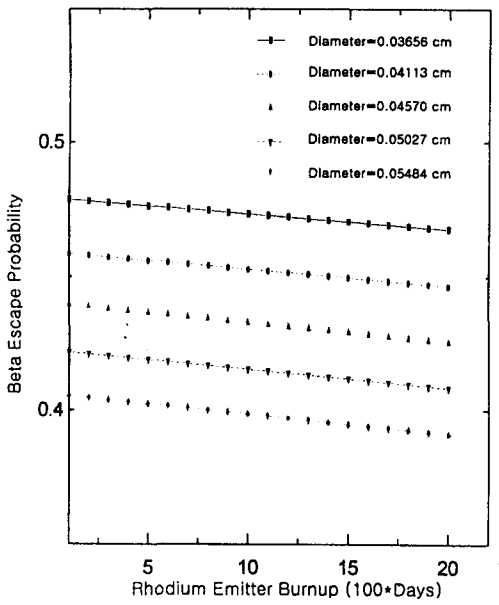

Fig. 8. Beta Escape Probability vs. Rhodium Emitter Burnup (Days) for Different Diameters at a Neutron Flux Level of 8× 10^{13} Neutrons/cm^2 • sec

density. The average beta escape probability calculated by CE tends to slightly increase as the rhodium depletes. But physically, the average beta escape probability shall decrease as the rhodium depletes because the betas are generated deeper inside as the rhodium depletes. The average beta escape probability calculated by CE is contradicted to the physical nature of beta travel in the rhodium emitter. However, the results of the BETAESC program show a slight decrease of the average beta escape probability in accordance with the depletion as shown in Figs. 7 and 8. CE calculated the average beta escape probability of near 42 % and a slight increase for the higher burnup for the typical 0.0457 cm diameter of the rhodium emitter due to the uncertainty in the calculations, assuming that the average beta escape probability is constant through the detector life. The BETAESC program calculates the average beta escape probability of 44 % for the typical 0.0457 cm diameter of a fresh rhodium emitter and estimates that it is reduced to 42.5 % with a depletion of 80 %. The trends of an average beta escape probability versus the diameter of the rhodium emitter are shown in Fig. 8 and are the same each other as expected. This means that the average beta escape probability decreases as the diameter of the rhodium emitter increases.

Fig. 4 showed the sensitivity depletion laws are independent of the reactor core neutron flux variation. Fig. 5 showed that a different geometry has different sensitivity depletion laws. The average beta escape probability changes by about 1.5 % through the residence time in the reactor core as shown in Figs. 7 and 8. Because CE assumed the average beta escape probability is constant, this change of 1.5 % will contribute to the uncertainty in the sensitivity. This uncertainty propagates to the uncertainty of the neutron flux interpretation since the sensitivity depletion laws

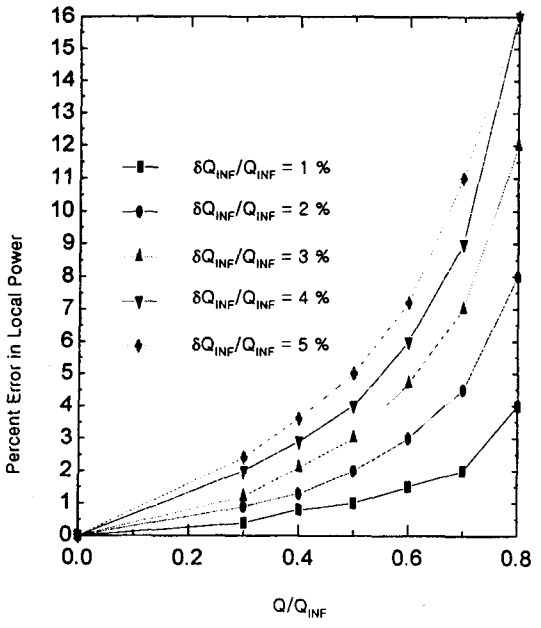

Fig. 9. Local Power Uncertainty as a Function of Detector Depletion

of Eq. (8) are used to interpret the signal into the local neutron flux in the reactor core. This error will also propagate to the uncertainty of the total peaking factor. The uncertainty in Q is directly related to the uncertainty in sensitivity, neutron flux, and local power interpretation. Fig. 9 [8] shows that the reduction in the maximum uncertainty of Q, δQ_{INF}, reduces the uncertainty in sensitivity. In case that the uncertainty of the total power peaking factor can be reduced to a degree of about 1 %, the life of a rhodium detector can be lengthened to about 10 % or more of the existing detector life as shown in Fig. 9[8].

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 to calculate the burnup-dependent neutron flux distribution and rhodium atom density during depletion. Assumptions of the BETAESC program on the electron escape probability calculation are that electron generation is non-uniform and dependent on the neutron flux distribution inside the emitter and that the electron generated is isotropic. This causes the BETAESC program to be slightly time-consuming. Calculation by the BETAESC program is performed off-line and, therefore, provides the designer with useful information. The calculational model of a burnup-dependent average electron escape probability was not reported and a constant electron escape probability was used in the nuclear industry. This may cause an uncertainty in the total peaking factor to be larger. The uncertainty of the sensitivity depletion curve decreases as that of the average beta escape probability decreases. The lifetime of the rhodium SPND increases as the uncertainty of the sensitivity depletion curve decreases. Therefore, the reduced uncertainty of the average beta escape probability lengthens the lifetime of the existing rhodium SPND. Because the cycle length of refueling was recently lengthened from 12 months to 15, 18 or 24 months due to economic reasons, it is required to redesign the rhodium SPND. It is recommended that the RHODIUM and BETAESC programs be used to establish the improved sensitivity depletion law to design the rhodium SPND of different diameter from the existing SPND. The RHODIUM and BETAESC programs can reduce the uncertainty in the average beta escape probability. The reduction of the uncertainty in the average beta escape probability causes the uncertainty to be reduced in the reactor power. Due to the cost, the exposure to radiation and the longer fuel cycle, there is a strong incentive that the loading density of the in-core instrumentations is reduced and the lifetime of the detector is lengthened. These objectives can be

achieved by reducing the uncertainty, which is amplified as the rhodium depletes. The calculational tools in the present work provide the sensitivity depletion laws and show the reduction of the uncertainty to about 1 % or more in interpreting the signal into the local neutron flux compared to the method employed by CE. The reduction of an uncertainty by 1 % in interpreting the signal into the local neutron flux reduces the uncertainty by about 1 % in interpreting the signal into the local power and lengthens the lifetime of rhodium SPND by about 10 %.

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