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Neutron Sensitivity Calculation of a Cobalt Self-Powered Neutron Detector Using with Monte-Carlo Method

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1. Introduction

A Self-Powered Neutron Detector (SPND) is one of devices for in-core fluxes detecting without an external electricity source. The SPND emitter is consisted with neutron sensitive material. Generally, the SPND produces a delayed current signal with beta decay and a prompt current signal with neutron capture reaction and gamma reaction. The prompt current signal has the advantage of having an immediate reaction, but has the disadvantage of weak signal strength, and the delayed current signal tends to be the opposite to the prompt one.

The SPND is consisted of cylindrical shape with emitter, insulator and collector. When neutrons or gamma rays react with the emitter, it generates electrons and these electrons cross insulator area to make electric signal in collector area.

For calculating sensitivity of SPND with Monte-Carlo code such as MCNP, many assumptions must be considered. Although many studies have been conducted for sensitivity calculation computational simulation of SPND, the sensitivity evaluation to cobalt SPND has not shown good results due to the complex decay chain of Cobalt-59.

Cobalt SPND is using (n, γ, e) reaction to generate signal current. With this interaction between neutron and Co-59, relatively high prompt signals made with cobalt SPND and only 0.24% of delay signal is generated in Co-60m. Since Co-60's half-life time is very long as around 5 years, it became background signal current after depletion.

So, unlike other SPNDs (Rhodium, Vanadium, etc.), cobalt shows that prompt signal and relatively low signal comparing with other delayed signal SPNDs.

In this paper, computational simulation for cobalt SPND's initial and delayed sensitivity calculations were performed.

2. Detector Sensitivity Calculation Model

In the SPND, when emitter generates electrons continuously, electric field is formed in insulator region. In the MCNP, effect of electric fields can't be considered as part of code. So appropriate assumptions and equations needed for simulating electric field. Space charge effect is one of main assumption for sensitivity calculation. Space charge effect is phenomenon that electric field disturb the movement of electrons. when electrons continue to be released, the cathode becomes relatively polarized and pulls the electrons back together, disturbing the movement of electrons to release them, forming a space charge around them to form a cloud-like electron cluster. In the SPND, space charge effect is occurred in insulator region and the critical distance becomes the limit of electron movement from emitter to collector. To implement effect of this electric field generated by the space charge, the critical distance is derived, where the electric field intensity becomes zero.

SPND has typical cylindrical geometry and in the cylindrical symmetry, electric field E obeys Poisson equation [4]. This electric field can be defined as function of radius and charge density. So, it can be expressed that electric field in insulator region as equation (1).[3]

$$\frac{\partial E}{\partial r} + \frac{E}{r} = \frac{\rho(r)}{\varepsilon} \qquad (1)$$

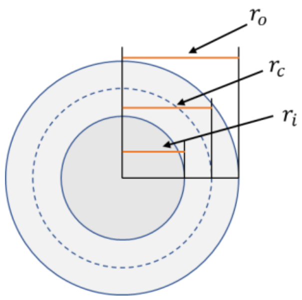
E : electric field, r : radius
$\rho(r)$ *: charge density,* ε *: dielectric constant*

And with first linear order differential equation's solver is used for equation (1) to transformation function of the radius of an electric field. Boundary condition was set to have no potential difference inside the insulator. With this boundary condition, equation (1) can be derived as equation (2).

$$E(r) = \frac{1}{r\varepsilon}\left(\int_{r_i}^{r} \rho(r')r'dr' - \frac{1}{\ln(r_o/r_i)}\int_{r_i}^{r_o} dr'' \frac{1}{r''}\int_{r_i}^{r''} \rho(r')r'dr'\right) \qquad (2)$$

r_i *: insulator inner radius,* r_o*: insulator outer radius*

r_i and r_o each means that insulator inner radius and outer radius such as figure 4.



r_o: insulator outer radius
r_c: critical radius
r_i: insulator inner radius

Figure 1. Cross-section of SPND (only emitter and insulator) and radius approximation.

In the Figure 1, critical distance is shown as r_c between insulator regions.

Because of space charge effect, it needs to consider additional equations driven from equation (2). Fraction f means that refers to the fraction at which electrons generated in the emitter return due to the space charge effect. It can be expressed as equation (3).[4]

$$f = \frac{\ln(r_o)}{\ln(r_o/r_i)} - \frac{1}{\ln(r_o/r_i)} \frac{\int_{r_i}^{r_o} r\ln(r)\,\rho(r)dr}{\int_{r_i}^{r_o} r\rho(r)dr} \quad (3)$$

And for increasing calculation accuracy, insulator region is divided as several ring shape such as figure 2. Equation (4) is derived with divided insulator.

$$f = \frac{\ln(r_o)}{\ln(r_o/r_i)} - \frac{1}{\ln(r_o/r_i)} \frac{\sum_{j=1}^{n} \overline{r_j}\ln(\overline{r_j})\,\rho_j \Delta r_j}{\sum_{j=1}^{n} \overline{r_j}\rho_j \Delta r_j} \quad (4)$$

With f fraction rate, emitter to sheath current can be calculated with equation (5) and SPND sensitivity calculation using emitter to sheath current and neutron flux such as equation (6).

$$J_{ec} = J_{ei} - f(J_{ei} - J_{ic}) = (1-f)J_{ei} + fJ_{ic} \quad (5)$$

J_{es}: emitter to collector current,
J_{ei}: emitter to insulator current
J_{is}: insulator to collector current

$$Sensitivity = \frac{J_{ec}}{\phi} \quad (6)$$

ϕ: neutron flux

The factors of equation (5) can be tallied with MCNP F1 tally at boundary surface of each component. The sensitivity of SPND can be determined by using J_{ec} calculated by equation (6) and the neutron flux. Neutron fluxes can be obtained by analytical solutions and MCNP tally.

And, to calculate delayed current of detector, ORIGEN-S code in SCALE[6] and BETA-S are used.

The calculation model for the delayed signal uses the same basic assumptions, but unlike the prompt signal, the source term is defined differently. Instead of using the neutron spectrum, the beta spectrum from the decay of cobalt is used. The location of the source is also specified to be inside the emitter instead of outside the instrument, and the emitter material is calculated by changing its composition, assuming that it is also depleted.

3. Co-SPND Sensitivity Calculations

For the sensitivity calculation, arbitrary SPND is modeled such as table 1.

Table 1. Specification of the SPND model.

Part	Material	Density (g/cm^3)	Length (cm)	Radius (cm)
Emitter	Co-59	8.9	20.03	0.0995
Insulator	Al_2O_3	1.9	20.03	0.1615
Collector	Inconel-600	8.44	20.03	0.2025

And source neutron spectrum was set as typical light water reactor's one. Figure 2 shows that neutron spectrum used for sensitivity calculation. Neutron source term place at outer region of SPND collector. And neutron flux tallied at SPND outer boundary of collector with F4 tally.[5]

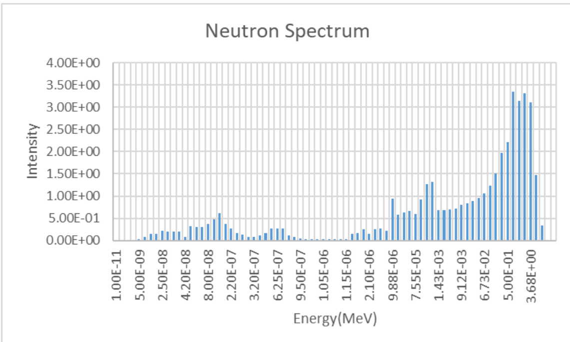


Figure 2. Neutron spectrum source for SPND sensitivity calculation.

Based on the material properties in Table 1, approximately 5.5 grams of cobalt-59 is used. This is entered into ORIGEN to perform a depletion calculation for about 5500 days, and the results are shown in Figure 3 and Table 2.

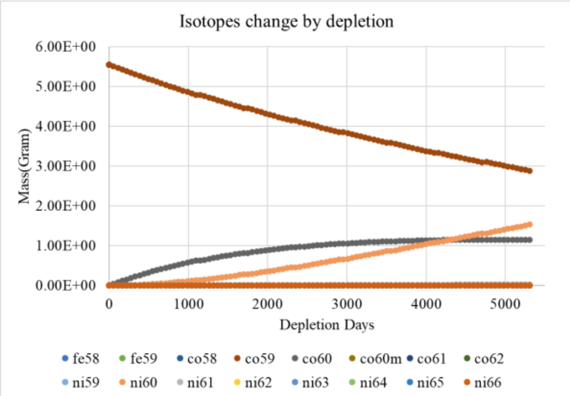


Figure 3. Origen depletion calculation result.

Table 2. Origen depletion calculation result with 4 depletion time.

Unit : Gram	Depletion days				
	0	548	2189	3830	4924
Co59	5.54	5.151	4.199	3.452	3.033
Co60	0	0.3579	0.9358	1.128	1.149
Ni60	0	0.0374	0.4185	0.9752	1.377

According to the ORIGEN calculation results in Figure 3 and Table 2, cobalt 59 decreases gradually with the depletion period, cobalt 60 becomes saturated after approximately 3000 days and the increase is significantly reduced, and nickel 60 tends to increase gradually.

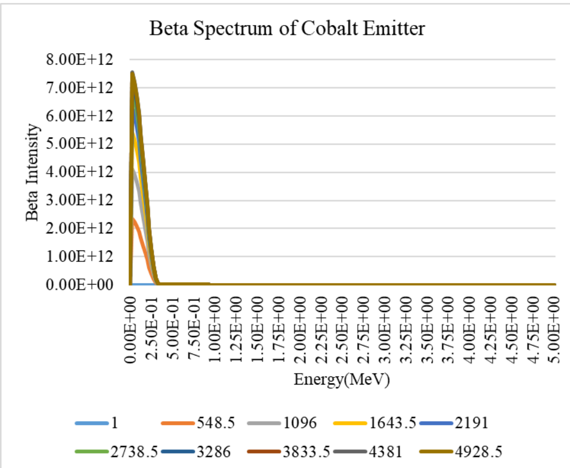


Figure 4. Beta spectrum source for Co SPND delayed signal sensitivity calculation.

The beta spectrum calculated with BETA-S is shown in Figure 5. Overall, the peak occurs in the lower energy region, with the peak rising as the combustion period increases. Because of the large contribution of cobalt 60 to the beta source, the peak as a function of burn time saturates around 3000 days, as it does for cobalt 60.

With this defined SPND sensitivity and the calculated information, a computational simulation code such as MCNP can be used to calculate the sensitivity of initial and post-depletion Co SPNDs.

Table 3. Sensitivity calculation results of Co SPND.

Sensitivity Unit : A/nv-sec	Prompt	Delayed
Initial	6.06E-22	-
After 548 days (1.5 year)	6.18E-22	5.51E-23
After 2189 days (6 year)	5.85E-22	4.58E-23
After 3830 days (10.5 year)	5.1E-22	4.38E-23
After 4924 days (13.5 year)	4.67E-22	4.23E-23

Table 3 summarizes the results of the sensitivity calculation of Co SPND. Calculations were performed for the initial and all four-depletion period. In the Table 3, the whole sensitivity tended to decrease as the depletion period increased. This is due to a decrease in the absolute amount of cobalt isotopes that generate the signal, and the decrease in sensitivity is greater for cobalt 59 than for cobalt 60.

4. Conclusion and Summary

In this paper, prompt and delayed sensitivity assessment of Co SPND was conducted through a computational simulation code. MCNP and ORIGEN were used as simulation codes, and BETA-S was also used to calculate beta spectra. The calculations were performed using four additional time steps depending on the initial state and depletion period. The results of the sensitivity calculation show that the overall sensitivity tends to decrease as the combustion period increases, and the sensitivity of prompt signals decreases more than that of delayed signals. This is due to the overall decrease in cobalt nuclides due to combustion, and to a lesser extent, because the main source, cobalt 60, decreases only slightly in saturation.

In the future work, more detailed analysis including shorter time intervals will be conducted.

Reference

[1] H. D. Warren, Calculational Model for Self-Powered Neutron Detector, Nuclear Science and Engineering, Volume 48, Pages 331-342, 1972

[2] Hyunsuk Lee, Sooyoung Choi, Kyoon-Ho Cha, Kwangho Lee & Deokjung Lee, New calculational model for self-powered neutron detector based on Monte Carlo simulation, Journal of Nuclear Science and Technology, Vol. 52, No. 5, 660–669, 2015

[3] N. P. Goldstein, A MONTE-CARLO

Calculation of the Neutron Sensitivity of Self-Powered Detectors, IEEE Transactions on Nuclear Science, Volume: 20, Issue: 1, p549 – 556, 1973

[4] L. Vermeeren and R. Van Nieuwenhove, Online gamma dose-rate measurements by means of a self-powered gamma detector, IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 49, NO. 4, AUGUST 2002

[5] C. J. Werner, MCNP USER'S MANUAL Code Version 6.2, 2017, LA-UR-17-29981

[6] W.A. WIESELQUIST, R.A. LEFEBVRE, M.A. JESSEE, Eds., SCALE Code System, ORNL/TM-2005/39, V.6.2.4, (2020)

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