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Calculation of Prompt SPND Sensitivity Considering the Space Charge Effect

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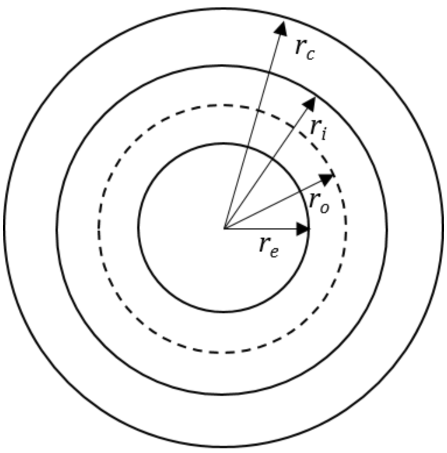
1. Introduction

The Self-Powered Neutron Detectors(SPNDs) are used to monitor neutron flux in the nuclear power plant. There are two types of SPNDs. One is delayed SPNDs which emit the beta particles, and prompt SPNDs, which emit the captured gamma rays after neutron absorption. Delayed SPNDs are routinely utilized in nuclear power plants.

The sensitivity analysis method for delayed SPNDs was first developed by Warren [1]. Following Warren's analytical approach, Goldstein [2], Lee [3], and Vermeeren [4] applied the Monte Carlo method to improve the SPND sensitivity analysis technique.

The initial SPNDs sensitivity analysis model proposed by Warren [1] is consider only the delayed SPNDs. Thus, did not consider the space charge effect. This SPNDs sensitivity analysis model is suitable for the delayed SPNDS. Subsequently, Warren [5] proposed other analytical method by considering the space charge effect, which is applicable the prompt SPNDs. Later, Mahant [6] researched the space charge effects in two type SPNDs.

This paper employs the Monte Carlo code MCNP6 [7] to analysis whether the space charge effect inside the SPNDs affects its sensitivity. The results were compared with measured experimental data to evaluate the accuracy of the space charge effect.



r_e: emitter radius
R_i: insulator radius
R_o: critical radius
R_c: collector radius

Fig. 1. Cross-section of the SPND

2. SPNDs Sensitivity Analysis Model

The SPNDs mainly consist of Emitter, Insulator (typically Al_2O_3 or MgO), and a Collector (Inconel), as shown in the Fig. 1. The electric field is formed in the insulator region of SPNDs. The electric field equation is expressed in eq. (1). The region that the electric field value is zero is the critical radius (or potential peak radius). If the electron emitted from emitter exists in the critical radius, the electron repelled to emitter. After the space charge model assume the permittivity is constant.

$$\frac{dE(r)}{dr}+\frac{E(r)}{r}=\frac{\rho(r)}{\varepsilon} \tag{1}$$

$E(r)$: electric field
ε : permittivity
$\rho(r)$: charge density

2.1 Non Space Charge's method

Warren [1] initially proposed the concept of uniform space charge in insulator region of SPNDs to calculate the sensitivity of delayed SPNDs. According to this method, the charge density in insulator of SPNDs is assumed to be uniformly distributed. Eq. (2) is the electric field for uniform charge density distribution in insulator region from eq. (1). The electric field is only determined by radius of SPNDs. Also, the critical radius (r_o) is determined only the emitter and insulator radius in eq. (3).

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

$$r_o=r_i\left[\frac{1-(r_e/r_i)^2}{2\ln(r_i/r_e)}\right]^{1/2} \tag{3}$$

All electrons passing the critical radius (r_o) assumed to contribute to the SPND signal. Therefore, the probability of electron escape through r_o must be determined. The minimum energy required for electron escape can be obtained based on the material properties of the insulator and the emitter, as well as their ratio, in Warren's paper [1].

2.2 Considering Space Charge Model

Warren [5] proposed the new analytical method for the prompt SPNDs. The previous method assumed the charge density distribution is uniform, however, the new method assumed the charge density is proportional to 1/r in insulator. Thus, introduced the potential peak radius (r_p), which differs from critical radius used in prior method. While critical radius was independent of the material properties of the emitter and insulator, potential peak radius was influenced by the material properties of the detector and experimental values in eq. (4). δ is determined by experiment and depends on the type of emitter used in a SPND.

$$r_p = \frac{r_i(1 - r_e / r_i)}{\ln(r_i / r_e)}(1-\delta) \tag{4}$$

Goldstein[2] calculated the SPND neutron sensitivity using Monte Carlo method. This sensitivity calculation considered the space charge effect. The electric field equation considering the charge density is eq. (5). Define the repelled fraction of the electrons generated from SPNDs in eq. (6). If the electrons generated from emitter don't pass the point that electric field is zero, the electrons repelled to emitter.

$$E(r) = \frac{1}{r\varepsilon}\left[\int_{r_i}^{r_c} r' \rho(r') dr' - \frac{1}{\ln(r_c / r_i)}\int_{r_i}^{r_c} dr'' \int_{r_i}^{r''} r' \rho(r') dr'\right] \tag{5}$$

$$f = \frac{\ln(r_c)}{\ln(r_c / r_i)} - \frac{1}{\ln(r_c / r_i)} \frac{\int_{r_i}^{r_c} r \ln(r) \rho(r) dr}{\int_{r_i}^{r_c} r \rho(r) dr} \tag{6}$$

3. Sensitivity Result

Fig. 2 shows difference for SC (Space charge) and NSC (Non space charge). Electric fields were calculated from eq. (1) using numerical method. It was observed that the position of the critical radius (Electric field value is zero) changes depending on the consideration of space charge. The difference in the critical radius affects the probability of electron escape.

The gamma sensitivity of each emitter was compared considering space charge effects. In most cases, there was no significant difference compared to the measured data. The measured data was detected from a 1MW pool-type research reactor [5].

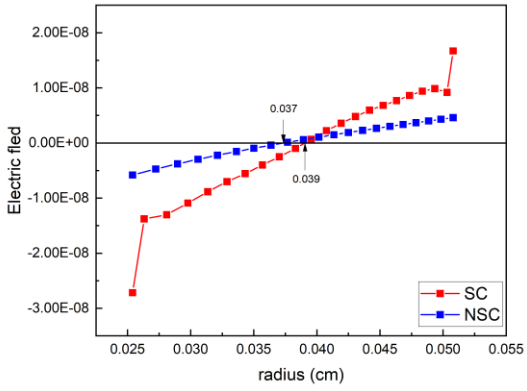


Fig. 2. The electric field of uniform charge density and non-uniform charge density

Table I: External gamma ray sensitivity of SPND for emitters

Sensitivity(10^{-23} A/cm gv)

	Warren	SC	Measured
Yb	5.6	3.33	3.58±0.43
Hf	7.4	5.01	4.68±0.58
Gd	5.9	3.73	3.74±1.54
Pt	8.5	5.14	5.37±0.4
Co	-2.2	-1.94	-1.44±0.08

Cobalt and Platinum are used in SPNDs, which primarily respond to prompt signals. Table II and Table III show neutron and gamma sensitivity for Cobalt and Platinum. In the case of neutron sensitivity, the results did not show a significant impact from the space charge effect. However, for gamma sensitivity, the space charge effect had a substantial influence. Depending on the space charge effect of external gamma rays, the sensitivity results vary greatly.

Table II: External neutron and gamma ray sensitivity of SPND for Cobalt

Sensitivity(10^{-23} A/cm gv)

	Warren	SC	NSC	Measured
S_{neu}	4.9	2.58	3.85	3.0±0.1
S_{gam}	-2.2	-1.94	-12.4	-1.44±0.08

Table III: External neutron and gamma ray sensitivity of SPND for Platinum

Sensitivity(10^{-23} A/cm gv)

	Warren	SC	NSC	Measured
S_{neu}	1.4	1.30	1.75	1.4±0.4
S_{gam}	8.5	5.14	-3.48	5.37±0.4

For detectors that generate strong signals, such as rhodium, which is mainly used in delayed SPNDs, the space charge effect is expected to have little impact because the external gamma-ray signal is very small. However, when using SPNDs with relatively smaller signals, the space charge effect significantly influence sensitivity evaluation due to external gamma rays.

4. Conclusion

To evaluate the signal sensitivity of Self-powered Neutron Detectors (SPNDs) considering space charge effects, the sensitivity of each emitter was compared with measured data. Additionally, the neutron and external gamma-ray sensitivities of Co and Pt SPNDs were analyzed. While the space charge effect did not significantly impact neutron signal sensitivity, it was found to have a considerable influence on external gamma ray sensitivity.

Acknowledgement

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