SELF-POWERED DETECTORS FOR POWER REACTORS: AN OVERVIEW

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Abstract: In this paper, Self-Powered Detectors (SPDs) for applications in nuclear power reactors have been reviewed. Based on their responses to radiation, these detectors can be divided into delayed response Self-Powered Neutron Detector (SPND), prompt response SPND and Self-Powered Gamma Detector (SPGD). The operational principles of these detectors are presented and their distinctive characteristics are examined accordingly. The analytical models and Monte Carlo method to calculate the responses of these detectors to neutron flux and external gamma rays are reviewed. The paper has also considered some related signal processing techniques, such as detector calibrations and detector signal compensations. Furthermore, a couple of failure modes have also been analyzed. Finally, applications of SPD in nuclear power reactors are summarized.

1. Introduction

Since their invention in 1964 [1], Self-Powered Detectors, also known as Hilborn detectors, have been used extensively and successfully in nuclear power reactors as in-core detectors for flux mapping, regulation and protection [2][3]. A SPD is essentially a coaxial cable with a short length of the central conductor replaced by a metal (called emitter) that emits energetic electrons when exposed to radiations (neutron and gamma), as shown in Fig.1 [4]. The flow of electrons from the emitter to the outer sheath (called collector) can be detected as a measure of the radiation flux. Because there is no need to apply external power to generate the measurement signal, they are called “Self-Powered Detector”. A typical SPD consists of three parts: the emitter, collector, and insulator [1].

SPD has many advantages, such as no power supply needed, simple and robust structure, small in size for in-core installation, stable under high temperature and pressure, and low burn-up for most emitters. SPD also has some drawbacks, such as delayed response of some emitters and limited operating range because of low neutron sensitivity [5].

The objective of this paper is to provide an overview of the existing detectors and their potential applications. The paper is organized as follows. The classification and operational principles of SPD is summarized in Section 2. The characteristics of various SPDs are examined in Section 3. A survey of the sensitivity calculation models for the SPDs is provided in Section 4. Some signal processing aspects of the measurements, such as calibration and compensation, are discussed in Section 5 and a couple of detector failure modes are examined in Section 6. The applications of SPDs in power reactors are covered in Section 7.

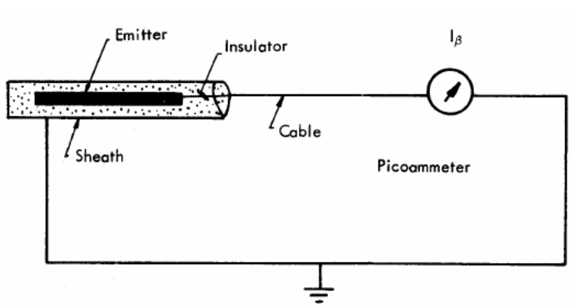

Figure 1: Configuration of a SPD.

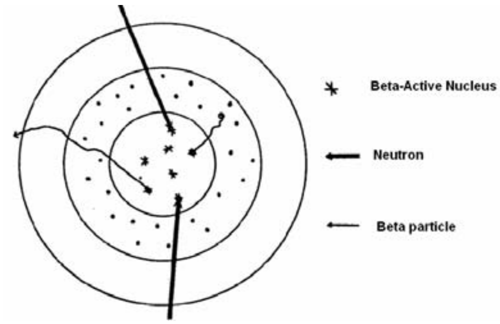

Figure 2: Delayed response SPND

2. SPD Classification and Operational Principles

2.1 Classification

According to their responses to radiation, SPD can be divided into Self-Powered Neutron Detector (SPND) and Self-Powered Gamma Detector (SPGD). Furthermore, SPND can be subdivided into delayed response SPND and prompt response SPND [6]. From the mechanical point of view, SPD can be divided into Integral SPD and Modular SPD. An integral SPD is constructed in a continuous metal sheath, while a modular SPD is made from separate detector and lead cable sections [7]. In all types of detectors, Al_2O_3 and MgO are often used as the insulator and Inconel is often used as the collector, because of their good nuclear and mechanical properties [6].

2.2 Operational Principles

The operational principle of a delayed response SPND can be represented as (n, β^-) [8]. Neutrons are absorbed by the emitter, which causes it to undergo beta decay. The current between the emitter and the collector is a result of the betas reaching the collector or escaping from it [6]. This process is shown in Fig. 2 [9]. The typical emitter materials are Rhodium and Vanadium.

The operational principle of a prompt response SPND can be represented as (n, γ, e) [10]. The emitter is made of material that can instantaneously emit gamma rays (called capture gamma) after capturing neutrons. A portion of the gamma rays (about 1-2%) will generate Compton electrons and photoelectrons within the detector, and these secondary electrons can reach the collector and produce current [6]. This process is shown in Fig. 3 [6]. The typical emitter materials are Cobalt and Inconel etc.

The current generation mechanism of a SPGD is similar to the prompt response SPND. The difference is that the gamma rays are reactor gamma rays coming from external of the detector. The process can be shown as (γ, e) and is illustrated in Fig.4 [6]. A typical emitter material is Platinum.

The contribution of pair production to the prompt type detectors is minor [9].

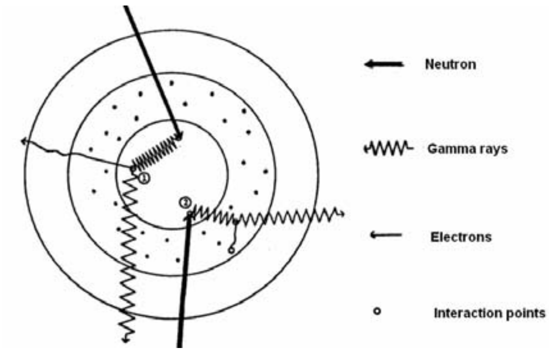

Figure 3: Prompt response SPND

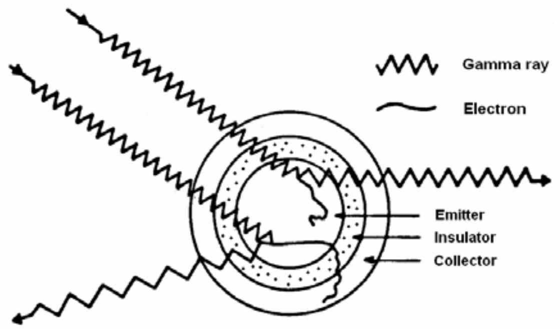

Figure 4: SPGD

3. SPD Characteristics

There are four potential current components in the output of a SPD; the delayed neutron component due to beta decay, the prompt neutron component due to neutron capture gamma, the prompt gamma component due to prompt reactor gamma and the delayed gamma component due to delayed reactor gamma, which is about 1/3 of the total reactor gamma. Their fractions are are denoted as: n, N, Γ and γ, respectively [10] [11].

Recalling the operational principle, it is seen that the delayed SPND has the highest current generation efficiency among the SPDs, because every captured neutron will give rise to an electron [6]. It has almost pure neutron sensitivity n. Therefore, delayed response SPND is highly accurate and more immune to noise. But its signal is delayed.

The two prompt types SPDs share many similarities, such as they both have mixed neutron sensitivity and gamma sensitivity. Their signals are mainly prompt, either N or Γ. Their outputs both have some delayed components n and γ. The four current components have varied amplitudes from an emitter to another emitter. Their outputs are relatively week because only a fraction (about 1-2%) of the gamma rays will generate photoelectrons and Compton electrons. For SPGD, the output is the difference between the outward electron flow and the inward electron flow [6]. Because the neutron sensitivity of SPD will burn-up but the gamma sensitivity will suffer almost no burn-up, their signal compositions change with cumulated exposure to radiation [10].

The characteristics of individual detectors are summarized as Table 1 below.

Emitter Material	Neutron cross section	Response Time	Burn-up Rate in a neutron flux of $10^{13} n/cm^2/s$	Signal Composition
Vanadium	4.9 barn	Delayed	0.012%/month	99% $t_{1/2}$=3.76m, 1% prompt
Rhodium	145 barn	Delayed	0.39%/month	92% $t_{1/2}$=42s 8% $t_{1/2}$=4.4m
Platinum	24 barn	Prompt	0.03%/month	Γ=0.3, N=0.52, γ=0.15, n=0.03
Pt-Clad Inconel	N/A	Prompt	N/A	88.7% prompt
Cobalt	37 barn	Prompt	0.094%/month	Long lived n buildup
Inconel	N/A	Prompt		N=104.8%

Table1. Characteristics of some SPDs [6] [7] [11] [12]

4. Sensitivity Calculation

The sensitivity of a SPD is the ratio between the detector current and the radiation flux [5]. Several models for sensitivity calculation are briefly reviewed in this Section.

4.1 Analytical Calculation Model of Delayed Response SPND

Warren's model [4] sets the foundation for the sensitivity calculation of delayed response SPND. The neutron capture rate, the electron escape probability from the emitter and the effect of the insulator are investigated in this model. The insulator's effect is accounted for with the assumption that there exists a space charge in the insulator when exposed to radiation. The electrons that can not overcome the potential peak of the space charge will be expelled back to the emitter and cancel itself there. Therefore, there is an average minimum energy *EMIN* that an electron escaped from the emitter must have to overcome the potential peak as a current contributor.

4.2 Analytical Calculation Model of Prompt SPD

Warren and Shah's model [8] is a well-known calculation model. The model accounts for the interactions of external gamma and capture gamma with the detector. The interactions considered can be compactly represented as (n, e_{ic}), (γ, e_{ce}), (γ, e_{pe}), (n, γ, e_{ce}) and (n, γ, e_{pe}), where *ic* = internal conversion, *ce* = Compton electron and *pe* = photoelectric electron. The contribution of (n, β^{-}) is calculated using the model in Section 4.1. The sensitivity of a prompt type SPD can be obtained by summing the contributions of all the interactions mentioned above that take place both in the emitter and the collector.

4.3 Monte-Carlo Method for SPD Sensitivity Calculation

The Monte-Carlo method can build up the complex processes in a SPD as a sum of series of event chains. The variables' values at each event are determined using random numbers, which reflect the probability distribution of the real process. Therefore, the Monte-Carlo approach is capable of dealing with more complicated problem [9].

The Monte-Carlo approach based on modern MCNP computer code is used in recent works. For example, the position-dependent beta escape probability of a Rhodium SPND is calculated using MCNP in [13], and in [14] the sensitivity of a SPGD is calculated using MCNP in coupled photo-electron mode.

5. Calibration and Compensation

5.1 Calibration of a SPD

Among different calibration methods, there are three calibration techniques: absolute calibration, comparison calibration and in-core calibration, as is shown in Table 2 [7].

Delayed type SPND usually does not need on-line calibration. Because the sensitivity of a prompt SPD varies with neutron to gamma ratio, neutron sensitivity burn-up and so on, they need to be calibrated on-line [10] [15].

Method	Calibrated by
Absolute calibration	Wire activation analysis
Comparison calibration	Standard SPND
In-core calibration	1. Fixed in-core low burn-up detectors 2. Movable in-core fission chamber or SPD 3. Activation analysis

Table 2: Calibration methods

5.2 Compensation of a SPND

5.2.1 Speed Compensation of Delayed Response SPND

The high accuracy of delayed response SPND makes it a desirable detector not only for in-core flux monitoring but also for reactor control. However its slow response to neutron flux transits prevents its direct use for control purpose. Models have been developed to investigate the rhodium SPND transfer function for compensation of the inherent time delay. Digital methods, e.g. the dominant pole Tustin method, direct inversion method and Kalman filter method, and analog method have been investigated [16] [17].

5.2.2 Compensation of Background Noise

Background noise compensation can be achieved by the use of a separate background cable and the use of twin axial lead cables. It can also be achieved by optimum geometrical design [5], and best estimation of the noise.

6. Failure Modes

Even though the detector element in a SPD detector can operate reliably in-core for at least 8-10 years, however, degradation and failure in other parts of the detector, such as connectors, wiring, and insulation may happen [18]. Two major failures of a SPD are circuit open and insulation resistance degradation. An open circuit fault results in the lost of all or part of the signal. It may also appear as intermittent transients [19].

The leakage resistance of the detector should be above 10^{12} ohms under normal ambient room conditions and above 10^{6} ohms under irradiation [20]. The insulation resistance may decrease because of moisture contamination in the insulator or because of sheath failure. Another possible cause is the insulator degradation due to the radiation effects [19].

7. Applications of SPD

SPNDs can be used for in-core neutron flux or power mapping, reactor control and protection. They can also be used for neutron noise analysis [5].

Delayed SPND provides an accurate localized measurement of neutron flux. Therefore, it is a good candidate for in-core flux mapping. The instantaneous responses of prompt type SPDs to radiation transits make them good candidates for reactor regulation and protection [15].

The reactor neutron noise observed from the SPDs, together with other in-core or ex-core instrumentations, can be used for monitoring the reactor internal vibration [21] and detector self validation and so on [12].

The well-known Straight Individually Replaceable (SIR) detector assembly progresses from the coiled flux detector assembly. Advancement from the SIR assembly leads to the invention of the Hybrid Encapsulated Straight Individually Replaceable (HESIR) detector assembly [20].

8. Conclusion

SPDs are used extensively in nuclear power reactors. They can be divided into SPGD, prompt response SPND and delayed response SPND. They measure the radiation flux by virtue of the gamma (reactor gamma or neutron capture gamma) induced electrons or neutron induced beta decays. Delayed response SPND is accurate and noise immune, but its signal is delayed. SPGD and prompt response SPND can follow the instantaneous flux change but need to be calibrated on-line. The sensitivities of SPDs can be calculated analytically or using Monte-Carlo based methods. SPDs can be used in-core for reactor monitoring, control, protection and neutron noise analysis. They can be calibrated by a variety of methods. Delayed response SPND can be compensated for the possibility of expanding their usage to reactor control. Faults may happen in some parts of SPDs, such as circuit open and insulation resistance failure.

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