SENSITIVITY OF DEVELOPED SELF-POWERED NEUTRON DETECTOR

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1. Abstract

The continuous and precise spatial neutron flux measurement is one of the most requirement for safe and reliable operation of nuclear power plants. Self-powered neutron detector (SPND) is the most suitable device used as in-core flux monitors for the last three decades in nuclear power reactor world wide. A developed technique was used for SPND emitter to provide the proper response time and radiation sensitivity. An emitter composed of two suitable materials (Rh and Ir). The sensitivity of the detector and burn up of the alloy emitter were calculated and compared with the experimental published one.

Keywords : SPND, Burn up, Alloys emitter

2. INTRODUCTION

Self-powered neutron detector (SPND) is a rugged miniature device used to measure high neutron flux in the core of a reactor. It is compact and small in size desired for in-core installation and capable to withstand high temperature and pressure in the reactor core. As its name implies, it operates without any applied voltage. They are classified as delayed or prompt depending on the predominant mode of signal generation. Several studies of both types have been carried out theoretically as well as experimentally [1-7]. The structure of SPND is a coaxial cable consisting of an inner electrode (emitter), surrounded by insulation and an outer electrode (collector). A schematic diagram for SPND is given in figure(1).

Preferably the lead cable and detector sections are integral, i.e. the signal wire of the lead cable mates directly to the emitter; the insulation of both sections are identical and the collector of the detector section is also the outer sheath of the lead cable section. Detectors constructed in this manner are termed integral SPNDs. SPND assemblies may also be made from separate detector and lead cable sections.

For power reactor applications, typical emitter materials used in SPNDs include Rh, V, Ce, Hf, Pt, and Ag. Other emitter materials such as Cd, Gd and Er may be used in SPNDs but are not practical for power reactor application. An overview of the important characteristics of SPND emitter and the optimum choice of the emitter materials for different uses were given in references [8,9]. Table (1) gives some specifications for typical SPNDs material used in power reactors. These detectors can be divided into these which fast respond instantaneously to change in the reactor flux of which Co is the best one and those of which possess a delayed response, specially Rh and V.

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This work is devoted to putting a new mechanism to overcome the problems of slow Response and complex burn up function. Therefore, ways of increasing the Rh detector response is considered. The suggested mechanism is a new design for the emitter material which constructed with two materials (alloy emitter materials). This construction of the emitter dealing with solving the two problems mentioned previously: 1) Predicting the equilibrium detector current rapidly and also stable detector sensitivity. 2) Characterizing the non exponential burn-up function.

3. THEORETICAL CONSIDERATION

3.1 Sensitivity due to beta emission

SPND functioning is based on the emitting of beta particle from the emitter after capture the neutrons. Contribution of these β particles to the signal current \( I \) for a detector with length \( L \) and volume \( V \) is given by Warren model [2]:

\[
I = (e V / L) \cdot C \tag{1}
\]

where \( e \) is electron charge, \( \varepsilon \) is electron escape efficiency, i.e. the fraction of the electrons of energy \( E \) appearing at the emitter's surface per unit volume and time and \( C \) is neutron reaction rate and it is written in the form:

\[
C = \int_{E_{\text{max}}}^{E_{\text{th}}} \Sigma_{\text{th}} . S \, dE
\]

here \( E_{\text{max}} \) is the maximum thermal neutron energy.

Table (1) gives an overview of some specification for typical SPNDs used in power reactors [9].

<table>
<thead>
<tr>
<th>Emitter material</th>
<th>Rh</th>
<th>V</th>
<th>Co</th>
<th>Ag</th>
<th>Pt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emitt. diameter(d)mm</td>
<td>0.46</td>
<td>2.0</td>
<td>2.0</td>
<td>0.65</td>
<td>0.51</td>
</tr>
<tr>
<td>Emitt. length(L)mm</td>
<td>400</td>
<td>100</td>
<td>210</td>
<td>7000</td>
<td>3050</td>
</tr>
<tr>
<td>Insulator</td>
<td>Al₂O₃</td>
<td>Al₂O₃</td>
<td>Al₂O₃</td>
<td>MgO</td>
<td>Al₂O₃</td>
</tr>
<tr>
<td>Collector</td>
<td>Inconel</td>
<td>Inconel</td>
<td>Inconel</td>
<td>Stain.steel</td>
<td>Inconel</td>
</tr>
<tr>
<td>Collector diam.,mm</td>
<td>1.57</td>
<td>3.5</td>
<td>3.5</td>
<td>3.0</td>
<td>1.6</td>
</tr>
<tr>
<td>Sensitivity (A/nv)</td>
<td>3.6x10⁻²⁰</td>
<td>4.8x10⁻²¹</td>
<td>5.4x10⁻²¹</td>
<td>4.2x10⁻²⁰</td>
<td>2.5x10⁻²²</td>
</tr>
<tr>
<td>Burn-up rate % month At 10¹⁵ nv)</td>
<td>0.39</td>
<td>0.01</td>
<td>0.09</td>
<td>0.30</td>
<td>0.03</td>
</tr>
</tbody>
</table>

According to Warren’s model the electron escape efficiency can be calculated using the expression:

\[
\varepsilon = \frac{E_{\beta}}{3} \cdot \frac{1}{d} \cdot \left( \frac{K}{\rho} \right) \tag{2}
\]

where \( E_{\beta} \) is the maximum β energy in KeV, \( K = 6.5 \times 10^{-4} \, \text{gm(cm)}^2 \) KeV⁻¹ is the emitter density gm(cm)⁻² and \( d \) is the emitter diameter. The expression for neutron sensitivity due to β emission \( S_{n\beta} \) is given as [10]:
\[
S(A/cm) = \Sigma_{th} S\left(\frac{11}{14}\frac{d}{\rho}\frac{K}{e}\right)\left[\frac{1}{3}E_\beta - E_{min} + E_\beta^{7/2}\left\{\frac{5}{12}E_\beta^{7/2} - \frac{3}{2}E_\beta E_{min}^{7/2} + \frac{7}{4}E_\beta^{3}E_{min}^{5/2}\right\}\right]
\] (3)

Where \(\Sigma_{th} = 0.0225 \sigma_{th} \frac{P}{A}\) and \(S\) is the self-shielding factor for thermal neutrons given by the following expression [1]:

\[
S = 1 - \frac{4}{3}\Sigma_{th} \frac{d}{2} + \frac{1}{2}(\Sigma_{th} \frac{d}{2})^2 \left(\ln \frac{2}{d} + \frac{5}{4} - 0.577216\right)
\] (4)

where \(\Sigma_{th}\) is the thermal neutron capture cross-section in barn and \(A\) is the mass number of the emitter material. But \(E_{min}\) is the minimum energy that an emitter surface electron must contribute to current sensitivity of SPND.

### 3.2 Time-dependent detector sensitivity

The interaction of thermal neutrons with SPND detector as example Rh emitter can be expressed as:

\[
^{103}\text{Rh} \ (n,\gamma) \rightarrow ^{104}\text{Rh} \rightarrow ^{104}\text{Pd}
\] (5)

For Ir case the reaction can be written as:

\[
^{101}\text{Ir} \ (n) \rightarrow ^{102}\text{Ir} \rightarrow ^{102}\text{Pt}
\] (6)

We denote that:

<table>
<thead>
<tr>
<th>isotope symbol</th>
<th>element</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{103}\text{Rh})</td>
<td>(N^{53})</td>
</tr>
<tr>
<td>(^{104}\text{Pd})</td>
<td>(N^{64})</td>
</tr>
<tr>
<td>(^{101}\text{Ir})</td>
<td>(N^{17})</td>
</tr>
<tr>
<td>(^{102}\text{Pt})</td>
<td>(N^{28})</td>
</tr>
</tbody>
</table>

the rate of such change in the number density of Rh emitter with time equal burn-up and it can be written in the form of differential equation as:

\[
\frac{dN^{64}}{dt} = \phi \sigma_{th}^{53}N^{53} - \lambda N^{64}
\] (7)

Where \(\phi\) is the neutron flux and \(\lambda\) is the decay constant. Equation (7) can be rewritten as:

\[
\frac{dN^{64}}{dt} + \lambda N^{64} = \phi \sigma_{th}^{53}N^{53}
\] (8)

Under the steady state condition the above equation gives \(\frac{dN^{64}}{dt} = 0\), then

\[
N^{64} = \frac{\phi \sigma_{th}^{53}N^{53}}{\lambda}
\]
Multiply the above equation by integrating factor $e^{\lambda t}$ and by integrating one can obtain:

$$N_{Rh}^{64}(t) = \frac{\phi \sigma_{Rh}^{53} N_{Rh}^{53}}{\lambda} (1 - e^{-\lambda t})$$

This function was used for Rh sensitivity calculation. By similar way for Ir case $N(t)$ was expressed as:

$$N_{Rh}^{28}(t) = \frac{\phi \sigma_{Rh}^{17} N_{Rh}^{17}}{\lambda} (1 - e^{-\lambda t})$$

For alloy emitter the function $N(t)$ was given as:

$$N_{alloy}(t) = N_{Rh}^{64}(t) + N_{Ir}^{28}(t)$$

The sensitivity formula as a function of time can be formed as:

$$S_{np}(t) = \frac{eV}{L} e N(t) \sigma_{np} f_d$$  \hspace{1cm} (9)

where the flux depression factor $f_d$ is evaluated using the expression [1]:

$$f_d = \left[1 + \frac{2d/2}{2\lambda_T} \left( \ln \frac{2l}{\pi(d/2)} + \frac{3}{2} + 0.577216 \right) \Sigma_{np} \frac{d}{l} \right]^{1/2}$$

Where $\lambda_T$ is transport mean free path = 0.425 cm, and diffusion length $l$ = 2.76 cm. The effect of detector burn-up on sensitivity is to give the relative decrease rate in a given flux. The burn-up can be expressed as [11]:

$$\frac{1}{S_{np}} \frac{dS_{np}(t)}{dt}$$  \hspace{1cm} (10)

4. RESULTS AND DISCUSSION

The area where we have attempted to achieve improvements in the SPND detectors have involved devising ways of increasing the detector response. As in the case of Rh significant improvements in response can be achieved by increasing the emitter diameter. Since the signal from SPND(Rh and V) is predominantly due to the $\beta$ decay as example, $V^{52}$ following neutron capture in $V^{51}$, the sensitivity per unit length is expected to vary as the square of the emitter diameter, at least for small diameters [12]. Therefore, the sensitivity of Rh detector as a function of the emitter diameter is calculated, using eq.(3), the results are displayed in Fig.(2). From the figure, one can notice that the sensitivity does follow a square low for the emitter diameter, dash line. But at large diameter, the sensitivity increase more slowly. This is to be expected since as $d$ increases decreases. A least square fit was determined to the power law of the sensitivity for Rh SPND as:

$$S (Rh) = 38134 \times 10^{21} d^{1.1569} \text{ A m}^{-1}/(\text{n m}^{-2} \text{ s}^{-1})$$  \hspace{1cm} (11)

where $d$ is the emitter diameter in mm. The above reduced formula has the same behavior as the formula of the V and Pt SPND obtained by Allan [12].
In isotope $^{103}$Rh on neutron absorption $^{104}$Rh emits $\beta$ particles of 2.5 MeV and two half-life of 42s and 4.4min. The absorption cross section $\sigma$ of 150b. Main characteristics of the investigated Rh SPND are given in Table(2). The calculated values of different parameters which illustrated in the table were used for the calculation of the sensitivity as a function of the time using eq.(9). The obtained results are shown in Fig.(3). From the figure, one can notice the current sensitivity was decreased with time. This is due to the problem of complex burn-up. In order to achieve the burn up, a new idea on the design of the emitter is applied. A new construction of the emitter using two materials as alloy is investigated to improve the decrease of the sensitivity during increasing time. From the previous studies [6,8,9], Ir material which is the suitable one for the Rh SPND is select. The characteristic properties of Ir are tabulated in Table(2). The absorption cross section $\sigma$ is 426b and the maximum energy of $\beta$ emission is 0.7MeV. By the same way the sensitivity of Ir was calculated as a function of time. The results are given in Fig.(3). The different calculated parameters of Ir SPND emitter are tabulated in Table(2). A comparison between the behavior of the sensitivity of Ir emitter and Rh emitter with increasing time was shown in Fig.(3). We notice that at a short time the burn-up on sensitivity is to give the relative decrease rate on Rh emitter very fast compared with that of Ir emitter. But the escape efficiency of Rh is higher than that of Ir (see Table 2). Moreover the result of multiplication parameters ($\Sigma\Sigma_\nu\Sigma_\nu$) is nearly equal for both Rh and Ir emitter. For the previous reasons Rh and Ir as alloy emitter are selected.

Several percentage of alloy emitter were constructed and investigated from both Ir and Rh materials to treat the burn up problem and to provide a stable current sensitivity with time. The obtained results can be seen also in Fig(3). In the figure the behavior of the sensitivity during time was calculated for the curve(a)($90\%$Rh + $10\%$Ir ) emitter construction as shown the figure. Also curve (b) and (c) were illustrated the behavior of the sensitivity for the ($80\%$Rh + $20\%$Ir ) and ($50\%$Rh + $50\%$Ir)SPND emitters. The calculation of burn up rate per month at a constant neutron flux using Eq.(10) are obtained to be 0.35% & 0.29% & 0.18% for the three previous emitter construction respectively. The decrease of burn up rate leads to improve the performance of the detector and enhance the stable of the sensitivity.

Table 2: The calculated values of different parameters for Rh-SPNDs and Ir-SPNDs.

<table>
<thead>
<tr>
<th></th>
<th>Rh-SPND emitter</th>
<th>Ir-SPND emitter</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma$ burn</td>
<td>150</td>
<td>426</td>
</tr>
<tr>
<td>$E_B$(MeV)</td>
<td>2.5</td>
<td>0.7</td>
</tr>
<tr>
<td>Emitt density(gm cm$^{-3}$)</td>
<td>12.41</td>
<td>22.65</td>
</tr>
<tr>
<td>half-life</td>
<td>42s, 4.4m</td>
<td>19.15h, 74.4d</td>
</tr>
<tr>
<td>Macroscopic capture cross section $\Sigma$</td>
<td>10.886 cm$^{-1}$</td>
<td>30.268 cm$^{-1}$</td>
</tr>
<tr>
<td>Emitt. diameter(d)mm</td>
<td>0.508</td>
<td>0.508</td>
</tr>
<tr>
<td>Self-shielding factor</td>
<td>0.733</td>
<td>0.483</td>
</tr>
<tr>
<td>Flux-depression</td>
<td>0.9143</td>
<td>0.852</td>
</tr>
<tr>
<td>The constant factor(eV/L)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Escape efficiency (e)</td>
<td>0.735</td>
<td>0.436</td>
</tr>
</tbody>
</table>

5. CONCLUSION

The Rh-SPNDs are used for safety and control systems in the power reactors. The signals from the detectors are dominated by $(n,\beta)$ reaction. These detectors have slow response time.
of several minutes. With the help of special amplifiers the response time can be reduced to several seconds.

The rapid advances in SPND as in-core systems usage has been paralleled with advances in system design to enhance reliability. Therefore the suggested alloy emitter construction (Rh& Ir) is dealing with treating the problems of decreasing the detector current and keeping detector sensitivity stable. The increase of detector response can be achieved by increasing emitter diameter and the optimization of the Rh emitter diameter can be obtained due to the new formula of Eq.(11). On the other side the high burn up rate can be improved using the new construction of the emitter. As example adding 10% of Ir gives relative burn up rate of 0.34% per month while 20% of Ir is available to reduce the burn up rate to 0.29% per month and 50% of Ir decreases the burn up rate per month less than 0.18%.

REFERENCES

Figure (1): A schematic diagram for SPND.

Figure (2): Sensitivity per unit length as a function of the emitter diameter ($d$) for Rh-SPND.
Figure (3): Behaviour of sensitivity of alloy emitter (Rh&Ir)-SPND as a function of time.