Annals of Nuclear Energy 113 (2018) 519–525

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Technical note

Numerical optimization of Rhodium Self-Powered Neutron Detector

Qingmin Zhang [a,b,*], Xinxin Liu [a,b], Bangjie Deng [a,b], Liangzhi Cao [a,b], Chuntao Tang [c]

[a] Department of Nuclear Science and Technology, School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an 710049, China
[b] Shaanxi Key Laboratory of Advanced Nuclear Energy and Technology, Xi'an Jiaotong University, Xi'an 710049, China
[c] Shanghai Nuclear Engineering Research and Design Institute, Shanghai 200233, China

ARTICLE INFO

Article history:
Received 27 June 2017
Received in revised form 14 October 2017
Accepted 3 December 2017

Keywords:
Rhodium Self-Powered Neutron Detector
Geant4
Prompt current
Delayed current
Direct numerical model

ABSTRACT

Self-Powered Neutron Detector (SPND) has been widely used in reactors to monitor neutron flux due to its adaptability for in-core severe environment. As a typical representative, SPND with Rhodium as its emitter has been modeled in the frame of Geant4, which is good at tracing the history of the particles in simulation and very appropriate for directly simulating SPND's working mechanism. First of all, simulation model has been validated by simulating one existing typical SPND. Then, the performances' dependences on the detector's dimensions have been studied systematically. Finally, SPND's geometries have been optimized and the suggested optimal design gives a neutron sensitivity of 1.03×10^{-19} A·cm^2·s and a ratio of prompt current of 80.22%. Additionally, this work is also helpful to optimize all the SPNDs for customized requirements.

© 2017 Elsevier Ltd. All rights reserved.

1. Introduction

Self-Powered Neutron Detectors (SPNDs) have been popularly utilized in reactor cores for in-core neutron flux depiction (Ma and Jiang, 2011) owing to their excellent advantages for severe in-core environment (high temperature, high pressure and strong radiation): tiny size, self-powered feature, simple and robust structure (Todt, 1996). Based on their emitters' interactions with neutrons, the SPNDs are classified into two types: one's current is prompt to neutron flux (^{59}Co, ^{195}Pt, ^{180}HfO$_2$), while the other's current has delayed component (^{103}Rh, ^{51}V, ^{107}Ag, ^{109}Ag) (Goldstein and Todt, 1979). To compensate the response delay, many dynamic compensation methods have been developed (Hoppe and Maletti, 1992; Mishra et al., 2014; Park et al., 1999; Kulacsy and Lux, 1997; Zhang et al., 2017). The compensation methods' essence is to extract the prompt current component from the measured current and then to correct with the prompt sensitivity coefficient (Zhang et al., 2017), so SPND's prompt sensitivity coefficient is the most important performance parameter.

Generally, SPND is consisted of emitter, insulator and collector. Its current is formed by the flow of the electrons which generate in insulator or emitter, and then are collected by collector (Neutron Detectors and Reactor Instrumentation, 2017). Due to the greater complexity of its physical mechanism, such an analytical model would be difficult to be used (Goldstein, 1973). It's obvious that Monte-Carlo method is favorable to optimize the design of SPNDs. However, the previous methods (Goldstein, 1973; Lee et al., 2001; Vermeeren, 2015) are not direct and the performance study is not complete, so the optimization of the detector design is still difficult to be performed.

Geant4 is a toolkit for simulating the passage of particles through matter (Agostinelli et al., 2003; Allison et al., 2006, 2016); offering the flexibility to trace the history of each particle during simulation, which enables the full and direct simulation of SPNDs. Accordingly, Geant4 was used for SPND modeling in our study. As a typical representative with delayed current (Todt, 1996), Rhodium SPND was chosen to verify our method.

2. Numerical modeling and its validation

In this section, a numerical model was established in the frame of Geant4 and validated with experimental results.

2.1. Detector construction

As shown in Fig. 1, Rhodium SPND in simulation is a typical cylinder structure and consists of 3 components: emitter, insulator and collector, all of which are co-axial (Lee et al., 2001).

For validation purpose, the dimensions and materials of SPNDs were chosen according to the related references (Todt, 1996; Kantrowitz, 1987), as listed in Table 1. The radius of ^{103}Rh emitter

* Corresponding author at: Department of Nuclear Science and Technology, School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an 710049, China.
E-mail address: zhangqingmin@mail.xjtu.edu.cn (Q. Zhang).

https://doi.org/10.1016/j.anucene.2017.12.008
0306-4549/© 2017 Elsevier Ltd. All rights reserved.

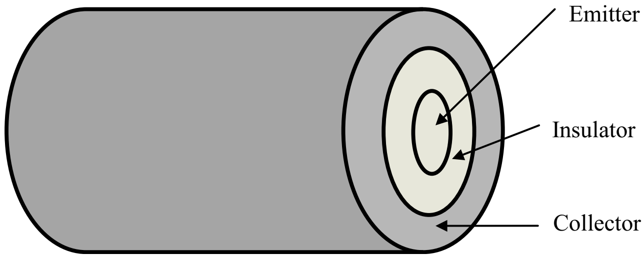

Fig. 1. The structure of Rhodium SPND.

Table 1
The structural parameters of the Rhodium Self-Powered Neutron Detector.

Components	Material	ρ (g/cm^3)	R_{in} (mm)	R_{out} (mm)	L (mm)
Emitter	^{103}Rh	12.41	0.00	0.230	400
Insulator	Al_2O_3	3.569	0.230	0.535	400
Collector	Inconel-600	8.44	0.535	0.785	400

is exactly same to the reference (Todt, 1996); however the thicknesses of insulator and collectors were not mentioned in the reference (Todt, 1996), so the typical values were adopted in this study according to the reference (Kantrowitz, 1987). In Geant4, the detector model was constructed according to Fig. 1 and Table 1. The components of Inconel-600 are 0.015% of S, 0.03% of P, 0.5% of Si, 0.5% of Cu, 0.15% of C, 8.0% of Fe, 15.5% of Cr, 74.305% of Ni (The components of Inconel-600, 2017). All the elements except Rh were in natural abundance (Table of Isotopic Masses and Natural Abundances, 2017).

2.2. Physics lists

The decay scheme of ^{103}Rh (n, γ) reaction for thermal neutron is shown in Fig. 2, which was updated from the decay scheme in reference (Banda, 1976) with the cross sections in reference (Neutron Activation Properties of Isotopes Useful for Neutron Activation Analysis, 2017).

G4HadronElasticPhysicsHP, G4EmStandardPhysics_option4, G4RadioactiveDecayPhysics, G4HadronPhysicsQGSP_BIC_HP and G4DecayPhysics (The Selection of Physical List, 2005) were added. It's found that G4HadronPhysicsQGSP_BIC_HP could not simulate the production of ^{104m}Rh, so G4NEUTRONXS was used to simulate the decay branch of ^{104m}Rh from ^{103}Rh's neutron capture, which was set to be exactly consistent with the cross section. In order to simulate the process that secondary electrons drift from emitter or insulator to collector, the threshold for electrons were set to be 100 eV.

2.3. Primary particles

The primary particles are the neutrons, which were all generated on the collector's surface uniformly in vertexes and isotropically in directions. The typical neutron energy spectrum (d'Utra Bitelli et al., 2009) in reactor core could be used to simulate the SPND response for the neutrons in reactors and the thermal neutrons with a kinetic energy of 0.025 eV could also be utilized to study its response to thermal neutrons.

2.4. Response analysis method

Geant4 can only simulate one event for each time, so all the neutrons were assumed to start to react with the detector at t = 0. Only the electrons, which generated in emitter or insulator and arrived at collector, were recorded with their arrival time. Consequently the unit impulse response current $h(t)$ could be derived by the following formula:

$$h(i\Delta t) = \frac{M(i) \cdot e}{N\Delta t} \quad (i = 0, 1, 2, \ldots) \tag{1}$$

where Δt is the width of time bin (s), N is the number of simulated neutrons, i is the ith sampling point, $h(i\Delta t)$ is the value of the unit impulse response current at t = iΔt, $M(i)$ is the number of collected electrons in the ith time bin and e is the unitary charge (1.6×10^{-19} C). In this paper, Δt was chosen to be 0.1 s.

So the response of SPND for neutron N(t) (neutrons/s)are expressed by

$$I(t) = N(t) * h(t) = \int_{-\infty}^{+\infty} N(\tau)h(t-\tau)d\tau \tag{2}$$

It's mentioned in reference (Weinberg and Wigner, 1958) that neutron flux doesn't depend on the shape of volume element. For our case, neutron flux $\Phi(t)$ can be calculated by Eq. (3).

$$\Phi(t) = \frac{N(t)}{\mathrm{A}} = \frac{N(t)}{2rL} \tag{3}$$

where A is the area of SPND axial section (cm^2·s), r is the outer radius of SPND's collector (cm) and L is the length of SPND (cm).

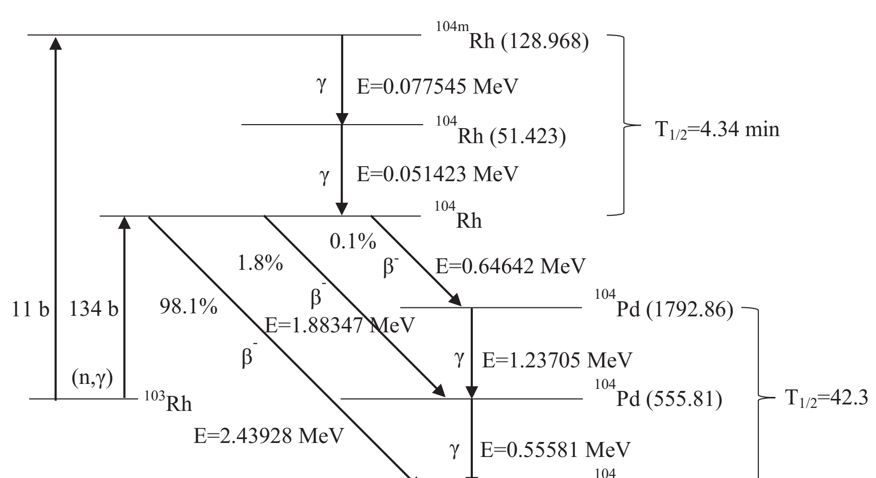

Fig. 2. The decay scheme of ^{103}Rh (n,γ) reaction.

Download English Version:

https://daneshyari.com/en/article/8067236

Download Persian Version:

https://daneshyari.com/article/8067236

Daneshyari.com