CH01000255

ABSOLUTE ON-LINE IN-PILE MEASUREMENT OF NEUTRON FLUXES USING SELF-POWERED NEUTRON DETECTORS : MONTE CARLO SENSITIVITY CALCULATIONS

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ABSTRACT

Self-powered neutron detectors (SPND) are well suited to monitor continuously the neutronic operating conditions of driver fuel of research reactors and to follow its burnup evolution. This is of particular importance when advanced or new MTR fuel designs need to be qualified. We have developed a detailed MCNP-4B based Monte Carlo approach for the calculation of neutron sensitivities of SPNDs. Results for the neutron sensitivity of a Rh SPND are in excellent agreement with experimental data recently obtained at the BR2 research reactor. A critical comparison of the Monte Carlo results with results from standard analytical methods reveals an important deficiency of the analytical methods in the description of the electron transport efficiency. Our calculation method allows a reliable on-line determination of the absolute in-pile neutron flux.

1. Introduction

On-line in-pile monitoring of the neutron flux is routinely performed in many research reactors by means of self-powered neutron detectors (SPNDs). This information is of crucial importance for programs dealing with the production of radioisotopes, the activation of samples (e.g. Si doping) and also for the study of the radiation impact on fuel and material properties. With respect to the driver fuel of research reactors, SPNDs can be used effectively to monitor continuously the neutronic - and hence thermal - operating conditions of such fuel and to follow its burnup evolution. This is of particular importance when advanced or new MTR fuel designs need to be qualified through representative irradiation tests in the same or another research reactor. In this case well-calibrated SPNDs will allow to verify the actual irradiation conditions of the MTR fuel as compared to the neutronic calculations.

The general SPND operation principle is well understood, but a detailed knowledge of all contributions to the detector sensitivity is often lacking, and SPND signals are considered to be reliable for interpretation only in a relative way. As the detector sensitivity depends on the neutron spectrum, on the detector surroundings, on the temperature, ..., experimental calibrations are only valid as long as these conditions remain the same. From the theoretical side, analytical models were developed already in the early 70s [1-3] and, albeit with some modifications, they are still being used [4-6], but they require experimental input and they exhibit some important failures in the detailed description of all relevant physical phenomena.

This paper deals with the recent development of a detailed MCNP-4B-based Monte Carlo approach for the calculation of the absolute neutron sensitivity of several SPNDs. The method contains no adjustable parameters, but the global sensitivity can of course only be computed if the neutron spectrum is known. A critical comparison between our Monte Carlo method and the standard analytical model [1-2] will be presented.

2. The MCNP-4B based Monte Carlo model

A self-powered neutron detector consists of a cylindrical metallic emitter surrounded by an insulator (MgO or Al_2O_3) and a sheath, usually made of Inconel or stainless steel (see figure 1). After neutron impact, several possible interactions lead to the creation of energetic electrons (mainly in the emitter). A fraction of these electrons is sufficiently energetic to cross the insulator. These electrons constitute a current which can be measured by connecting a current meter between the emitter and the sheath. SPNDs can be classified in two groups. In the delayed SPNDs the main process is the production of β rays upon decay of unstable isotopes formed after neutron capture ; typical response times are of the order of a few minutes. In prompt SPNDs γ rays instantaneously produced after neutron capture create energetic electrons (by photoelectric effect, Compton scattering, or pair formation).

Of course also γ rays from outside the detector can contribute to the detector current via similar processes, so the SPND have also some γ sensitivity. In many cases however, opposite currents due to electrons originating from the emitter and the sheath cancel to a large extent, leading to a small detector signal contribution.

Already in the seventies, a Monte Carlo approach for the SPND sensitivity calculation was proposed by Goldstein [7-8]. Because of the limited computer capacity in those days, his model neglected several processes (neutron captures taken into account only in the emitter, electrons produced only via first order Compton interaction, no Bremsstrahlung included, electron transport modelled using an average stopping power,...). Still the agreement between his calculated sensitivities - without any adjustable parameter - and experimental data was generally reasonably good. Meanwhile extensive Monte Carlo codes describing the generation and the transport of neutrons, γ rays and electrons have become available. We used the Los Alamos MCNP-4B code [9] as a basis to construct a model for the calculation of the neutron sensitivity of SPNDs.

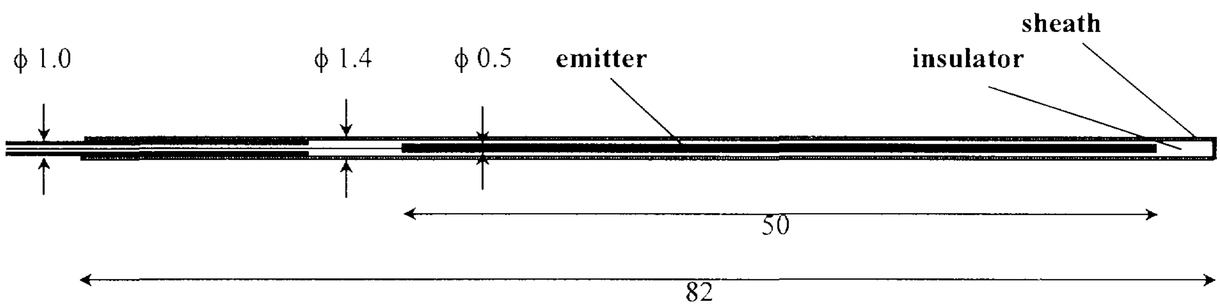

Figure 1 : Longitudinal cut of an SPND with typical dimensions (in mm)

Starting from a user-defined neutron, γ or electron source (position, initial direction and energy distribution), the MCNP-4B code [9] calculates the time evolution of the ensemble of electrons (directly from the source or produced via γ interactions), γ rays (from the source or produced after neutron capture) and neutrons.

The modelled neutron interactions cover elastic and inelastic scattering and capture, using extensive cross section libraries (mostly from ENDF). If the library for the isotope under study includes also γ production data, the prompt emission of γ rays after neutron capture is also modelled. The calculation for the γ rays includes energy loss and electron production via incoherent (Compton) scattering, coherent (Thomson) scattering, the photoelectric effect and electron-positron pair production. To calculate properly the electron transport, the electron path is divided into a large number of steps, according to the work of Seltzer and Berger (ETRAN code) [10]. For each step, the energy loss is sampled from a distribution taking into account the energy straggling. For the path calculation each step is further divided in substeps; for each of these substeps the Goudsmit-Saunderson theory is used to calculate the angular deflections. To conclude the calculation for every substep, the production of Bremsstrahlung photons and the production of knock-on electrons (produced by electron-electron scattering) are accounted for.

MCNP-4B does not follow the history of the unstable activated nuclei, produced by neutron capture. These will decay with their characteristic time and emit β and/or γ rays. To include this effect, which is crucial for the calculation of the sensitivity of delayed SPND, the calculation has to be performed in two (or three) steps : first the production rate and the spatial distribution of the activated nuclei is calculated from a specified neutron source, and next this information is used to define the spatial distribution of an electron (β) source (or a γ source) for the calculation of the electron currents. For the initial velocity direction a random distribution is assumed. The energy distribution for the electrons is calculated according to the Fermi β energy distribution [11,12] with the appropriate β end-point energy ; for the γ ray energy distribution and intensity, experimental data are needed.

For some isotopes (e.g. ^{103}Rh), the libraries associated with MCNP-4B do not include the generation of γ rays upon neutron capture. In this case a similar procedure as described above has to be applied to take into account the effect of prompt γ rays.

A neutron (or γ) source is defined with an origin uniformly sampled on the outer surface of the detector and with an initial direction proportional to cos(θ), θ being the angle between the direction and the surface normal. As initial energy 40 energy bins in the range from 1 meV to 10 MeV were taken for the neutron source and 20 energy bins from 0.02 MeV to 14 MeV for the γ source. As output of the code we obtain (directly or in two steps as explained above) the net charge deposit in the respective parts of the detector (emitter, insulator, sheath). Usually the major contribution to the resulting current is the net charge deposit in the emitter (usually positive since negatively charged electrons are leaving). If all electrons stopped in the insulator would diffuse further to the sheath, it would be the only contribution. In order to determine the fraction of electrons stopped in the insulator that return to the emitter, the insulator is divided into 25 concentric segments and the charge deposition in each of these segments is calculated (by MCNP-4B). This information is used to solve the Poisson equation for the potential profile in the insulator, assuming a zero potential at the inner and the outer insulator radius. Assuming that all electrons that are stopped closer to the emitter than the potential extremum position, are driven back to the emitter by the space charge field, the fraction f of electrons ultimately returning to the emitter can be calculated. The net current is finally calculated as the net charge deposit in the emitter plus f times the net charge deposit in the insulator (which is negative if more electrons are stopped than emitted). To convert the obtained 'current per incoming particle' into a sensitivity ('current per flux unit'), MCNP also calculates the neutron (or γ) flux per incoming particle at the detector surface.

It should be stressed that this calculation model is straightforward, without any adjustable parameters. This is not the case for the commonly used analytical Warren model [2], in which an adjustable pseudopotential is defined to bias the final destination of the electrons stopped in the insulator. The adjustment is performed using experimental data, so the Warren model is in a sense more a "fitting" model than a purely predictive model.

3. Evaluation of the standard analytical sensitivity calculation method

In the following we concentrate on the calculations for a specific SPND, which we recently irradiated in the BR2 reactor. This exemplaric approach will facilitate a detailed comparison of the different models ; the conclusions are quite generally valid. The considered SPND is a NEUTROCOAX Rh SPND of the type 2NNI-10. It consists of a rhodium emitter (length 5 cm, diameter 0.05 cm), surrounded by an Al_2O_3 layer (thickness 0.025 cm) and closed by an Inconel collector (thickness 0.02 cm) (see figure 1).

The calculated sensitivities for a neutron energy of 25 meV (thermal neutrons at 20 °C) are :

- analytical Warren model : 1.31 10^{-21} A / cm / (n/cm^{2}s)
- Goldstein MC calculation : 0.98 10^{-21} A / cm / (n/cm^{2}s)
- actual MCNP calculation : 1.15 10^{-21} A / cm / (n/cm^{2}s).

The MCNP value is 18% higher than the Goldstein value, which can be explained by the fact that Goldstein does not include the contribution from the capture γ rays and makes some other approximations (no photoelectric effect, less complete electron transport model,...).

The analytical Warren model result is 14% higher than our MCNP result. The origin of this difference can be found by writing the sensitivity S as a product of three components (considering only the (n,β) contribution) : $S = \varepsilon_c \cdot \varepsilon_e \cdot \varepsilon_i$, where ε_c is the number of neutron captures per unit neutron flux, ε_e the average β escape probability from the emitter, and ε_i the insulator crossing probability. For both calculations ε_c amounts to 2.6 10^{-21} A / cm / (n/cm^{2}s) – this means that 40 % of the neutrons crossing the emitter are captured - and for both ε_i is about 80 %. The difference in the obtained sensitivity is almost exclusively due to the β escape probability out of the emitter, which is 48% in the MCNP calculation and as large as 62 % in the Warren case. One important approximation that has been made in the latter model is the simplified description of the β energy spectrum. The applied β spectral density function is a low energy approximation (E<<0.5MeV) and does not provide for Coulomb effects in the β decay. This results in a too high weight for low energy β, and would thus lead to a lower ε_e (by about 20%), while we observe a too high ε_e. However, the effect of the β energy approximation is counterbalanced by another, even more crude approximation.

The Warren model treats the electron energy loss in a macroscopic way, using literature values for the average electron energy loss per unit distance and assuming straight electron paths. In reality however, electron scattering is very important and the followed path is much longer than the shortest distance between start and end point [13]. MCNP follows the electron on a microscopic scale including many possible collision processes. We validated this electron transport treatment by reproducing experimental transmission data [13] for electrons in the relevant energy range through Al foils with a thickness of the order of the emitter size. Figure 2 shows that the MCNP results agree perfectly with the experimental data. The Warren approximation would correspond to a 100 % transmission up to a thickness t_{lim} (0.18, 0.37, 0.56, 0.80 resp. 1.00 g/cm^2 for the electron energies 427, 727, 1011, 1370, resp. 1627 keV) and complete absorption for thicker foils, which clearly provides a poor description of the data. Not only the energy straggling is missing in these models, the electron transmission is also overestimated globally : the threshold thicknesses are well above the so-called extrapolated ranges (i.e. the thickness obtained after extrapolating from the linear part to 0 transmission). A comparison with extrapolated range data from [14] for Cu, Ag and Au shows the same trend, so also for Rh the MCNP approach should be much more appropriate.

For delayed SPND the effects of both approximations in the analytical model counteract each other, leading to reasonable final results. For the neutron sensitivity of prompt SPNDs and for gamma sensitivities, the error introduced by the basic electron transport model is fully reflected in the sensitivity result. In these cases a good agreement with experimental results could be obtained only after the introduction of a semi-empirical pseudopotential parameter in the analytical model.

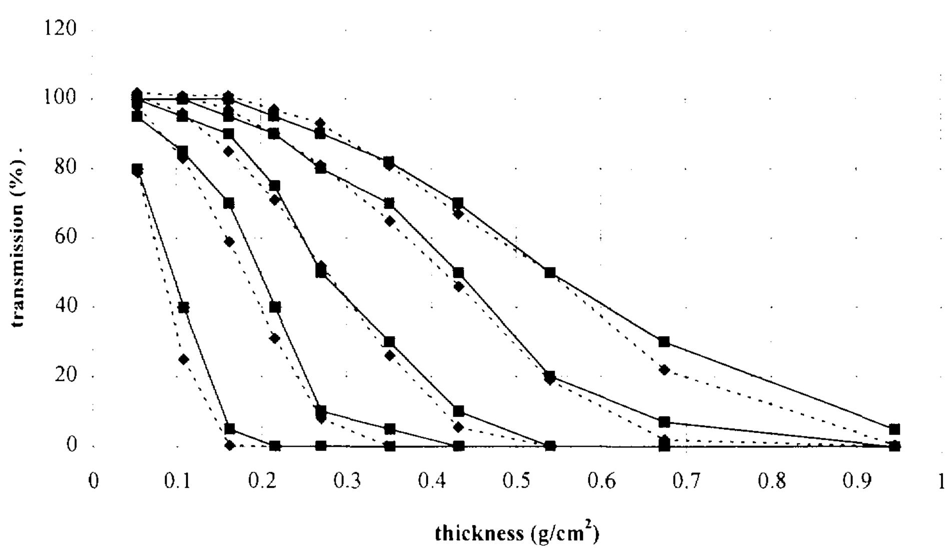

Figure 2 : Electron transmission probabilities through aluminium for energies of 427, 727, 1011, 1370, resp. 1627 keV. Dashed lines are from MCNP calculations, solid lines are experimental data from [13].

4. Comparison with experimental data

In order to validate our Monte Carlo model, we compare our results for the Rh SPND with experimental data. SPND currents during irradiations in two BR2 channels (E30 and L180) were recorded, and the corresponding thermal, epithermal and fast neutron flux were measured by activation dosimetry (total fluxes 8.9 10^{14} n/cm^{2}s and 2.8 10^{14} n/cm^{2}s). From the calculated relative neutron spectra the total SPND sensitivities, integrated over the complete spectrum, were calculated. Using the measured absolute thermal flux data, these sensitivities were converted into expected SPND currents, which can be directly compared with the measured currents :

	Channel E30	Channel L180
Measured current	2.64 μA	0.93 μA
Expected current from MCNP (this work)	2.65 μA	0.94 μA
Expected current from Goldstein [9]	2.06 μA	0.74 μA
Expected current from manufacturer's calibration	2.06 μA	0.76 μA
Expected current from the analytical model [1]	3.05 μA	1.08 μA

The MCNP sensitivities account perfectly for the observed current I_{obs}. Averaged over the two channels, the Goldstein Monte Carlo calculation leads to an expected current of 79 % of I_{obs}. From the detector sensitivity specified by the manufacturer, 80 % of I_{obs} is predicted, but here the contribution of the epithermal neutrons is neglected. Finally, the analytical model calculations for the complete neutron spectrum overestimate the current by about 16%.

5. Conclusion

A new Monte Carlo model was developed to calculate the neutron and the γ sensitivity of self-powered neutron detectors. The commonly used analytical model is critically evaluated through a detailed comparison with the Monte Carlo method. Provided the spectra are known, the method allows a reliable in-pile on-line measurement of the *absolute* neutron flux which is important for a quantitative study of fuel behaviour.

Acknowledgement

The author wants to thank Marcel Wéber for providing the experimental data used as benchmarks for the Monte Carlo method.

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