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Validation of the Monte Carlo model developed to assess the activity generated in control rods of a BWR

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ABSTRACT

Control rods are activated by neutron reactions into the reactor. The activation is produced mainly in stainless steel and its impurities. The dose produced by this activity is not important inside the reactor, but it has to be taken into account when the rod is withdrawn from it. The neutron activation has been modeled with the MCNP5 code based on the Monte Carlo method. The number of reactions obtained with the code can be converted into activity. In this work, a detailed model of the control rod has been developed considering all its components: handle, tubes, gain, and central core. On the other hand, the rod has been divided into 5 zones in order to consider the different axial exposition to neutron flux into the reactor. Results of the Monte Carlo simulation for the neutron activation constitute a gamma source in the control rod. With this source, applying again the Monte Carlo method, doses at certain distance of the rod have been calculated. Comparison of calculated doses with experimental measurements leads to the validation of the model developed.

1. Introduction

Control rods are activated by neutron reactions into the reactor. The activation is produced mainly in impurities contained in stainless steel as well as in the elements composing the steel alloy. The activity so generated will produce a dose around the rod, not important while it is inside the reactor, but it has to be taken into account when the rod is withdrawn from the reactor.

Activation reactions have been simulated with the MCNP5 code [1] based on the Monte Carlo (MC) method and the number of reactions can be converted into activity. In previous works a simplified model to estimate this activity was developed [2] and an estimation of the dose around the storage pool was performed [3]. In this work, a detailed model of the control rod has been developed considering all its components: handle, boron tubes, gain, and central core, and the rod has been divided into 5 zones in order to take into account the different axial exposition to neutron flux into the reactor.

An analysis of the results permits one to know the most important radionuclides produced by activation as well as the influence on the activity distribution of material composition, neutron flux, and control rod history.

A further MC model has been developed to estimate doses produced at points corresponding to the 5 zones considered in the rod. Comparison of these doses with experimental measurements near an irradiated BWR control rod leads to the validation of the model developed.

2. Activation

Control rods in a BWR are cross shaped; every blade of the cross having 18 stainless steel tubes containing CB_4 as neutron absorber. These tubes are closed by welding taps at both sides, and they are contained in a stainless steel gain with holes that allow proper cooling. The estimated life of one control rod is about 15 years.

The activity generated in the control rod depends on reaction cross sections, neutron spectrum, neutron flux distribution, concentration of precursors of each radionuclide, irradiation time, and control rod history. After withdrawing the rod from the reactor, activities decrease with time and disintegration constants.

First, it is necessary to estimate the interaction rate Q (reactions /cm^3 s) for each reaction:

$$Q = C\int \Phi(E)\sigma(E)\,dE \tag{1}$$

being C a normalization factor (at/b cm) depending on the target concentration; $\Phi(E)$ the neutron flux (n/cm^2 s); $\sigma(E)$ the microscopic cross section of the reaction (b).

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Table 1
Activation reactions produced in stainless steel of control rods.

^{14}N (n, p) ^{14}C	^{54}Fe (n, γ) ^{55}Fe
^{54}Fe (n, p) ^{54}Mn	^{58}Ni (n, γ) ^{59}Ni
^{59}Co (n, γ) ^{60}Co	^{60}Ni (n, p) ^{60}Co
^{58}Ni (n, α) ^{55}Fe	^{63}Cu (n, α) ^{60}Co
^{62}Ni (n, γ) ^{63}Ni	^{92}Mo (n, γ) ^{93}Mo
^{93}Nb (n, γ) ^{94}Nb	^{109}Ag (n, γ) ^{110m}Ag
^{107}Ag (n, γ) ^{108m}Ag	^{153}Eu (n, γ) ^{154}Eu
^{151}Eu (n, γ) ^{152}Eu	^{35}Cl (n, p) ^{36}Cl
^{177}Hf (n, γ) ^{178}Hf	^{46}Ti (n, p) ^{46}Sc
^{37}Cl (n, 2n) ^{36}Cl	^{64}Zn (n, γ) ^{65}Zn
^{27}Al (n, γ) ^{28}Al	

On the other hand, for each j-isotope generated, a matter balance can be done:

$$dN_j/dt = Q_j - \lambda_j N_j \quad (2)$$

integrating, the concentration (nuclei/cm^3) of j-isotope is obtained:

$$N_j(t) = (Q_j/\lambda_j)(1 - \exp(-\lambda_j t_i)) \quad (3)$$

being t_i the irradiation time.

For a cooling time (rod out of the reactor) t_e the concentration N_j becomes:

$$N_j(t) = (Q_j/\lambda_j)(1 - \exp(-\lambda_j t_i))\exp(-\lambda_j t_e) \quad (4)$$

and multiplying by λ_j to obtain activity:

$$A_j(t) = Q_j(1 - \exp(-\lambda_j t_i))\exp(-\lambda_j t_e) \quad (5)$$

It is a volumetric activity (Bq/cm^3). To obtain the total activity it is necessary to multiply by the cell volume. The maximum activity will be the asymptotic value, Q_j, considering an irradiation time very long ($\sim\infty$) and neglecting the cooling time.

Major activation reactions will be produced in steel mainly in gains and handle and mostly in impurities. The reactions considered are listed in Table 1.

3. Monte Carlo models

Monte Carlo models developed to assess the activity generated in control rods of a BWR are based on a detailed geometry of the control rod [4]. They also include an axial division of the rod in order to consider the control rod history, that is, the different periods and lengths of insertion during its permanency in the reactor core, so that the movement of control rods during reactor operation can be taken into account in the activation assessment. Dose rates around the control rod have been calculated and compared with measurements in order to validate the activation model.

3.1. Activation model

The interaction rate Q is calculated by MCNP using F4 tally and FM4 (tally multiplier card), which provides data for the reactions included in the calculation. MCNP tallies are normalized to be per launched particle. Therefore, it is necessary to multiply all results obtained with MCNP by the actual number of particles at the source. In this case, it should be considered the neutron population in the reactor that depends on the reactor power and the operation time. From the mean energy released per fission, 200 MeV, it can be calculated the number of fissions/W- s, that is, 3.12E+10 that multiplied by the mean number of neutrons per fission, ν, and the mean power of the reactor region considered as a neutron source, permits one to obtain the number of neutrons per second.

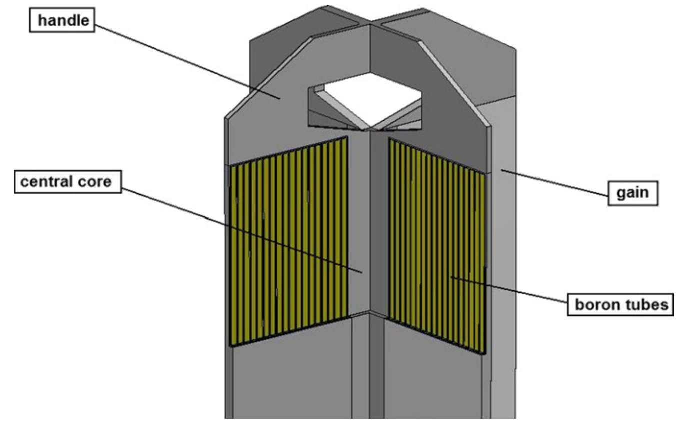

Fig. 1. Components of control rod model.

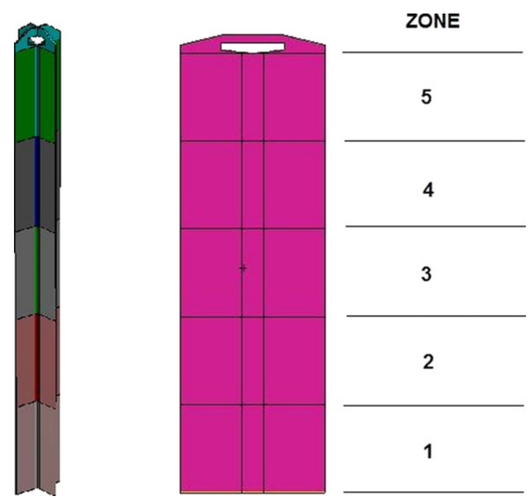

Fig. 2. Axial division cells of the model.

The detailed model considers the exact composition and components of the rod. It can be seen in Fig. 1 drawn with the SABRINA code [5]. Different parts of the control rod – handle, tubes, gain, central core – have been considered as independent cells in the model. Gain and central core cells have been divided into 5 parts in order to reflect the axial distribution of activity. It can be seen in Fig. 2 a scheme of the rod obtained with VISED [6].

The neutron spectrum used in calculations is listed in Table 2. It is based on a mean value of the neutron flux throughout the reactor core, modified by a different probability in each zone that considers the control rod history. Fluxes have been obtained by means of the CASMO code [7] for a GE14 fuel element with 20 GWd/t of burnup and 40% of void fraction without control.

Reactions and isotopes produced are listed in Table 1. Nevertheless, only those isotopes emitting gamma rays have interest from the point of view of dose calculation. Consulting disintegration schemes at the JANIS database [8], they remain the following: ^{28}Al, ^{54}Mn, ^{46}Sc, ^{60}Co, ^{65}Zn, ^{94}Nb, ^{108m}Ag, ^{110m}Ag, ^{152}Eu, ^{154}Eu, and ^{178}Hf. From this list ^{28}Al can be eliminated a cause of its low half-life (2.24 min).

3.2. Validation model

The dose is calculated by MCNP using an F4MESH tally with DE, DF card, which provides flux to dose conversion factors.

Each component of the control rod presents different activity. Therefore, each cell in the source must have different photon