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Determination of the Linear Power in MOX Fuel Rods Irradiated at BR2 Reactor

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The high flux materials testing reactor BR2 is regularly used for the irradiation of new types of fuel elements (rods, plates). Detailed inter-comparison of experimental and theoretical methods of determining the distribution of power in MOX fuel rods is presented in this paper. The MCNP model of the high flux materials testing reactor BR2 was used for a simulation of the irradiation of MOX fuel rods. Calculations of the effective heating energy per fission in the irradiated MOX fuel rods were performed in order to determine the absolute values of the thermal power in MOX rods. The gamma-spectrometric measurements as well as the results from the thermal balance method are compared with the theoretical calculations. The calculated linear power distribution in MOX rods differs from the measured distribution on average not more than 5%.

KEYWORDS: BR2 reactor, MOX fuel rods, irradiation, thermal balance, γ-spectrometry, prompt and delayed photons, Monte Carlo calculation

1. Introduction

The experimental program at the high flux materials testing reactor BR2 mainly concerns the irradiation of new types of fuel elements (rods, plates) as well as in-core and vessel materials for various reactor-types. In particular the CALLISTO in-pile loop provides a representative environment for the irradiation of LWR fuel and/or materials under realistic PWR conditions (water flow, 155 bar, 300°C, adaptable water chemistry). The loop comprises three in-pile sections (IPS); each IPS can receive a square basket containing nine 9.5 mm outer diameter fuel rods.

This paper concerns a particular irradiation program where the burn-up of nine pre-irradiated MOX fuel rods, all loaded in one IPS, had to be increased to predetermined values. Like in most R & D fuel programs it was necessary to determine the accumulation of the fluence for each specific rod. A particular effort is therefore undertaken to accurately measure the overall produced energy and to determine the power distribution among the nine rods. Several methods can be used to determine the heating energy: the on-line thermal balance method, gross γ-spectrometry after irradiation, radiochemical analysis on samples from the rod (this method needs to cut the rod and is only used exceptionally for calibration purposes).

The thermal balance method allows for on-line measurement of the total heating energy in an in-pile section of the CALLISTO loop. To determine the detailed distribution of heating energy in the irradiated fuel rods one has to use preliminary calculated power peaking factors. Various neutron transport codes may be applied for calculation of the radial and axial power peaking factors.

The γ-spectrometric measurement [1] of activity of fission products over the length of the fuel rods provides information about the axial distribution of linear power and the fission rate. This method gives the fission rate distribution in fuel rods with high accuracy.

To compare the γ-spectrometric measurements and the thermal balance measurements we have to know the effective heating energy per fission event in the considered MOX rods.

Calculations of the mean and the peak linear power distributions in MOX rods placed into the CALLISTO loop were performed using a very detailed MCNP model of BR2. The model includes a description of the real inclinations of all channels of the BR2 core. The in-pile section IPS-1 of the CALLISTO loop is located near the periphery of the BR2 core: it consists of two thick stainless steel tubes; the inner tube contains borate cooling water and a shroud tube with the experimental MOX fuel rods (see Fig.1).

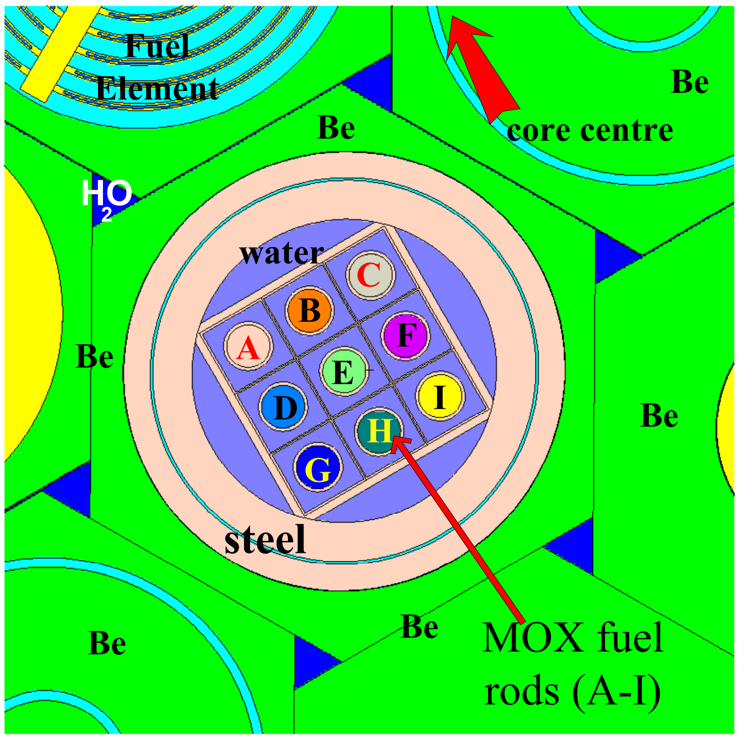

Fig. 1 In-pile section IPS-1 containing 9 MOX fuel rods in the shroud tube

The concentration of Pu in the MOX fuel before irradiation varied from 8.5% to 12.6%. The cladding material of all rods is Zircaloy 4. The pellet diameter is equal to 0.823 cm, the length of fuel rods is 100 cm. MOX rods were initially irradiated in the BR3 reactor at a nominal power of 40.9 MW for 4000 hours and then in the BR2 reactor for 8 cycles. During the whole irradiation history in the BR2 reactor, the MOX rods resided in IPS-1 loaded in channel K49 of the CALLISTO loop.

In this paper we consider the particular irradiation cycle 05/98A with nominal power P_{BR2} of 60.7 MW. After this cycle a gross γ-spectrometry was performed on the rods.

The mean variation of the nuclide composition in the MOX fuel rods during the irradiation history was calculated by Ch. De Raedt [2] and used in previous calculations of power distribution in MOX rods with the DORT code [3].

2. Calculation of the thermal power in MOX fuel rods

The MCNP code [5] is used for calculating the distribution of the neutron flux density in MOX fuel rods. The number of fission reactions in the fuel rod n_f^B per fission neutron in BR2 is defined as:

$$n_f^B = \sum_i \int_E \int_{V_B} n_i \sigma_f^i(E)\Phi(r,E)dEd^3r, \tag{1}$$

where n_i is the atomic concentration of nuclide in the MOX fuel, $\sigma_f^i(E)$ is the microscopic cross-section for the fission reaction of the nuclide i, $\Phi(r,E)$ is the neutron flux density calculated by MCNP and normalised per one fission neutron in BR2.

The power in the fuel rod, P_B, normalized per nominal BR2 power is obtained by using n_f^B and the intensity of the fission neutrons in BR2

$$P_B = Q_{eff}^B \frac{\nu_{BR2} P_{BR2}}{\kappa_{eff} Q_{eff}^{BR2}} \left(\sum_i \int_E \int_{V_B} n_i \sigma_f^i(E)\Phi(r,E)dEd^3r \right) \tag{2}$$

where P_{BR2} is the nominal power of BR2; ν_{BR2} is the mean number of neutrons released in BR2 per fission; κ_{eff} is the effective multiplication factor.

We have to know the effective heating energy, Q_{eff}^B, for irradiated MOX fuel rods and Q_{eff}^{BR2} value for the BR2 reactor. The linear power in the fuel rods is calculated as the ratio of the power P_B to the length L of the fuel rods.

3. Total effective energy released in fission

A detailed discussion of the effective energy Q_{eff} released in the fission reaction for fissionable nuclides of U, Pu is given in the paper of M.James [4]. The recommended values of the useful energy released in fissionable materials include the kinetic energy of fission fragments, E_k; total kinetic energies of emitted neutrons, E_n; energy of photons (prompt-E_γ^f, and delayed- E_γ^d) and beta particles, E_β

$$Q_{eff} = E_k + E_\beta + E_\gamma^f + E_\gamma^d + E_n - \Delta E_{\beta\gamma} - E_\nu \tag{3}$$

where $\Delta E_{\beta\gamma}$ is the energy released after the mean decaying life of the fuel and E_ν is the energy of the antineutrino. For a decaying period greater than 3 years, $\Delta E_{\beta\gamma}$ is about 0.17 MeV/fiss for ^{235}U [4]. In addition to the fission energy useful for heating, the energy of photons produced by neutron capture reactions should be taken into account. The effective energy for fission reaction (3) includes the kinetic energies of all emitted particles that are dissipated in the fuel or in surrounding structural materials. The effective fission energy for ^{239}Pu exceeds the one for ^{235}U by 3%.

The heating energy for prompt photons in all materials in the BR2 core is equal to Q_γ^{BR2}=11.2 MeV/fis. Effective fission heating energy, Q_{eff}^{BR2}, normalized per fission event in the BR2 core can be calculated easily taking into account that the fuel is mainly ^{235}U and that all kinetic energy of fission fragments, the energy of β-particles and the energy of delayed photons are deposited in the core. We then obtain: $Q_{eff}^{BR2} = Q_F + Q_\gamma^{BR2} + E_n = 196.4$ MeV/fiss, with Q_F=180.4 MeV/fiss for ^{235}U [4] and E_n=4.8 MeV/fiss.

However, we need to determine the effective heating energy Q_{eff}^{B} in a small single fuel rod with its normalization per fission event in this rod. The various components of the heating energy in the MOX fuel rods are:

- the kinetic energy of fission fragments, E_k, and the energy of β-particles, E_β, produced in decay reactions of fission fragments. The track length of fission fragments is small and all energy of fission fragments is deposited locally in the fuel rod. Using the fission rates, n_f^i, for constituent nuclide i and total energies E_k, E_β for U and Pu nuclides we determine the average energy of fission fragments and β-particles, $Q_{k\beta}$=177.3 MeV/fiss for the MOX fuel rods.
- the loss of the kinetic energy of fission neutrons, Q_n, in elastic and inelastic collisions in fuel rods during their slowing down;
- the heating energy of prompt gammas, Q_γ^B, produced in fission and capture reactions;
- the heating energy of delayed gammas coming from fission products in BR2 fuel elements, $Q_{\gamma,BR2}^{d}$, and generated in MOX rods, $Q_{\gamma,B}^{d}$.

The prompt and delayed photons may escape from the fuel rod and interact with structural elements surrounding the fuel rod. The estimation of the photon leakage from the MOX fuel rods and calculations of their heating energy were performed using the MCNP and the SCALE codes.

The γ-heating energy in MOX fuel rods can be determined as a sum of contributors of heating energy from the prompt and delayed photons

$$E_\gamma = \int_E \int_{V_B} \varphi^{p,\gamma}(r,E) H_\gamma(E) dE d^3r + \int_E \int_{V_B} \varphi_{BR2}^{d,\gamma}(r,E) H_\gamma(E) dE d^3r + \int_E \int_{V_B} \varphi_{B}^{d,\gamma}(r,E) H_\gamma(E) dE d^3r \quad (4)$$

where $\varphi^{p,\gamma}$, $\varphi^{d,\gamma}$ are the γ flux density determined using the Monte Carlo code MCNP for prompt and delayed photons, $H_\gamma(E)$ is a heat response, V_B is the volume of the MOX rod.

For calculation of the energy deposition, $\varepsilon_{\gamma,B}^{B}$, in MOX per delayed photons emitted by fission products in MOX fuel rods, the MCNP code was used to simulate the transport of photons from the external source of delayed photons distributed in MOX rods. The spectrum of delayed photons was calculated using the SAS2H module of the SCALE code and normalized per total power in MOX rods. The contribution to the effective heating Q_{eff}^{B}-value normalized per fission reaction in MOX rods is

$$Q_{\gamma,B}^{d} = \varepsilon_{\gamma,B}^{B} I_{\gamma,B}^{B} \frac{Q_{eff}^{BR2}\kappa_{eff}}{n_f^B P_{BR2} \nu_{BR2}}, \quad MeV/fiss \quad (5)$$

where $I_{\gamma,B}^{d}$ is the intensity of delayed γ emitted by fission products in MOX rods, n_f^B is the number of fission events in MOX per fission neutron. Substituting parameters calculated using the MCNP and the SAS2H module of the SCALE codes we obtain the contribution from the delayed photons $Q_{\gamma,B}^{d}$=0.94 MeV/fiss.

The mean heating energy, $\varepsilon_{\gamma,BR2}^{B}$, in the MOX fuel rods per delayed photons emitted from the BR2 fuel elements was calculated using the MCNP code for the external γ-source distributed in BR2 fuel elements. The contribution to the effective heating energy, Q_{eff}^{B}, was renormalized per fission in MOX rod

$$Q_{\gamma,BR2}^{d} = \frac{\varepsilon_{\gamma,BR2}^{B} I_{\gamma,s}^{d} Q_{eff}^{BR2} \kappa_{eff}}{P_s n_f^B \nu_{BR2}} = 0.69 \qquad MeV / fiss \qquad (6)$$

where P_s and $I_{\gamma,S}^{d}$ are the thermal power and the intensity of delayed photons generated in the BR2 fuel elements.

The source of prompt photons is calculated in the MCNP automatically for fission and neutron capture reactions. The average heating energy of prompt photons in the fuel of MOX rods was calculated directly using the MCNP code with normalisation per one fission event in MOX rods $\overline{Q}_{\gamma}^{B}$ =11.3 MeV/fiss.

The total effective heating energy in MOX fuel rods normalized per fission in MOX is defined as the sum of the average energy of fission fragments, the energy of beta-particles, $Q_{k\beta}$=177.3 Mev/fiss; the heating energy from prompt photons, $\overline{Q}_{\gamma}^{B}$ =11.3 MeV/fiss; the heating energy of delayed photons emitted by BR2 fuel elements, $Q_{\gamma,BR2}^{d}$ =0.69 MeV/fiss, and by MOX fuel elements, $Q_{\gamma,B}^{d}$=0.94 MeV/fiss. The loss of the kinetic energy of fission neutrons in the MOX rods is very small and we neglect its contribution. The effective heating energy for MOX rods was thus calculated using the formula

$$Q_{eff}^{B} = Q_{k\beta} + Q_{\gamma,B}^{d} + Q_{\gamma,BR2}^{d} + \overline{Q}_{\gamma}^{B} = 190.2 \qquad MeV / fiss \qquad (7)$$

The contribution from the delayed photons produced in the BR2 fuel elements to the heating in the Callisto loop is relatively small, because of the large distance between the BR2 fuel channels and MOX rods. Moreover, most delayed photons produced in MOX rods escape from the rods and lose their energy outside the MOX rods. However for an irradiation channel where the six neighbouring channels contain BR2 fuel elements, the contribution from these delayed photons should not be neglected.

4. Validation of the BR2 model

4.1 Heating energy in CALLISTO loop

The gamma heating in IPS-1 of the CALLISTO loop has been measured by loading the shroud tube with stainless steel dummy rods. The thermal balance method was used to determine the gamma heating inside IPS-1 of the CALLISTO loop. The measured power was 27.8 kW. The calculated power including the heating by prompt photons and the contribution of the delayed photons from fission products in BR2 fuel elements, was:
P_{γ}^{B} =26.5 kW .

The ratio of the gamma heating energy to the total heating energy in the MOX fuel is equal to 5.9%. Taking into account the heating in the cladding of the rods, in the water and in the spacer grid, this ratio becomes equal to 9.8%. The corresponding ratio in the BR2 core is equal to 5.8%. This difference may be explained by the presence of a larger amount of stainless steel 316 and boron in the cooling water in the channel containing IPS-1 compared to the majority of channels in the core where the main structural materials are aluminum, water and beryllium.

4.2 Comparison of the thermal balance method and MCNP calculation

In the thermal balance method the mean and the peak linear power in each fuel rod is not measured directly in the experiment but determined using a preliminary calculated distribution of power between the various fuel rods. The total power in all MOX fuel rods is determined by measuring the temperature of the cooling water at the inlet and outlet of IPS-1 and the flow rate in this in-pile section [6].

The radial and the axial peaking factors for fuel rods are calculated ordinary by using approximate 2-D neutron diffusion and transport models. The mean linear power in the MOX rods is calculated using the expression $l^{calc} = P_B / L$, where L is the length of the fuel. The comparison of the calculated linear power in MOX rods, l^{calc}, and the measured one obtained from the thermal balance method, l^{TBM}, [6] are presented in Table 1. The mean ratio of the calculated results to the measured is equal to 0.98. The mean ratio of the calculated peak linear power to the obtained from the thermal balance method is equal to 1.04.

Table 1 Ratio of the calculated mean linear power, l^{calc}, in MOX fuel rods to the measured values by the thermal balance method, l^{TBM}, and by spectrometry, l^{γ}.
I^{calc} and I^{γ} are the calculated and measured fission rates.

MOX rod	l^{TBM}, [6] W/cm	Ratio		
		l^{cal}/l^{TBM}	I^{cal}/I^{γ}	l^{TBM}/ l^{γ}
F6547 (A)	190.6	0.98	0.90±0.05	0.92
F6548 (B)	169.9	0.97	0.94±0.05	0.96
F6549 (C)	192.8	0.98	0.94±0.05	0.96
F6680 (D)	181.2	1.01	0.94±0.05	0.94
F6678 (E)	142.6	0.98	0.97±0.05	0.99
F6677 (F)	180.4	0.95	0.92±0.05	0.96
F6673 (G)	176.2	1.00	0.94±0.05	0.94
F6679 (H)	141.6	0.97	0.95±0.05	0.98
F6674 (I)	173.8	0.94	0.92±0.05	0.98
Mean value for all rods	172.1	0.98	0.94±0.05	0.96

4.3 Comparison of the gamma-spectrometric measurements and calculated distribution of fission rate in MOX rods

The total fission rate in MOX rods was measured after the irradiation cycle 05/98A using the γ-spectrometer and published in the SCK-CEN report [1]. The total fission rates, $I_{f,B}^{calc}$, in MOX rods were calculated using the MCNP model

$$I_{f,B}^{calc} = n_f^B \frac{P_{BR2}\nu_{BR2}}{Q_{eff}^{BR2}\kappa_{eff}}, \quad n_f^B = \sum_i \int_E \int_{V_B} n_i \sigma_f^i(E)\Phi(E)dEdr \qquad (9)$$

where n_f^B is the fission rate in the rods per fission neutron. Comparison of the total fission rates measured by the γ-spectrometric method and calculated using the MCNP model of BR2 is shown in Table 1. The mean ratio of the calculated fission rate to the measured value obtained by γ-spectrometry is equal to 0.94. The systematic deviation of 6% is comparable to the experimental uncertainty of 4.4% [1].

The measured peak fission rate, $M_{f,B}^{\exp}$, is obtained using the measured total fission rate, $I_{f,B}^{\exp}$, and the shape factors, $k_z^{\exp}$, determined in γ-spectrometric measurements [1]

$$M_{f,B}^{\exp} = k_z^{\exp} I_{f,B}^{\exp} / L \qquad (10)$$

The ratio of the calculated to the measured peak fission rate for various MOX rods changes from 0.93 to 1.05. The mean value for the ratio of the calculated and measured peak rates is equal to 0.99.

4.4 Comparison of the γ-spectrometric and the thermal balance methods

The mean linear power, l^γ, in the fuel rod was determined using the measured fission rates, $I_{f,B}^{\exp}$, in the γ-spectrometric method and the effective heating energy Q_{eff}^B=190.2 MeV/fiss for MOX fuel rods : $l^\gamma = I_{f,B}^{\exp} Q_{eff}^B / L$. The difference in the linear power obtained by two methods belongs to the spread range 0.92 – 0.99. The mean deviation of the thermal balance (TBM) results from γ-spectrometry method is equal to 0.955. However, the experimental error of the γ-spectrometry measurement is equal to 4.4%.

The peak linear power, m^{th}, in fuel rods in the γ-spectrometry method was determined using the peak fission rate, $M_{f,B}^{\exp}$, and the effective heating value, Q_{eff}^B=190.2 MeV/fiss, calculated for the MOX fuel rods: $m^{th} = M_{f,B}^{\exp} Q_{eff}^B$.

The ratio of the peak linear power in fuel rods obtained by the thermal balance method to the values in the γ-spectrometry method for various rods varies from 0.88 to 1.03. The mean ratio for all rods is equal to 0.95. The mean ratio defines the difference in the total power for all fuel rods. The systematic deviation of 5% observed in the present calculations between the thermal balance and the gamma-spectrometry methods is comparable with the experimental error in the γ-spectrometric method 4.4%. The error of determining the linear power in the thermal balance method is about 7-8%.

5. Conclusion

Benchmark comparisons of the fission rate and the power distribution in MOX rods obtained in the thermal balance measurements; in γ-spectrometric measurements; and in theoretical calculations were performed for the MOX fuel rods irradiated at the BR2 reactor.

The mean linear power calculated using the MCNP model of BR2 is lower by 2% than the power measured in the thermal balance method. The peak linear power in calculations is higher than expected from the thermal balance method by 4%. The experimental error of the thermal balance method is equal to 7-8%.

The total fission rate in MOX rods calculated using the MCNP model of BR2 is systematically lower by 6% than the fission rate measured by the γ-spectrometry method. The calculated maximum in the distribution of fission rate coincides with the γ-spectrometry results within the error margin of ± 5%. The error of the γ-spectrometry results is equal to 4.4% [1].

The mean linear power determined using the fission rate in the γ-spectrometry analysis and using the calculated effective heating energy for MOX rods (190.2 MeV/fiss) differs from the thermal balance method by 5%.

The presented analysis demonstrated that the γ-spectrometry measurements, the thermal balance measurements and the theoretical model of BR2 reactor give the average deviation between them of about 5-6% for the fission rate distribution, for the linear power and for the peak linear power in fuel rods, which is less than the experimental errors.

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