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A GAMMA HEATING CALCULATION METHODOLOGY FOR RESEARCH REACTOR APPLICATION

Y. K. LEE

CEA – Saclay, DEN/DM2S/SERMA/LEPP, 91191 Gif sur Yvette Cedex, France

and

J.-C. DAVID and H. CARCREFF

CEA – Saclay, DEN/DRSN/SIREN/LASPI, 91191 Gif sur Yvette Cedex, France

ABSTRACT

Gamma heating is an important issue in research reactor operation and fuel safety. Heat deposition in irradiation targets and temperature distribution in irradiation facility should be determined so as to obtain the optimal irradiation conditions. This paper presents a recently developed gamma heating calculation methodology and its application on the research reactors. Based on the TRIPOLI-4 Monte Carlo code under the continuous-energy option, this new calculation methodology was validated against calorimetric measurements realized within a large ex-core irradiation facility of the 70 MWth OSIRIS materials testing reactor (MTR). The contributions from prompt fission neutrons, prompt fission γ-rays, capture γ-rays and inelastic γ-rays to heat deposition were evaluated by a coupled (n,γ) transport calculation. The fission product decay γ-rays were also considered but the activation γ-rays were neglected in this study.

1. Introduction

After the shutdown of SILOE reactor in 1997, OSIRIS is the only operational MTR in France. To continue operating this research reactor, which achieved its first criticality on Sep. 1966, the refurbishment programs concerning reactor fuel rack, reactor tank and other equipments, were realized during past years [1]. To optimize the irradiation program, the modern radiation transport code TRIPOLI-4 [2] was recently introduced to calculate the plate-by-plate full core model and to improve the design and the performance of the irradiation facility in the OSIRIS reactor.

On design of irradiation targets and irradiation facility, one of the goals is to determine if the neutron flux is high enough for irradiation program and another goal is to evaluate the gamma heating in order to obtain an optimal temperature distribution in targets. The auxiliary heating system could be introduced according to the need of the experiments and the safety-related cooling system must be considered when the gamma heating is too high in the irradiation facility.

To evaluate the gamma heating in the in-core or ex-core irradiation targets of the 70 MWth OSIRIS reactor, a calculation scheme has been used since several years. This calculation scheme computes capture γ-rays production using the neutron flux evaluated by the diffusion code DAIXY [3]. To calculate the gamma heating and the gamma attenuation in materials, the point-kernel code MERCURE-5 [4] is applied. Usually this calculation scheme is satisfactory for in-core irradiation program and acceptable for ex-core small target.

When a large target is settled in an ex-core irradiation position where the perturbed neutron flux could not be easily determined by the diffusion code or when the irradiation facility is complex and the γ-ray multi-layer buildup factors are difficult to evaluate, the above cited calculation scheme could lead to a larger uncertainty in gamma heating estimation. That is why the new gamma heating calculation methodology based on the TRIPOLI-4 Monte Carlo code was established in this study. With a specific continuous-energy library and an exact description of reactor core, reactor tank and irradiation facility, the coupled (n,γ) TRIPOLI-4 calculation should be better to estimate gamma heating.

This paper presents first the experimental calorimetric measurements in a large ex-core irradiation facility settled in the OSIRIS reactor and secondly, the associated heat deposition calculations based on the TRIPOLI-4 code. Comparisons of results and discussions will then be shown.

2. Research reactor OSIRIS and ex-core calorimetric measurement

The OSIRIS research reactor is a light water pool type reactor. The reactor core is made up of 38 MTR-type fuel elements in 7 x 8 matrix (Fig.1). Aluminium-clad fuel plates are arranged in edge plates to form fuel elements. Fuel elements are arranged into aluminium rack to form the reactor core. Several positions in the fuel rack are not occupied by fuel elements but by 6 control elements, 7 beryllium reflectors, and 5 experimental elements containing capsules.

The reactor core is designed with a Zircaloy tank containing 86 cooling channels and cords. The fuel meat in the fuel elements and control elements is composed of U_3Si_2 in aluminium matrix. The length of the fuel meat is 63 cm. The 20% enriched uranium is used in the fresh fuel for present operation.

The material testing experiments can be realized within the capsules of in-core experimental elements or within the peripheral ex-core facilities. The irradiation facility considered in this study was located in the northwest ex-core corner close to the reactor tank (Fig. 2). Shielding plates were fixed on the hot sides of the irradiation facility to reduce the gamma heating from the reactor core. The cooling channels are designed in hot faces for pumped coolant water flows. A cylinder space of 16.5 cm diameter prepared in the central part of irradiation facility is reserved for receiving the irradiation targets.

To carry out the calorimetric experiment, the irradiation target is removed from the central space of the irradiation facility while the calorimeter is inserted. The experiment was realized in the centre of the central space filled with water. Under the operating power between 60.47 and 61 MWth, the experiments were executed during 5 hours. The differential calorimeter, manufactured and calibrated by different teams of CEA-Saclay, is composed of four cylindrical aluminium cells (diameter 0.9 and height 5.2 cm, see Fig. 2). Two of the cells are filled with graphite, and the thermocouples are installed under the cylinder cells. The temperature difference between the graphite cell and the empty cell provides a measure of the nuclear heat deposition in the graphite.

The additional shielding plate, SS304 (thickness 1.1 cm), was inserted into the large cooling water channel of the irradiation facility to study the shield effect of γ-rays from the reactor core. Several axial positions were measured to test the axial distribution of gamma heating in the irradiation facility.

3. TRIPOLI-4 Monte Carlo code and research reactor heat deposition calculation

The TRIPOLI-4 Monte Carlo transport code, developed at CEA-Saclay, has been extensively used in the reactor core physics, criticality safety and radiation shielding calculations. Its lattice geometry is very helpful to define the repeated reactor core structure [5]. With continuous-energy library, the self-shielding calculations of radiative capture reaction are not necessary. The biasing techniques and the parallel calculation capability [6] of TRIPOLI-4 are indispensable to reduce the waiting time in coupled (n,γ) calculations.

With the powerful geometry package, the OSIRIS reactor core was exactly described with the TRIPOLI-4 code so as to take into account the water layers between fuel plates, the cooling channels in the fuel rack and the annular channels of the reactor tank. (Fig. 2). The configuration of the ex-core irradiation facility and the measurement device were also described in detail using the combinative and the analytical geometry options of the TRIPOLI-4 code. Since the measurements were realized on the middle level of fuel meat to obtain the maximum axial gamma heating, only reactor tank and pool water were considered in TRIPOLI-4 model for the upper and the lower parts of the reactor core.

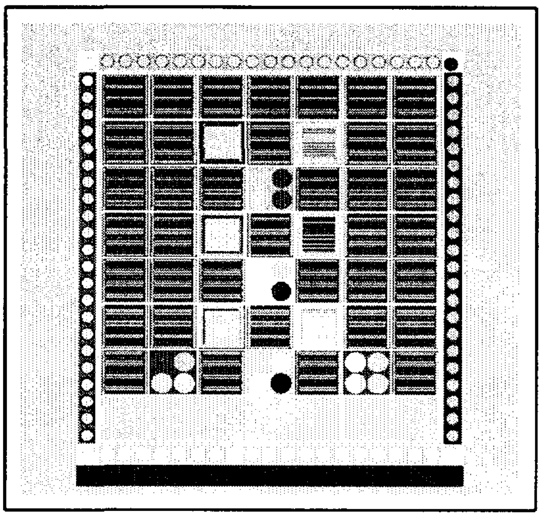

Fig. 1 OSIRIS reactor core, reactor tank and beryllium reflector configurations. (Drawing from the TRIPOLI-4 input)

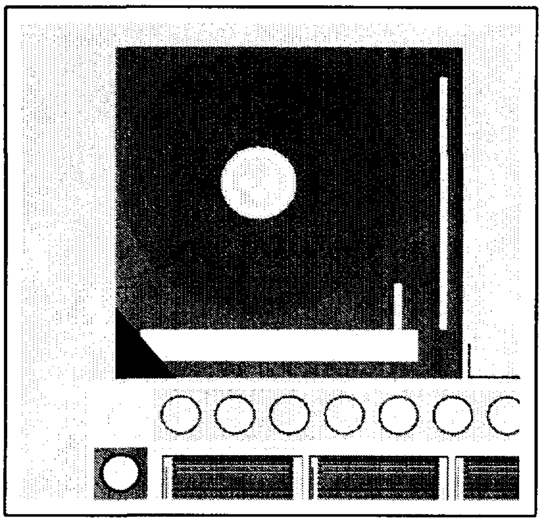

Fig. 2 Irradiation facility and calorimetric apparatus settled in ex-core water pool. (Drawing from the TRIPOLI-4 input)

The full core power map in the TRIPOLI-4 transport calculations was prepared by the diffusion code DAIXY using the loading data of the operation cycle F164. The gradient of the neutron source emitted from the fuel meat in the northwest corner was considered in detail in related fuel elements. Taking into account the perturbation, from the pool water and the irradiation facility, on the local power distribution is important for the present study because of the experiment positions.

Due to variation of operating power during experiments, the neutron source intensity in the TRIPOLI-4 calculations was determined by assuming a fixed power of 65 MWth, 200 MeV and 2.432 neutrons per fission. The DARWIN burnup code [7] was used to generate the gamma source of fission product decay γ-rays and a burnup of 90,000 MWd/t was applied to obtain the intensity and the energy spectra.

Biasing techniques were performed in TRIPOLI-4 coupled (n,γ) calculations to speed up the simulation of neutrons and γ-rays transport. It was necessary but delicate to carry out the biasing parameters for these two particles in the coupling calculation. A compromise should be taken so as to avoid over biasing neutron transport and to obtain converged results for γ-rays. The automatic multi-group INIPOND biasing scheme was helpful for the reactor core and pool zones, and the local biasing using the 'window' option was needful for the zone containing irradiation facility and calorimeter.

Considering the various temperatures of the reactor core, reactor tank and cooling waters, a specific continuous-energy library was prepared in order to obtain the correct capture γ-rays from coupled (n,γ) simulation. Since the temperature distribution in the irradiation facility was not available, an estimated one has been chosen. To simplify the compositions data in TRIPOLI-4 simulation, the fresh fuel was taken all over the reactor core, the nickel absorber in fuel plates was neglected and the hafnium control plates in control elements were removed.

In the four small cylinder cells of the calorimeter, neutron and gamma fluxes were calculated by the TRIPOLI-4 code. Using the kerma factor of graphite, the conversion to heat deposition was done [8]. Parallel calculations of TRIPOLI-4 were run with a cluster of workstations. For a typical coupled (n,γ) calculation, 12 SUN ultra-1 workstations during 14 hours were necessary to produce acceptable converged results in the small volumes of the cylinder cells.

For heat deposition evaluation, different TRIPOLI-4 calculations were realized to obtain the following contributions: prompt fission γ-rays, secondary γ-rays (capture γ-rays and inelastic γ-rays), fission product decay γ-rays and prompt fission neutrons. The heat deposition from activation γ-rays and associated beta particles are not treated in the present study but further investigations concerning these contributions from the major reactor structure materials and impurities are currently in progress.

4. Validation results and discussions

The heat deposition results of this study are presented in Table 1. Both measured and calculated values are normalized to 65 MWth. Two axial irradiation positions were presented: the first one is in the middle level (PM) of the fuel meat and the other one 10 cm lower. Both are located in the central water zone of the irradiation facility (Fig. 2). Dimensions of the shield SS304 are: 16.4 x 1.1 x 80 cm. Two types of results from TRIPOLI-4 calculations are given in Table 1: the upper one shows the maximum value obtained from the four small cylinders of calorimeter and the lower one the average of the four.

Actually the calculation results are about 15% smaller than the calorimetric measurements. The standard deviation of the TRIPOLI-4 Monte Carlo calculations is around 3% and the uncertainty of the measurement results is about 7%. The additional shielding inserted in the large water channel of the irradiation facility allows to reduce about 12% of gamma heating and the axial variations are similar between the calculated results and the measured values.

Table 1 Comparisons of heat deposition (W/g $_{\text{graphite}}$) between calorimetric experiment and TRIPOLI-4 calculation (OSIRIS normalized power: 65 MWth)

Position	Additional shielding	Experiment (calorimeter)	Calculation (TRIPOLI-4)	Ratio Cal. / Exp.
PM	water	0.508	0.444	0.87
			0.423	0.83
PM	SS304	0.460	0.393	0.85
			0.371	0.81
PM-10 cm	SS304	0.426	0.370	0.87
			0.358	0.84

Table 2 presents different contributions of heat deposition calculated by the TRIPOLI-4 code. Prompt fission neutrons contribute less than 5% of the total. Because the γ-rays energy spectra of fission products are relatively soft comparing with those of capture γ-rays and prompt fission γ-rays, the last two types of γ-rays contribute for about 75-80% of the total heat deposition. This is why the additional shielding is more effective to attenuate γ-rays from fission products. In fact, from the isolated evaluation of prompt fission γ-rays contribution and the calculated γ-rays spectra in calorimeter, the capture γ-rays contribute for about 50-60% of the total result and they are emitted not only from the reactor core but also from the pool water (E_γ: 2.2 MeV from hydrogen) and the irradiation facility (E_γ: 7.6 and 9.3 MeV from iron).

Table 2 Calculation determinated heat deposition from different γ-rays and fast neutrons (OSIRIS normalized power: 65 MWth)

Position	Add. Shielding	γ-rays		Neutrons	Total
		capture + prompt fission	fission products	prompt fission	(W/g $_{\text{graphite}}$)
PM	Water	0.342	0.081	0.021	0.444
PM	SS304	0.311	0.061	0.021	0.393
PM-10	SS304	0.293	0.056	0.021	0.370

To improve the future TRIPOLI-4 calculations, a power map considering all the perturbations from in-core and ex-core experiments will be helpful. The full core power map with a smaller mesh size and the fissile composition with burnup consideration in TRIPOLI-4 input could be useful to make better calculations. Finally, it is also interesting to investigate the activation γ-rays from reactor structure materials and to study the uncertainty of the calorimetric measurements.

5. Conclusions

This paper presents a recently developed gamma heating calculation methodology and its validation results for research reactor applications. Based on the TRIPOLI-4 Monte Carlo code, under the continuous-energy option and the plate-by-plate full core model, the coupled (n,γ) calculations were applied on the OSIRIS reactor to evaluate the nuclear heat deposition within a large ex-core irradiation facility.

Compared with the calorimetric measurements, the calculation results based on TRIPOLI-4 code are satisfactory. Results of this new calculation methodology could be eventually improved by considering the optimal power map preparation and the contribution from activation γ-rays, and computer CPU time by optimizing the biasing parameters in both neutrons and γ-rays transport [9].

The TRIPOLI-4 Monte Carlo code has been applied on several operational research reactors (ORPHEE, RHF, EOLE and CABRI) and new reactors design (RJH project [1] and ANSTO-RRRP bid) for reactor physics and radiation shielding calculations. The present gamma heating calculation methodology will be applied on RJH project to obtain the in-core and ex-core nuclear heat deposition map. Other applications of this calculation methodology include the new neutron sources design and the performance evaluation for cold and hot neutrons generations.

6. Acknowledgements

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