Nuclear Instruments and Methods in Physics Research A 799 (2015) 17–24

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

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

Parametric study of the energy deposition inside the calorimeter measuring the nuclear heating in Material Testing Reactors

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ARTICLE INFO

Article history:
Received 19 December 2014
Received in revised form
2 March 2015
Accepted 20 July 2015
Available online 29 July 2015

Keywords:
MTR reactors
Nuclear heating
Energy deposition
Differential calorimeter
MCNP5 Monte-Carlo Code

ABSTRACT

The nuclear heating measurements in Material Testing Reactors (MTRs) are crucial for the study of nuclear materials and fuels under irradiation. The reference measurements of this nuclear heating are especially performed by a differential calorimeter including a graphite sample material and two calorimetric cells. Then these measurements are used for other experimental conditions in order to predict the nuclear heating and thermal conditions induced in the irradiation devices.

This paper will present simulations with MCNP5 Monte-Carlo transport code (using ENDF/B-VI nuclear data library) to evaluate the nuclear heating inside the calorimeter during irradiation campaigns of the CARMEN-1P mock-up inside OSIRIS reactor periphery (MTR based on Saclay, France). The whole complete geometry of the sensor has been considered. The calculation method corresponds to a calculation in two steps. Consequently, we used as an input source in the model, the neutron and photon spectra calculated in various experimental locations tested during the irradiation campaign (H9, H10, H11, D9). After a description of the differential calorimeter sensor, the MCNP5 model used for the calculations of nuclear heating inside the calorimeter elements is introduced by two quantities: KERMA and energy deposition rate per mass unit. The Charged Particle Equilibrium (CPE) inside the calorimeter elements is studied. The contribution of prompt gamma and neutron is determined. A comparison between this total nuclear heating calculation and the experimental results in a graphite sample will be made. Then parametric studies performed on the influence of the various calorimeter components on the nuclear heating are presented and discussed. The studies of the influence of the nature of materials, the sensor jacket, the source type and the comparison of the results obtained for the two calorimetric cells leads to some proposals for the sensor improvement.

1. Introduction

Nuclear heating measurements in Material Testing Reactors (MTRs) are crucial for the experimental devices and the prediction of the temperature of the hosted samples [1,2]. Indeed, nuclear heating (usually expressed in W/g) can be described as the rate of energy thermally released in one gram of matter subjected to a nuclear radiation flux, and corresponds to the increased of the thermal agitation of the electrons inside the irradiated material leading thus to a temperature increasing. Nuclear heating inside materials located into MTRs outside the nuclear fuel locations is mainly due to the energy deposition induced by the photons (majority contribution) and neutrons (minority contribution). The emitted photons and neutrons interact with matter and produce a flux of charged particles which gradually decreases locally until thermal equilibrium is reached.

Nuclear heating is a great deal of interest at present in particular because a MTR with new experimental conditions and experimental possibilities is under construction at CEA/Cadarache “French Alternative Energies and Atomic Energy Commission”: Jules Horowitz Reactor (operational in late 2019). Indeed its expected nuclear heating rate will be higher than the value in European Reactor. It will be about 20 W/g for a nominal power of 100 MW [1], against for instance 13 W/g in the irradiation OSIRIS MTR reactor (CEA/Saclay Center) for a nominal power of 70 MW [2].

To improve the qualification of the nuclear heating inside experimental channels of the JHR reactor, a research program between CEA and the University of Aix-Marseille, called IN-CORE “Instrumentation for Nuclear radiation and Calorimetry On line in REactor”, started in 2009. This program has a dual objective. The first objective concerns the design of a new multi-sensor device (CARMEN, [3]) dedicated to measuring the axial profiles of experimental conditions inside JHR's

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http://dx.doi.org/10.1016/j.nima.2015.07.042
0168-9002/

experimental channels such as neutron and photon fluxes, and obviously nuclear heating. The second objective is to improve the measurement method used to quantify nuclear heating: radiometric differential calorimeter (from the sensor to its calibration). The first prototype of the multi-sensor device was already developed and tested successfully during two irradiation campaigns in the OSIRIS periphery in 2012 for nuclear heating levels up to 2 W/g [1,4]. This prototype included two mock-ups dedicated respectively to neutronic measurements (CARMEN-1N), or photonic measurements (CARMEN-1P). The CARMEN-1P mock-up contained a specific differential calorimeter [5].

The nuclear heating inside calorimeter (single-cell calorimeter or differential calorimeter) can be calculated by various methods. For instance, nuclear heating is often estimated by the KERMA quantity (Kinetic Energy Released per MAss unit) defined as the sum of the initial kinetic energies of all the charged particles liberated by uncharged ionizing radiation [6,7]. The KERMA calculation requires a Monte Carlo calculation by using neutron–photon coupled transport calculation to simulate the total heating (neutron+photon).

The amount of heat deposited in a single-cell calorimeter in the SAFARI-1 reactor is calculated, by using MCNP5 Monte-Carlo transport code, with two methods [7,8]: using the track length estimate of energy deposition (F6 tally) in a neutron–photon coupled mode (mode N P) or using the pulsed height tally (*F8 tally) which gives the energy distribution of pulses created in a detector.

In the OSIRIS reactor two methods to compute nuclear heating are implemented in TRIPOLI-4 code in the case of differential calorimeters composed by four cells or two cells (CALMOS calorimeter). The first one, based on energy balance method, uses the “deposited energy” estimator [9]. At each collision, an energy balance is made to obtain the kinetic energy carried by emitted particles. Charged particles are assumed to stay at the collision location and their energy contributes to the nuclear heating. The second method uses KERMA response functions which also are based on an energy balance but calculated beforehand.

However, the KERMA quantity is representative of the nuclear heating only when the Charged Particle Equilibrium (CPE) is reached and in the case of a system made of a single material. Therefore, another approach to determine the nuclear heating was used in the case of the complex differential calorimeter of CARMEN-1P device [1]. The authors considered another physical parameter which is more representative of nuclear heating: the energy deposition rate per mass by the generated charged particles. The determination of this quantity then requires neutron-photon-electron coupled transport calculations. Preliminary works were carried out with only a simplified geometry of the calorimeter (geometry reduced to the graphite sample). The results showed that the Monte Carlo calculations overestimate the measurements by about 20% [1].

This paper focuses on the estimation of the nuclear heating (prompt photons and neutrons) inside the different parts of the differential calorimeter by considering the complete geometry and by using these two quantities (KERMA and energy deposition rate per mass unit). The MCNP5 transport code [10] was used to calculate these two quantities. They were considered in the case of the irradiations of the differential calorimeter of CARMEN-1P performed in the periphery of OSIRIS reactor. Thus after having detailed the model of nuclear heating, including the complete geometry of the calorimetric cells and their housing, the impact of the thickness and of the type of housing material are determined. A comparison of the two estimated quantities is realized in the case of neutron contribution and photon contribution. A comparison between this total nuclear heating calculation and the experiment results in a graphite sample will be given. Then, the influence of the nature of the sample and of the material composing the sensor body is studied thanks to the energy deposition inside the sample. The results are compared with the current sensor configuration (a sample made of a reference material: graphite and a body made of aluminum (Al5457). Each energy contribution (neutron and photon) is given and discussed. Finally a comparison between the sample calorimetric cell and the reference calorimetric cell is presented.

2. Modeling of nuclear heating inside the calorimeter

This paragraph is dedicated to the description of the modeling of nuclear heating in the differential calorimeter of CARMEN-1P device, which was irradiated in the periphery of the OSIRIS reactor. This modeling is performed by using the MCNP5 transport code using ENDF/B-VI nuclear data library.

2.1. Origin of the nuclear heating and its estimations

Inside a nuclear reactor, a number of particles are generated: neutrons, photons (γ, X…), light charged particles (electron and positron), heavy charged particles (fission fragments, proton, alpha…). Most of the energy deposition in nuclear fuel area comes from the total absorption, of the kinetic recoil energy from fission products, by the atoms and molecules forming the medium. Apart from the fuel elements, the generated radiations – particularly photons, neutrons and light charged particles (beta) – deposit their energy in the matter. The emitted photons and neutrons interact with the material and produce a flux of charged particles which gradually decreases until thermal equilibrium is reached in the material. The successive energy deposits create local heating that induces a temperature increase in the material.

Outside the fuel, nuclear heating of materials has three components:

- Prompt gamma (fission, capture and scattering), which represents the major component. This heating comes primarily from energy deposition during photon–matter interactions by photoelectric effect, Compton scattering, and pair production;
  Delayed gamma, emitted by radioactive decay of fission products. The delayed gamma come from the activated nuclei due to the fission fragments which undergo radioactive decay to produce more gamma photons with a delay from the fission reaction.
- Neutrons, which are minority. They come from the following reactions: elastic and inelastic scattering of neutrons, (n,γ), (n,p) or (n,α) reactions.
  Furthermore, activated nuclei due to the neutron capture undergo radioactive decay to produce more gamma photons and β-particles with a delay from neutron capture. In this study the neutron-activation of the device was not considered.

In the OSIRIS's core, the most part of nuclear heating in graphite inside the four-cell calorimeter is due to the prompt gamma (about 62%), then to the decay-gamma (about 21%) and finally to the neutron contribution which is not negligible (about 17%) [6]. These contributions depend on the sample nature. The nuclear heating due to neutron contribution is almost negligible when the atomic number of material (> graphite atomic number) increases. So in this study the neutron absorbing materials were not considered.

A part of the energy carried by photons and neutrons are transferred via interactions to charged particles. The transferred energy per mass unit of all charged particles, in the form of kinetic energy, corresponds to the quantity KERMA. Moreover, the generated charged particles (electrons) deposit their energy in the medium: this energy deposition per mass unit corresponds to the absorbed dose.