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State of the art on nuclear heating in a mixed (n/γ) field in research reactors

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ABSTRACT

This article aims at inventorying the knowledge on nuclear heating measurements in a mixed (n,γ) field in low-power research reactors using ThermoLuminescent Detectors (TLDs), Optically Stimulated Luminescent Detectors (OSLDs) and Ionization Chambers. The difficulty in measuring a mixed (n,γ) field in a reactor configuration lies in quantifying the contribution of the gamma photons and neutrons to the full signal measured by these detectors. The algorithms and experimental protocols developed together with the calculation methods used to assess the contribution of the neutron dose to the total integrated dose as measured by these detectors will be described in this article. This 'inventory' will be used to summarize the best methods to be used in relation to the requirements.

1. Introduction

Nuclear heating in nuclear reactors is arousing a great deal of interest at the moment as the measurement of such heating is an important issue for research reactors. These measurements form databases which are used to qualify and/or experimentally validate current and future calculation sheets, for example for the future technological irradiation reactor called the Jules Horowitz Reactor (JHR) [1] which is currently being built at the French Atomic Energy and Alternative Energies Commission/Cadarache Center, or the Generation IV prototype reactor called ASTRID [2] which is currently in its conceptual design phase. This qualification and/or validation are usually carried out in low-power reactors for which the measurement conditions are perfectly mastered (good knowledge of geometry, material compositions, irradiation conditions…). Nuclear heating is a key parameter in providing an optimal design for nuclear reactor cooling systems, and in predicting the irradiation conditions in experimental devices designed to carry samples for investigation under nuclear radiation [3]. Most of the heating in the fuel results from the total absorption of the kinetic recoil energy from fission products. The radiation exiting the fuel – such as gamma photons and neutrons – is responsible for nuclear heating outside the fuel.

The maximum nuclear heating rate expected in the future JHR reactor is $20\,\mathrm{W\,g^{-1}}$, which is well above the $13\,\mathrm{W\,g^{-1}}$ currently reached in the OSIRIS irradiation reactor at the CEA/Saclay Center [4]. This level of nuclear heating rate should be compared with measurements performed in critical mock-up reactors of very low power, such as MINERVE and EOLE at the CEA/Cadarache Center, where nuclear heating amounts to anything from 10^{-7} to $10^{-6}\,\mathrm{W\,g^{-1}}$ [5,6]. The energy in Zero-Power Reactors (ZPRs) is insufficient to raise the temperature, which renders calorimetric measurements impossible [4,7]. Nuclear heating is determined via measurements of the deposited energy per unit of mass (absorbed dose expressed in grays) in the different materials under investigation. The deposited energy is the quantity that can be accessed both by measurement and by calculation, and is sufficiently representative of nuclear heating. In order to measure the deposited energy of photon and neutron rays in a medium, a detector that is sensitive to such radiation needs to be employed. Generally speaking, the detecting material is not necessarily made of the same material as the medium into which it is inserted. These detectors are very small to avoid disturbing the medium in which the measurements are to be recorded, such as post-irradiation measurements by Thermoluminescent Detectors (TLDs), Optically Stimulated Luminescent Detectors (OSLDs) and online measurements by ionization chambers.

The measurement of the gamma energy deposited in a mixed (n,γ) field in a reactor poses a number of serious difficulties owing to the sensitivity of most detectors, especially to thermal neutrons [8]. For this reason, the signal issued by these detectors can be interpreted as resulting from the sum of three terms, corresponding to the total gamma energy deposited (prompt+delayed) to

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be measured, the contribution of thermal neutrons, and the contribution of both epithermal and fast neutrons respectively. The difficulty lies in differentiating between the contributions of neutrons and photons within the integrated signal measured in a reactor environment.

This article aims at providing a state-of-the-art summary on the problem of measuring gamma heating in a mixed (n,γ) field in research reactors, particularly by means of TLDs, OSLDs and ionization chambers. Firstly, the different techniques used to measure the gamma energy deposited in the reactor are described (Part II). Secondly, an inventory of the different experiments performed in a reactor environment across the world and especially at the CEA/Cadarache Center is given (Part III). Thirdly, the detection methods used to separate neutron contributions from the integrated signal are detailed (Part IV). Finally, the inventory in the fourth section will help to provide a summary of the best method to be used in relation to requirements (Part V).

2. Principle of nuclear heating measurements in experimental reactors

Nuclear heating can be described as the thermal energy released in a material having been subjected to a nuclear radiation flux, which corresponds to the increased thermal agitation of the electrons comprising the material and thus a temperature increase in the material. The quantity of energy dissipated in a reactor core varies and depends on the location of interaction, the type of interaction, the type of incident radiation and the type of target medium. Most of the energy deposited in nuclear fuel results 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 radiation exiting the fuel – particularly photons (γ or X), neutrons and light charged particles (beta) – deposits its energy in the material. The emitted photons and neutrons interact with the material and produce a flux of charged particles that gradually slow down until thermal equilibrium is reached in the material. When charged-particle equilibrium is reached in the medium, the Kinetic Energy Released in Materials (KERMA) quantities and the absorbed dose are equal. A medium is said to be in charged-particle equilibrium when a charged particle with a certain energy level and of a certain type exits the volume for every incoming charged particle with the same energy and of the same type.

Nuclear heating is determined via measurements of the deposited energy per unit of mass in the different materials under investigation. The absorbed energy is the quantity that can be accessed both by measurement and by calculation, and it is sufficiently representative of nuclear heating. In order to measure the absorbed dose of nuclear radiation in a medium, a detector that is sensitive to such radiation needs to be employed. Generally, the detector material is not necessarily the same material as the medium in which it is placed, the ideal solution is a detector with a similar composition to that of the medium under investigation. The means for measuring the absorbed dose in reactors can be divided into two categories:

- Passive detectors, operating on the principle of thermoluminescence (TLDs), optically stimulated photoluminescence (OSLDs) and radio-photoluminescence (RPL).
- Active detectors, such as counters comprising an electrically polarized chamber and filled with a gas, or optical-fiber detectors based on OSL.

The phenomenon of luminescence can be explained by the imperfect crystal structure which always contains a high level of defects – whether fabrication defects or defects due to the presence of foreign atoms in the basic chemical composition (impurities) – which result in intermediary energy levels situated between the valence band and the crystal conduction band. During the irradiation of TLDs/OSLDs, some of the deposited energy is stored in the detector by the creation of electron/hole pairs at different levels (see Fig. 1(a)).

If additional stimulation is applied after irradiation, the trapped electrons are released and a quantity of light is emitted. This stimulation can be either thermal (e.g. TLDs) or optical (e.g. OSLDs). The heating of the TLD in the readout chamber leads to the recombination of the electron/hole pairs and the emission of light (see Fig. 1(b)).

This light emission is proportional to the radiation energy deposited in the detector and is measured by the photomultiplier tube in the readout chamber whose operating principle is illustrated in Fig. 2.

Two parameters contribute to the trap emptying of the TLD: the heating temperature and the readout time. Most modern readers use the pre-heating plateau method developed by PORTAL [9] at the CEA in 1965. Problems occur because the sensitivity of TLDs greatly depends on the experimental conditions such as the heating laws, the annealing procedures (resetting), the energy and the type of incident radiation. Ref. [10] details the detector principle based on thermoluminescence.

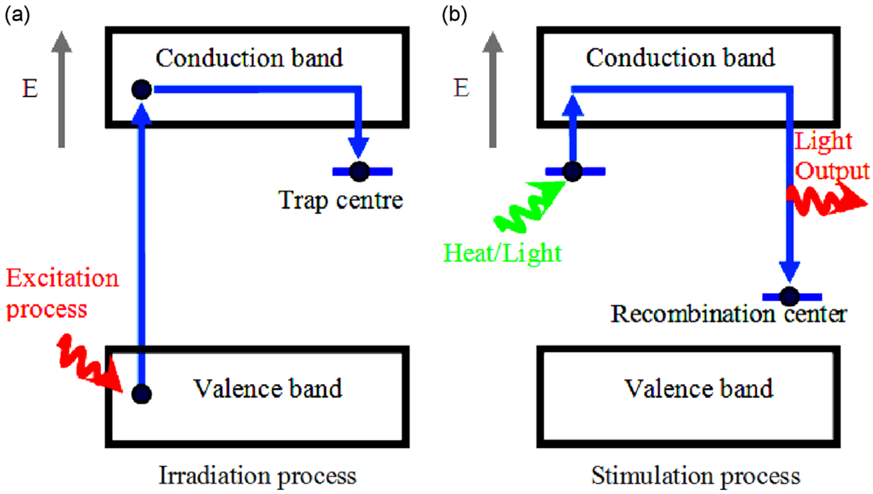

Fig. 1. Simplified diagram of the TL and OSL processes. (a) Irradiation process and (b) Stimulation process.