Assessment of Irradiation Performance in the Jules Horowitz Reactor (JHR) using the CARMEN Measuring Device

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Abstract—**The development of the JHR experimental devices rely on the operational feedback from previous French material testing reactors (i.e. SILOE and OSIRIS). The experimental devices used for the irradiation of structural material were already facing technological limitations, in particular regarding the control of irradiation temperature and of the thermal gradients in the experimental samples, which is essential to ensure the quality of the experiments. Obtaining satisfactory thermal fields (in compliance with the setpoint and the homogeneity) is all the more difficult as the level of nuclear heating is higher in the JHR. This paper attempts to characterize the irradiation conditions in different experimental positions of the JHR and to compare them with the conditions and the empirical criteria of maximum acceptable temperature measured in OSIRIS. The study shows that the irradiation conditions obtained inside the experimental devices can sometimes be significantly different from the measured conditions using instrumentation devices. The interpretation of the experimental results and their transposition to other situations will always require a calculation versus measurement adjustment and the intensive use of computer simulation. However, despite all simulation and transposition efforts, the control of temperature conditions is not yet fully demonstrated and nothing will ultimately replace experimental validation.**

Keywords —**Material Test Reactor (MTR), differential calorimeter, experimental devices, Reactor Pressure Vessel (RPV).**

I. Introduction

The Jules Horowitz Reactor (JHR) is a Material Test Reactor currently under construction at Cadarache. It will serve to conduct experiments for the qualification of materials under irradiation and to produce radioisotopes for medical applications [1][2]. The material testing experiments require accurate monitoring of the irradiation conditions in terms of neutron flux (level and spectrum) and nuclear heating. A key aspect is to regulate the temperature level and to get uniform temperature distributions (absence of gradients) in the material samples during the irradiation. These requirements ensure the quality of the experiments and therefore contribute to the value of the irradiation service to future JHR clients.

CARMEN is a multi-detector measuring device that will provide a comprehensive characterization of the radiation field in the experimental channels of the JHR. The measurements performed with this device can serve as a preliminary assessment of unperturbed irradiation conditions, before the introduction of the real experimental device at that location. The present study aims at reproducing the CARMEN measurements by simulation and connecting them to the irradiation conditions expected inside the MICA and the OCCITANE test devices - which are respectively devoted to in-core and out-core experiments for the irradiation of steel materials.

Section 2 presents the MICA and the OCCITANE test devices for structural material irradiation in the JHR. Section 3 presents the CARMEN measuring device. Section 4 examines modelling aspects for nuclear heating measurements with a differential calorimeter. In section 5, the study evaluates the transfer function between the CARMEN measurements (unperturbed conditions) and the actual nuclear heating inside test devices (perturbed conditions). Finally, section 6 attempts to integrate the feedback from the IRMA test device operation in the OSIRIS reactor.

II. The Experimental Devices for the Irradiation of Structural Materials in the JHR Reactor

A. The MICA test device

The MICA test device provides irradiation capabilities to study the structural material aging at high dpa-rates. There are

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ten in-core positions available to host this device: seven small channels located inside the fuel elements, and three large channels that could receive either a large irradiation device or an additional fuel element (see Fig. 1). Design studies and development of these devices rely on accurate nuclear heating calculations thanks to the experimental validation programs conducted in zero power reactors [3].

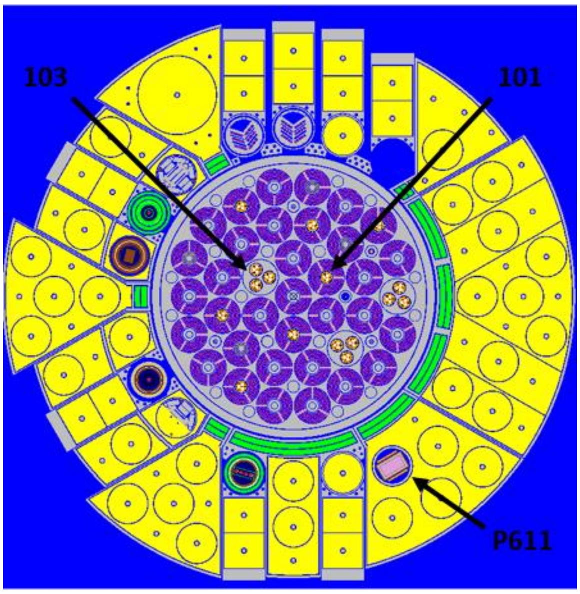

Fig. 1. Radial layout of the JHR reactor core model with TRIPOLI-4®.

As illustrated in Fig. 2, the MICA test device is inserted in the central axis of a fuel element. The material samples are loaded in a sample holder in the centre of the MICA device. The inner stainless steel tube of 24 mm in diameter limits the available space for the samples, which are immersed in static NaK eutectic. The good thermal conductivity of this liquid metal ensures optimal cooling and homogeneous thermal distribution in the samples. Surrounding the inner tube, some electric heating elements are embedded in order to reach and to regulate the setpoint temperature in the experimental zone. They allow flattening of the axial temperature gradients imposed by the axial nuclear heating profile. Several thermocouples are monitoring online temperatures while specific dosimeters are dedicated to evaluate, after irradiation, the integrated fast neutron fluence.

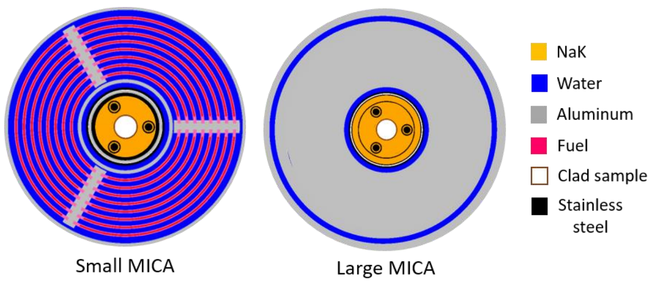

Fig. 2. The MICA test device.

B. The OCCITANE test device

The OCCITANE is a capsule-type experimental device used to study the accelerated aging and embrittlement of structural materials under irradiation, with the aim of anticipating the service life of steel vessels in Light Water Reactors. The RPV (Reactor Pressure Vessel) steel samples should be irradiated at low damage rate of about 1 mdpa per EFPD (Equivalent Full Power Day) to reach a total of 0.1 or 0.2 dpa (i.e. it takes about one year to reproduce the damage cumulated during 40 years in a standard NPP). Hence, the OCCITANE will be located outside the core, at position P611 (see Fig. 1), in the first row of JHR reflector. Independently of the neutron spectrum and nuclear heating imposed by the JHR, the test device must make it possible, if needed, to modify the irradiation conditions in the studied material samples. An important requirement is to be able to adapt the neutron spectrum and to regulate the internal temperature to cover the widest experimental field. Thus, the OCCITANE test device must meet the following specifications:

- A fast neutron flux in the range of $3{\cdot}10^{12} \leq \varphi_{\,>1\,\mathrm{MeV}} \leq 5{\cdot}10^{12}\ \mathrm{n{\cdot}cm^{-2}{\cdot}s^{-1}}$;
- A homogeneous temperature distribution regulated between 260°C and 330°C;
- A neutron spectrum ratio, denoted as Rs (see the forthcoming definition below), lying between $2.3 \leq Rs \leq 2.5$.

The neutron spectrum transitions observed between internal and external walls of a RPV are often characterized by a physical quantity defined as the spectrum ratio: $Rs = \Phi\,(E > 0.1\ \mathrm{MeV}) / \Phi\,(E > 1\ \mathrm{MeV})$, varying in the range of 2.4 at the inner wall, up to 8 at the outer wall [4]. In connection with experimental data from the irradiation programs previously carried out in the OSIRIS reactor, the test device must be able to reproduce a subset of irradiation conditions identical to those of the IRMA capsule in OSIRIS reflector, offering a spectrum ratio close to 2.4. However, it is also desirable to propose extended spectral tailoring capabilities, to be able to increase the spectrum ratio up to Rs = 8, if needed.

The experimental zone, covering a surface area of 30 x 60 mm², can host an arrangement of various type of samples (creep, tensile, Charpy and microstructure specimens) stacked on top of each other, on 60 cm height corresponding to the fissile column of the core. The axial damage gradient follows the fast neutron flux profile (see Fig. 5). Between each cycle, the sample holder is rotated by an angle of 180° to azimuthally homogenise the neutron fluence in the experimental samples.

In order to control the irradiation temperature with homogeneous distribution, it is necessary to regulate with electric heating elements and to provide thermal insulation of the furnace, meanwhile reducing the nuclear heating in the experimental zone. Therefore, two screens are embedded in the device and optimized for that purpose (see Fig. 3):

- A flat tungsten screen of variable thickness, placed against the sample holder, to attenuate the gamma rays coming directly from the core;
- A cylindrical neutron screen of variable thickness attached to the outer refrigeration tube, made of boron carbide to absorb thermal neutrons.