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EXPERIMENTAL MATERIAL IRRADIATION IN THE JULES HOROWITZ REACTOR

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ABSTRACT

The Jules Horowitz Reactor (JHR) will provide test capabilities to study the behaviour of material under irradiation for the benefit of existing nuclear plants (life time extension, internal components behaviour, fuel cladding optimisation) as well as for the development of structural and fuel material necessary to implement future reactors.

Beside conventional rigs which will be needed to irradiate large quantities of samples, there will be a strong emphasis in the JHR on highly instrumented rigs in which the irradiation parameters will be controlled in order to get deep insight information to improve prediction capabilities through numerical modelling. As usual, temperature and flux have to be determined accurately, and should be homogeneous through the test sample, but there is also a need to control and measure externally applied stresses and strains in situ during neutron irradiation. These data are essential in order to derive predictive models on the behaviour of materials under irradiation.

This paper will focus on the development of irradiations rigs dedicated to material studies under high neutron flux, representative of the conditions encountered in the core of nuclear power plants. Several rig designs will be presented which are dedicated to studies of tubular samples used for fuel cladding in light water reactors. Basic design requirements for these rigs have been the ability to apply controlled uniaxial and/or biaxial load and to measure axial and/or radial strains under neutron irradiation. Besides the scientific prospects given by such rigs, these ambitious experiments have also the purpose to stretch the demands on the reactor design.

Keywords: JHR, Material Testing Reactor, material experimental irradiations, sodium/potassium,

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1.INTRODUCTION

Nuclear energy will play an important role in the energetic mix since it contributes to limit energy supply dependence and greenhouse gas production.
Existing nuclear plants will follow a long-term trend driven by the plant life extension and management, reinforcement of the safety, waste and resources management, flexibility and economics improvement.
In addition to extending performance and safety of existing and coming plants, R&D programs are taking place in order to assess and develop new reactor concepts.
In depth technical assessments will be required both for optimising existing and coming plants and for validating new reactor concepts. Industry and safety bodies need to have access to experimental capabilities and technical expertise since qualified knowledge is needed for predicting lifetime of structural component, for improving fuel management and reactor operation, and for developing new fuels and material. The Jules Horowitz Reactor (JHR) [[1]] will offer modern irradiation experimental capabilities for studying material and fuel performance under irradiation in order to meet industrial and safety needs related to the current and next generation power reactors.
JHR engineering team are developing irradiation rigs to obtain high performances and to accommodate numerous specimens, fluence monitors and thermocouples in limited available space.
Among other rigs, the so-called “M3” device address tests of few material samples under high flux, with severe temperature requirements and on line mechanical and irradiation parameters control. Samples holders are developed in the frame of a coordinated action from the 6th European Framework program.
Besides its own interest as a state of art experimental device, M3 design also challenges the reactor dimensioning.

2.IN-PILE MATERIAL TEST DEVICE

The in-pile M3 test device is a stainless steel double-wall rig with a controlled gas gap. This generic rig could host different types of sample holders designed for each specific experiment.

The sample holder geometry depends on the type and number of samples to be irradiated. It holds also the experimental instrumentation such as thermocouples, neutron dosimeters, pressure sensors, strain gauges, displacement transducers, etc …

An important requirement for these rigs is to control the temperature of the samples as well as to keep the temperature distribution homogeneous. The gamma heating induced by the high neutron flux induces a non homogeneous heating of structures and samples, and therefore the device must have the capacity to correct this inhomogeneous distribution of temperature.

The irradiation rigs for material irradiation will cover a wide range of temperature and environments, but in this paper we will focus on a temperature range from about 280°C to 500°C and liquid NaK as a cooling media.
In this case, the accurate temperature control of the samples is possible by the means of a small in-pile loop of circulating NaK (Figure 1). Indeed, an annular electromagnetic pump (as shown in figure 2) located above the active zone allows the fluid flowing down after being previously pre-heated by the mean of electric heater situated just above the pump. Then after traveling through the active zone around the samples, the fluid is cooled down by a heat

exchanger located at the bottom of the rig. Finally, the fluid returns upwards in the gap between the rig inner wall and the sample holder shell. The dimensions of the electromagnetic pump are reduced to fit in the casing of the device

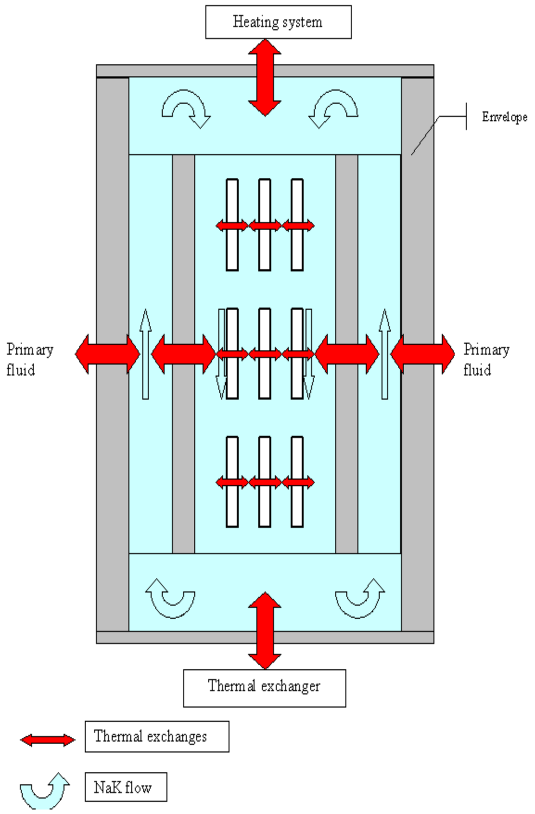


Figure 1 : Schematics of M3 device

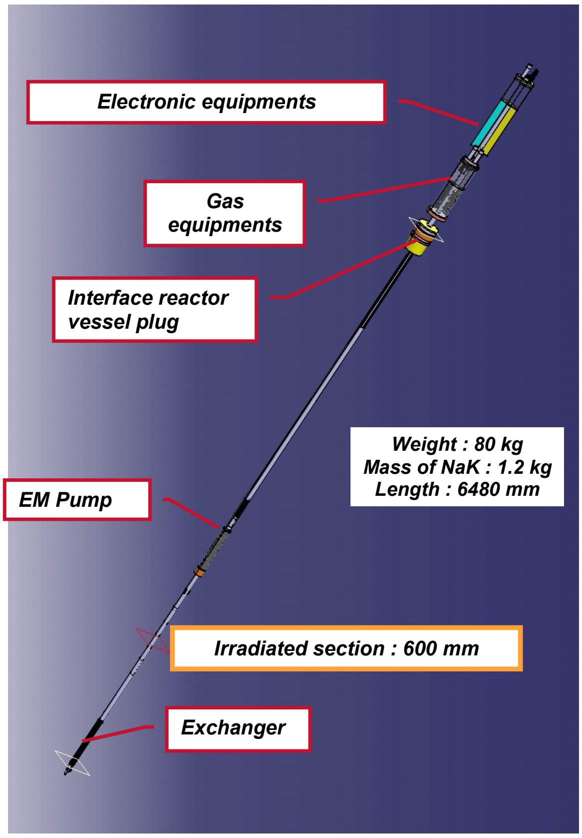


Figure 2 : Schematics of the EM pump

Pressure control systems are designed to avoid the long tubes between in-pile and out-of-pile equipment and to improve flexibility and handling of the test device. However, for special purposes an internal pressure monitoring of samples is still possible by applying a small pressure tube between in-pile and out-of-pile parts.

Concerning the instrumentation signals, there are two processing paths. The usual one, independent wires between in-core sensors and out-of-core data acquisition system, is kept for all the nuclear safety data. For the non-safety sensors technological studies are performed regarding signal processing and specific cable allowing to transport power and measuring signals.

A feasibility study established the capability to implement the on-board electronics above the lid (as shown in figure 3) with small overall dimensions (cylinder of 500 mm height with diameter of 120 mm). The electronics allow to digitize the signal of 50 sensors (35 thermocouples, 5 strain gauges and 10 self-powered neutron detectors), with sealed connections, an operating temperature of 60°C and a level of irradiation estimated at 0.3Sv/h.

The theoretical demonstration is acquired with certain limitations in terms of level of irradiation.
This in-rig electronics reduces the number of cables between the in-core equipment and the out-of-core data acquisition system.

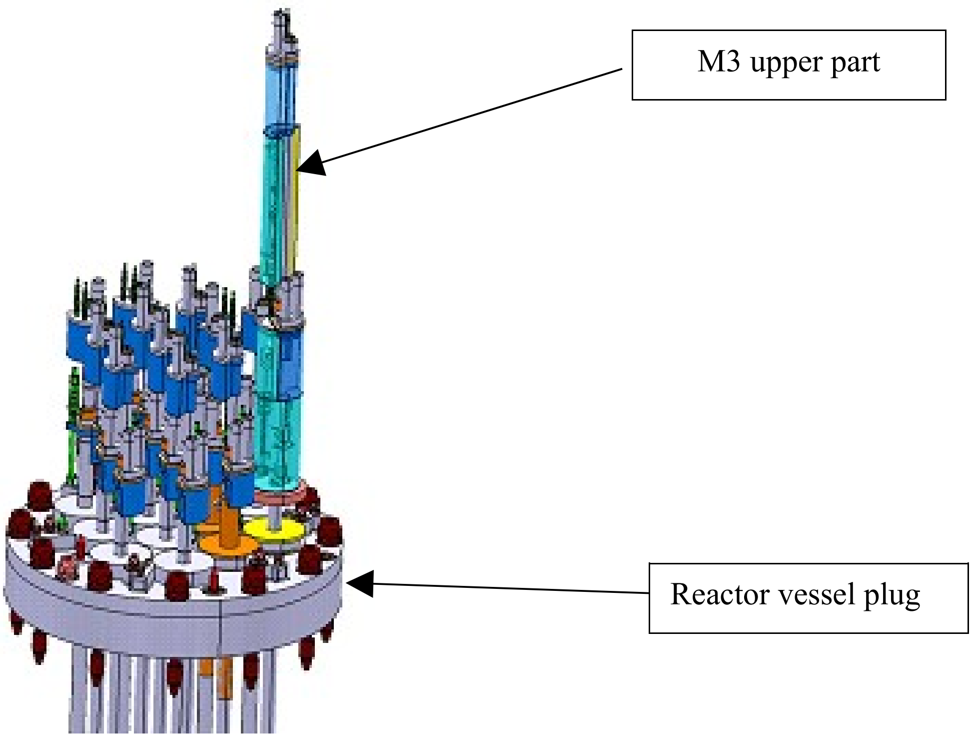


Figure 3: General view of the vessel plug and the top part of the M3 device.

All the experimental parameters are controlled from the reactor control room. Safety parameters are also sent to the reactor control room and all the safety actions are automatic.
The M3 test device is designed to improve rig handling between each reactor cycle and hot cell operations. The integrated systems used for gas control, fluid circulation and signal processing are optimized to reduce dimensions of the upper part of the device.

The safety approach of the M3 test device is consistent with the safety rules applied to the reactor.
The major safety concern is the liquid NaK circulation inside the experimental device. In order to prevent interaction between liquid NaK and the water of the reactor primary circuit, , the double barrier should be classified as a containment barrier with specific quality requirements.

Besides, the device should be also classified on the point of view of safety for the reactor reactivity increase in case of ejection. To avoid this risk a double anti-liftoff system is foreseen.

3.MAIN CHARACTERISTICS OF JHR IN-CORE TESTS

In the following, the main characteristics are presented assuming a basic sample holder. More complex sample holders can be implemented.

The in-core test channel geometry is given in the table below:

	Available space
Diameter	25 mm
Active length	600 mm

The experimental conditions are summarized in the following table:

	Irradiation conditions	Comments
Location	In-core in the highest neutron flux	Several positions available.
Gamma heating	10 to 20 W/g (steel)	Depending on in-core location
Fast neutron flux (> 1 MeV)	2.5 10^{14} to 5 10^{14} n.cm^{-2}.s^{-1}	Depending on in-core location (16 dpa/y on steel at the max.)
Thermal neutron flux	~2.5 10^{14} n.cm^{-2}.s^{-1}	Depending on in-core location
Type of cooling fluid	NaK	Alternative coolants are possible
Cooling /heating	EM pump - Flow rate range : 2 m^3/h	
Nominal temperature	Up to 600 °C	
Maximum temperature discrepancy over sample arrangement	7.5 °C Controlled by electrical heater and heat exchanger with reactor circuit	Within a reactor power variation of ±10 % around nominal value
Maximum heat exchange	50 kW	
Gas blanket	Argon, 2 bar	Other gas possible
Thermal gap filling gas	He, 4 bar	Other gas possible

4.EXEMPLE OF A SPECIFIC SAMPLE HOLDER FOR CONTROLLED BIAXIAL STRESS STATE EXPERIMENTS

4.1.Purpose and motivations

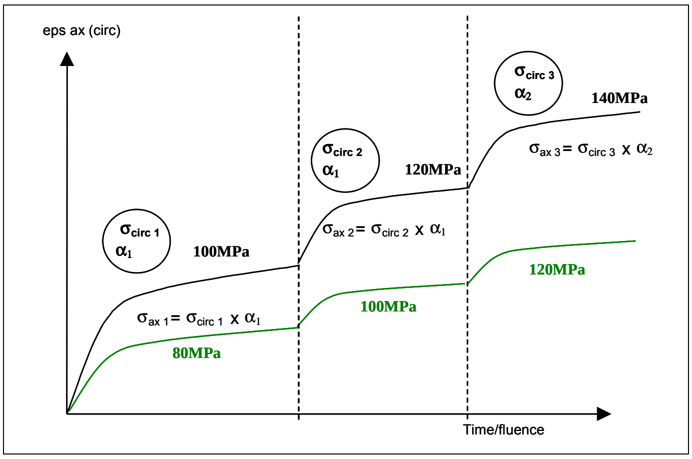
There is a need for an experimental tool to study the anisotropy of the mechanical behavior of textured materials, such as cladding tubes of PWR, under irradiation. For this purpose a specific sample holder to be used in the M3 test device is under development. This sample holder allows mechanical testing in controlled biaxial stress conditions. In the past, test devices have been used to study specimen behavior under uniaxial tension [[2], [3]] or under internal pressure [[4], [5]], but there has been no instance of a device capable of applying both loading modes simultaneously.

4.2.Description of a creep experiment with stress increments and control of the biaxiality ratio

The goal is to apply a creep load on tubular specimens with an imposed biaxiality ratio (σ_{ax} / σ_{circ}) and to control both axial and circumferential stresses during irradiation, with or without changing the biaxiality ratio.

- On line measurement of axial and diametral strain of the samples is necessary. If possible, it would be useful to measure the diametral strain at different axial locations.
- There should be a capacity to test simultaneously more than one sample at a time (two or three at least). With constant axial load and internal pressure, we can obtain different stress levels (by using different wall thickness of tube samples) at almost constant biaxiality ratio.
- There should also be a capacity to test one or more unstressed specimen. The interest is dual: it could provide samples to study the effect of pre-irradiation and in pile deformation (growth, swelling) of unstressed specimens.

Creep with stress increments and control of the biaxiality ratio



If several specimens (stressed and unstressed) :
•Different initial stress for same biaxial ratio
•Growth determination
•Effect of material evolution under irradiation (hardening, etc…) : (stress i specimen j = stress i+1 specimen j+1)

Figure 4: Scenario of a creep experiment

An example of the loading scenario that can be imposed to the specimen is given in Figure 4, in which three different steps are applied, with three different circumferential (hoop) stresses and two different biaxiality ratios.
This scenario will enable us to derive the stress dependence of the deformation rate by comparing the two samples (80 MPa for sample A vs 100 MPa for sample B). When the secondary steady state of creep is reached, the stress level is raised: in the second phase, the stress level of sample A is now 100 MPa – by comparing the steady state deformation rate to that of sample B in the first phase will provide information on the irradiation hardening. Changing the biaxiality ratio in the third phase can give access to anisotropy parameters.

4.3.Specifications

In order the derive behavior laws on this type of material, stresses must be known within 1% (even if the demand on the control could be a few %). The device should have the capacity to apply stresses up to 400 MPa.

We would like to be able to vary the biaxial ratio from 0 (pure hoop stress) to +/- infinity (pure axial stress, tension or compression).

In order to derive behaviour laws on these materials, the strain should be known with 10^{-2} accuracy, which, for our sample geometry, implies a sensitivity of 1 µm for the on-line strain measurement.

For a target temperature between 300°C and 400°C, the spatial gradients must remain lower than 5°C and the temperature should be known with a precision of about 1°C. Moreover it is then necessary to have an accurate mapping of the temperature, taking in account that in the JHR the gamma heating can reach a level of about 20 W/g.

4.4.Description of the sample holder

Circumferential stress is controlled by internal pressure and axial stress by pneumatic internal bellows and the ratio between these stresses is the required biaxial ratio (see Figure 5). In the case of in-pile tests, geometrical constraints demand for a “size optimised” solution. The best way to apply a controlled axial load is by using bellows, the sample being in tension or compression, whether the pressure inside the bellow is higher than that of the outside. In order to make this system more compact, the idea of placing the bellows inside the tubular samples emerged.

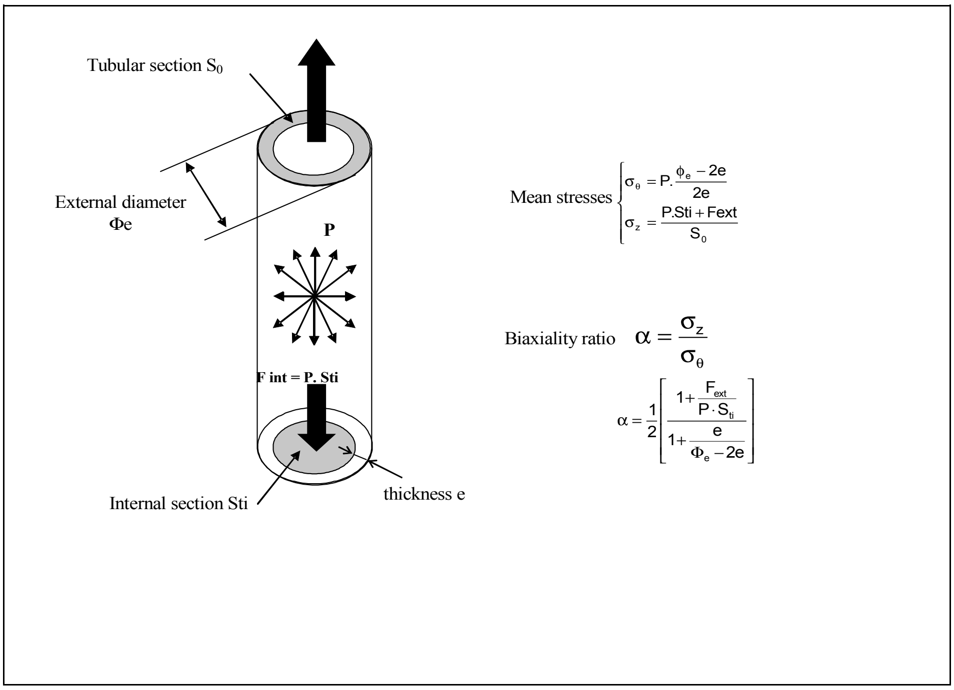
The strain measurements will be performed using a LVDT system for the axial deformation [3]. For the diametral deformation a strain gauge system inspired from that of the Zircimog experiment [4] is considered but with a displacement system in order to measure the diameter in several axial locations. This rig is being developed and will be tested in the coming years in an existing MTR to validate the technical options chosen.

5.CONCLUSION

The Jules Horowitz Reactor experimental capability will offer a wide range of material irradiation devices, meeting both up-to-date scientific and technological state-of-art. The development of this capability is currently in progress, in particular through an European collaboration within the 6th Framework Program.

The M3 in-pile test device was presented with the innovative addition of an electromagnetic pump to ensure good temperature homogeneity throughout the samples.

An example of the specific sample holder is given to illustrate the experimental capability of the JHR facility to carry out highly instrumented material tests under simultaneous irradiation and controlled loading and strain measurements .



$$\begin{cases} \sigma_\theta = P.\frac{\phi_e - 2e}{2e} \\ \sigma_z = \frac{P.Sti + Fext}{S_0} \end{cases}$$

$$\alpha = \frac{\sigma_z}{\sigma_\theta}$$

$$\alpha = \frac{1}{2}\left[\frac{1 + \frac{F_{ext}}{P \cdot S_{ti}}}{1 + \frac{e}{\Phi_e - 2e}}\right]$$

Figure 5 : Biaxial stresses in a tubular sample

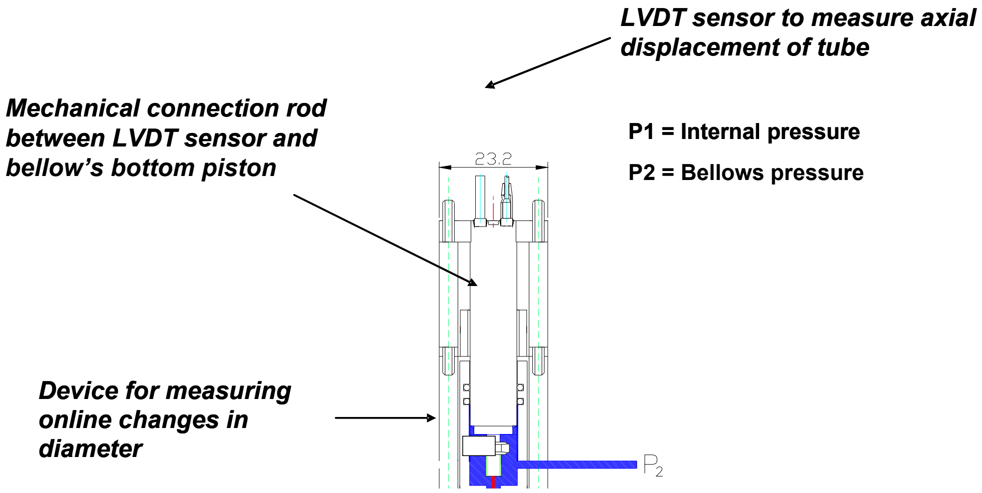


Figure 6: Schematics of the sample holder

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