# Fuel and material irradiation hosting systems in the Jules Horowitz Reactor

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## ABSTRACT

The Jules Horowitz Reactor (JHR) is a high performance Material Testing Reactor under construction in southern France (CEA/Cadarache research centre), that will carry out experimental irradiations for Nuclear Power Plants (NPP) and fuel vendors, utilities, safety organizations and research institutes. Therefore CEA is developing a set of test devices that will be operational for the start up of the reactor or few years later. These experimental hosting systems will have to fulfil experimental needs concerning current NPP technologies (GEN II-III) and future reactors (GEN IV) as well.

Experimental programs could be related to either fuel basis properties acquisition, mastering of margins or improvement of fuel products (clad and pellet), in term of performance, safety, maximum burn up, innovative materials or extension of validation domain of fuel performance codes.

Then the present paper will describe the main experimental hosting systems currently under design:

- The MADISON device will be available at the JHR start up, and will allow testing the comparative behaviour of several instrumented fuel rods (between 1 to 8 rods of up to 60 cm fissile stack height) under NPP normal operating conditions (no clad failure expected).
- The ADELINE device will be available for the JHR start up, and will allow testing a single experimental rod up to its operating limits. The fuel rod will be tested under conditions that correspond to off-normal situations with possible occurrence of a clad failure. The first version so called ADELINE “power ramps” will focus on the clad failure occurrence during one of these abnormal situations.
- The LORELEI device will be available few years after the reactor start up and will allow testing a single rod under accidental situation that may lead to fuel damage. It will be able to reproduce all sequences of a LOCA-type transient, including the re-irradiation, the loss of coolant and the quenching phases, on a separate effect approach.

In-core and in reflector material test devices will be presented as well, corresponding to large ranges of irradiation conditions, in terms of temperature, neutron flux and neutron spectra. A special attention focuses on the improvement of the thermal stability and gradients in the interest zones of irradiated samples. Some specific devices will be described such as equipments designed to the qualification of reactor pressure vessel steels (OCCITANE test device), to the studies of creep-swelling of structural materials (MICA test device) or to the study of the stress corrosion cracking assisted by irradiation phenomena (CLOE test device: a corrosion loop with an accurate water chemistry monitoring for PWR or BWR requirements).

## 1. Introduction

The Jules Horowitz (JHR) Material Testing Reactor will be commissioned by end 2017 as an international user's facility on the CEA Cadarache site. It will be dedicated to materials and fuel irradiations for the nuclear industry or research institutes and to radio-isotopes production for medical applications. A detailed presentation of the project status is given in ref. [1].

The design of this facility allows a large flexibility in order to comply with a large range of experimental requirements, regarding the type of samples (fuel or material), neutron flux and spectrum, type of coolants and thermal hydraulics conditions (LWR, Gen IV,…), in accordance with the scientific objectives of the programs. These experimental tools are under development and some of them will be available at JHR start up.

After a reminder of the main characteristics of the reactor plant, the experimental capacity of the facility is described and a focus on the main irradiation devices under development is given.

## 2. Main Characteristics of the JHR facility and experimental capacity

This facility is based on a 100 MWth pool reactor compact core cooled by a slightly pressurized primary circuit. The core tank is located in the reactor pool.

### 2.1 A modern facility with a large area dedicated to experiments

The nuclear facility comprises a reactor building with all equipments dedicated to the reactor and experimental devices and an auxiliary building dedicated to tasks in support for reactor and experimental devices operation (see Fig. 1).

The reactor building is designed to provide the largest experimental capacity possible with the largest flexibility. One half of this building is dedicated to the implementation of equipments in support to in-pile irradiations (for example, water loops). This corresponds to 700 $m^2$ over 3 floors for implementation of experimental cubicles and 490 $m^2$ over 3 floors for instrumentation and control equipments.

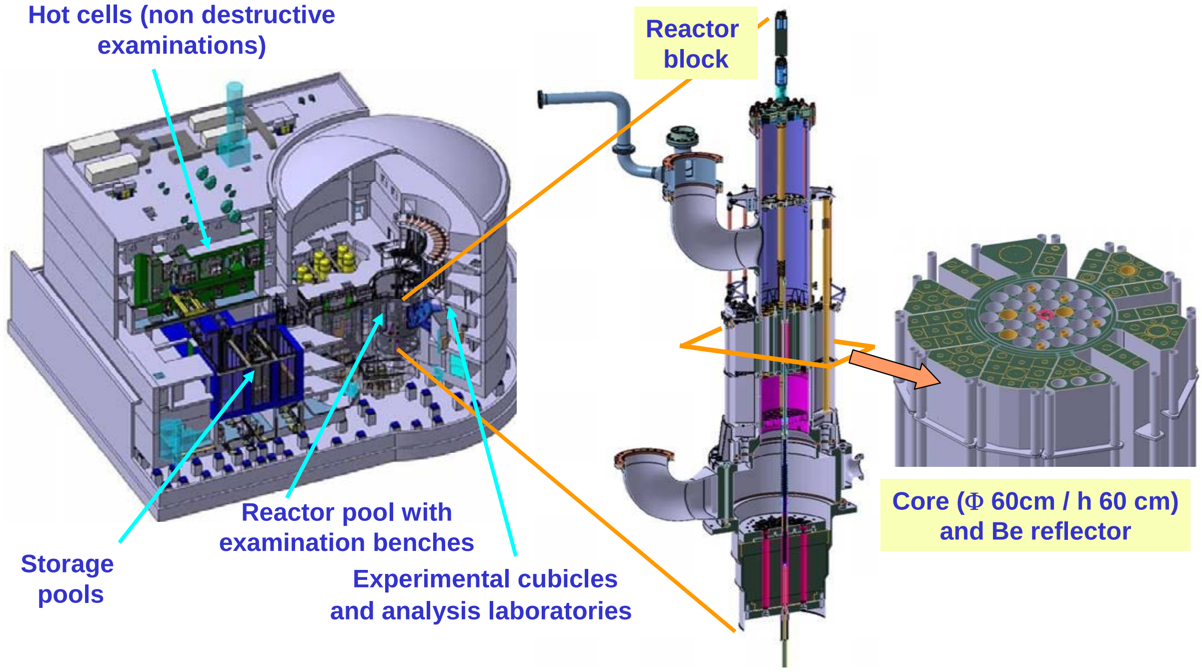

Fig. 1 Views of the JHR facility and the reactor core.

## 2.2 A powerful reactor with numerous irradiation sites and irradiation conditions

The design of the reactor (see Fig. 2) provides irradiation sites situated inside the reactor core with the highest ageing rate (up to 16 dpa/year) and irradiation sites situated in the Beryllium reflector zone surrounding the reactor, with the highest thermal flux. Numerous locations are implemented (up to 20 simultaneous experiments) with a large range of irradiation conditions:

- 7 in-core locations of small diameter (32 mm) with a high fast neutron flux (up to 5.5 E14 n.cm-2.s-1 perturbed flux above 1 MeV)
- 3 in-core locations of large diameter (80 mm) with a high fast neutron flux (up to 4. E14 n.cm-2.s-1 perturbed flux above 1 MeV)
- 20 fixed positions (100 mm of diameter and one location with 200 mm) with a high thermal neutron flux (up to 3.5 E14 n.cm-2.s-1 perturbed flux)
- 6 positions located on displacement devices located in water channels through the Beryllium reflector

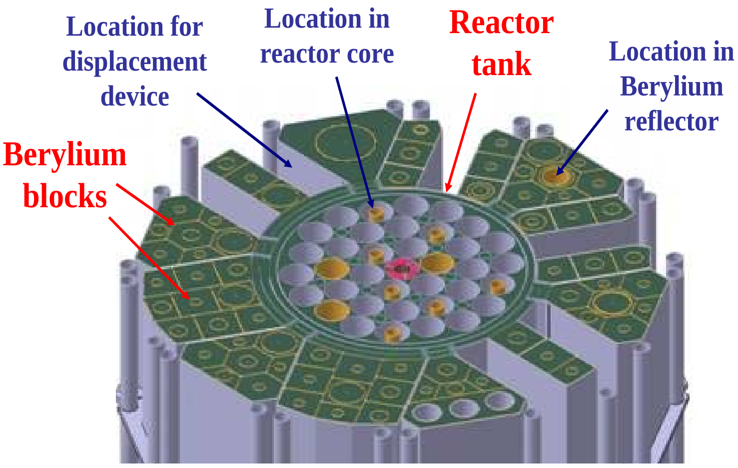

Fig. 2 Views of the experimental locations.

A typical reactor cycle is expected to last 25 days, and CEA targets to operate the reactor 10 cycles per year.

## 2.3 Non destructive examination benches

The JHR experimental programs will also take advantage from Non-Destructive Examination (NDE) benches, present in the facility with the aim of significantly improving the scientific quality of the JHR irradiation process:

- A coupled gamma scanning-X tomography bench located in the reactor pool (adapted to welcome irradiation devices) (see details in ref.[3])
- A neutron radiography bench located in the reactor pool (see details in ref. [2])
- A coupled gamma-X tomography bench, identical to the previous one and located in the storage pool of the Nuclear Auxiliary Building
- Non destructive examinations in hot cells after extraction from the experimental devices (visual inspection, photography, metrology and Eddy Current testing)

# 3. Irradiation hosting systems available at the JHR start-up

## 3.1 MADISON test device

This test device will carry out irradiations of LWR fuel samples (60 cm fissile stack) when no clad failure is expected. Consequently, the experimental conditions correspond to normal operation of power reactors (steady states or slow transients that can take place in nuclear power plants) (ref. [4]).

This experimental device is made of an in-pile part (holding the fuel samples) fixed on a displacement system. This system allows on-line regulation of fuel linear power on the samples. Thanks to the high thermal neutron flux in the JHR reflector, this is possible to reach high linear power even on high burn-up samples (as an example, it is possible to reach 400 W/cm for a burn up of 80 GWd/t for a common $UO_2$ fuel of initial enrichment 4.95%).

The in-pile part is connected to a water loop providing thermal-hydraulics conditions expected for a given experimental program. The water loop (implemented in a dedicated cubicle, see Fig. 3) allows reproducing the thermal-hydraulics conditions of nuclear power plants (PWR, BWR or WWER technologies) in terms of water loop pressure (up to 160 bar) and temperature (up to 320°C).

A specific chemical analysis system and a water treatment system allow a continuous regulation of chemical conditions.

In order to meet the large range of experimental needs expressed by the nuclear industry, the test section of the in-pile part has a large volume. This allows loading a large panel of sample holders from high embarking capacity (up to 8 samples) with low instrumentation to low embarking capacity (up to 1 sample), but highly instrumented.

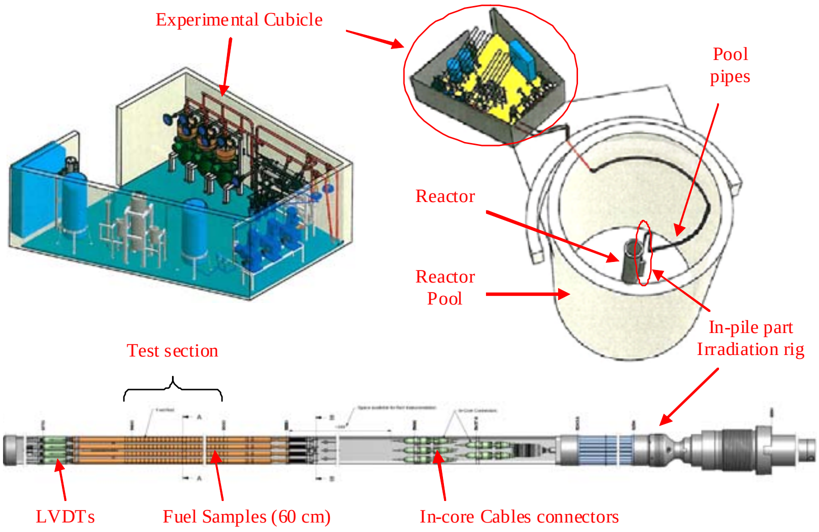

Fig. 3 View of the MADISON test device with focus on the water loop and on the first irradiation rig

The first irradiation rig version has a carrying capacity of 4 fresh or pre-irradiated samples (with a maximum of 2 sensors per sample) and is flexible enough to operate with 2 samples (highly instrumented).

For sample instrumentation, 5 tight high temperature and pressure connectors are implemented on the sample holder to allow the plug-in of specific instruments (see Fig. 3). The following instrumentation can be easily used in the first MADISON sample holder manufactured for the JHR start up: fuel central temperature, clad temperature, clad elongation, fuel stack elongation, fuel plenum pressure, fission gas release composition based on acoustic measurement device.

A second version of the MADISON sample holder is under investigation and is based on the previous one, but it will be limited to two rod samples when equipped with a diameter gauge.

In addition, the design of the test section allows on-line fuel samples linear generated heat rate measurement using thermal balance technique with a targeted 5% precision.

## 3.2 ADELINE test device

The ADELINE test device is able to hold a single experimental fuel rod from all LWR technologies to reproduce various experimental irradiation scenarios where clad failure is either a risk or an experimental objective (ref. [4]). Similarly to the MADISON experimental device, this experiment is made of an in-pile part and an out-of-pile water loop (see Fig. 4). Fresh or pre-irradiated fuel rods can be used to perform: power ramp tests, rod internal over-pressurization ("lift-off"), rod internal free volumes gas sweeping or power to melt approach margin mastering.

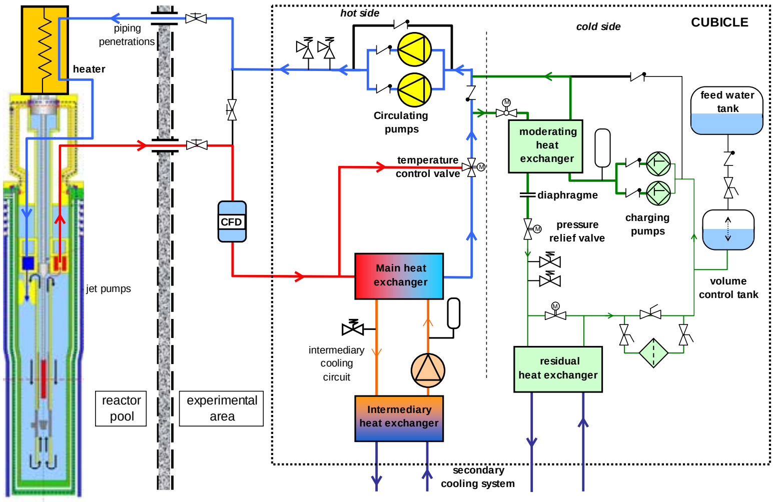

Fig. 4 Schematic diagram of the ADELINE loop

A first version is mainly dedicated to power ramps testing. In particular, the design of this device is optimized to provide a qualified thermal balance and a good accuracy on the clad failure instant and consequently a good knowledge of the linear power inducing the failure. A quantitative gamma spectrometry system allows quantifying the radiological source term released in the coolant since a rod fails.

Some enhancements are added in order to make on-line quantitative clad elongation measurement during power transients and to manage several successive experiments during one reactor cycle. In addition, this device can be easily upgraded in order to manage highly instrumented experiments with fuel and clad temperature measurement and fission gas release measurement by gas sweeping.

In a longer term, a second version will be dedicated to the study of the long-term post-failure behaviour in normal conditions (failure evolution, secondary hydriding, release of fission products and of fissile material…), coupled with the fission product laboratory.

A typical PWR power ramp sequence is made of the following phases (see Fig. 5):

- A low power plateau (from 0.5 up to 7 d) with control of clad surface temperature at 330°C (±10 °C) while the sample linear heat rate is controlled between 50 and 250W/cm, depending on customer's request
- A linear power ramp at a continuous rate ranging between 100 W.cm$^{-1}$.min$^{-1}$ and 700 W.cm$^{-1}$.min$^{-1}$. During this phase, clad surface temperature is stable at saturation condition, as soon as the sample reaches 350 W.cm$^{-1}$ at its peak level
- A high power plateau that may last 24h at a linear heat rate up to 620 W.cm$^{-1}$ (at the sample peak level).

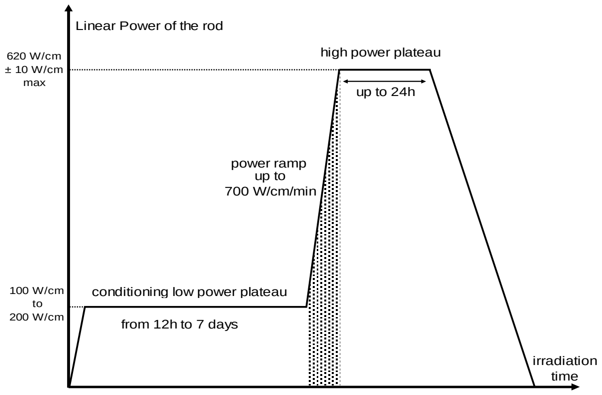

Fig. 5 Standard power ramp test time history

## 3.3 MICA test device

The MICA test device is devoted to the irradiation of materials, such as fuel cladding materials or NPP internal structures materials. It consists of 2 concentric tubes delimiting a gas gap (see Fig. 6), which is mainly used to adjust the temperature inside the internal tube (gap dimension, nature of the gas).

Electric heating elements are placed on the internal tube, embedded within an aluminium spray. This heating method ensures fine control of the samples temperature.

The MICA device has the same performances than the current CHOUCA test device widely used in OSIRIS reactor, i.e. irradiation of various geometries of samples in NaK (up to 450°C) or gas (up to 1000°C). These test devices are mainly designed for in core irradiations were fast flux can reach up to 16 dpa a year (at 100 MW).

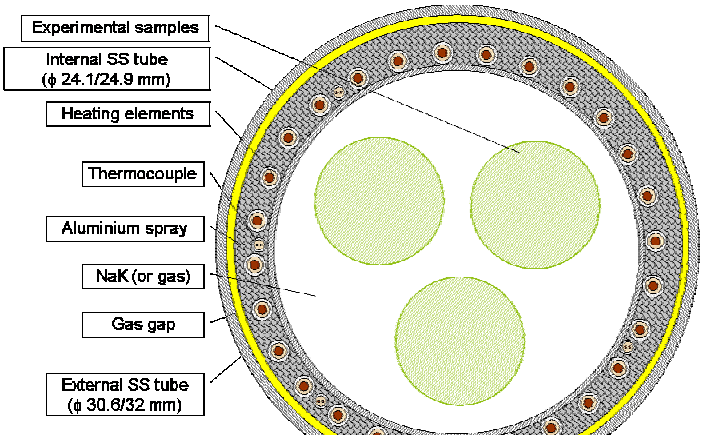

Fig. 6 MICA test device cross-section

Additional studies to fit to JHR features have been launched in two main directions:

- The specificities of JHR, in terms of test device outer dimensions, lead to an advanced integrated device head. The main constraints are the handling procedure and the co-activity in the reactor pool during the few days of refuelling (reactor shutdown between 2 cycles). The current design embeds the gas circuits control components (valves, pressure sensors, connection) and the electrical connections (instrumentation and electric heating elements). The goal of the new MICA top head is to keep safe but to make easier handling tasks for operators.

- The multipurpose carrier that MICA represents leads to keep most of widely former concepts that made CHOUCA devices successful but to improve their thermal behaviour in order to meet the requirements, particularly in temperature precision and gradients mastering. Then a specific effort has been made for a better physical properties assessment of the MICA components, and the aluminium spray in particular (using a set of MICA models). The MICA thermal behaviour is now more predictable thanks to a more accurate modelling.

## 4. Irradiation hosting systems available after the JHR start-up

### 4.1 CALIPSO test device

As the MICA hosting system, the CALIPSO test device (in-Core Advanced Loop for Irradiation in Potassium SOdium) is mainly dedicated to the irradiation of material samples immersed in NaK. Unlike MICA, NaK is not static within CALIPSO: a NaK flow is indeed induced with an innovative electromagnetic pump, implemented in upper in-pile part of CALIPSO (see Fig. 7). This embedded thermohydraulic loop features mainly an electrical heater and a heat exchanger as well.

CALIPSO meets the original need of a low temperature axial gradient (a maximum of 8 °C is the target) all along the samples stack, up to 450°C for a first step of development, and up to 600°C in a second phase. The setting of each parameter (power of heater, flow of the pump and efficiency of exchanger) will lead to a full control of the thermal conditions inside the test device and in particular in the sample location. First qualification tests with a regular scale CALIPSO model (and thus the innovative electromagnetic pump) are planned late 2013 using a dedicated experimental platform so called SOPRANO.

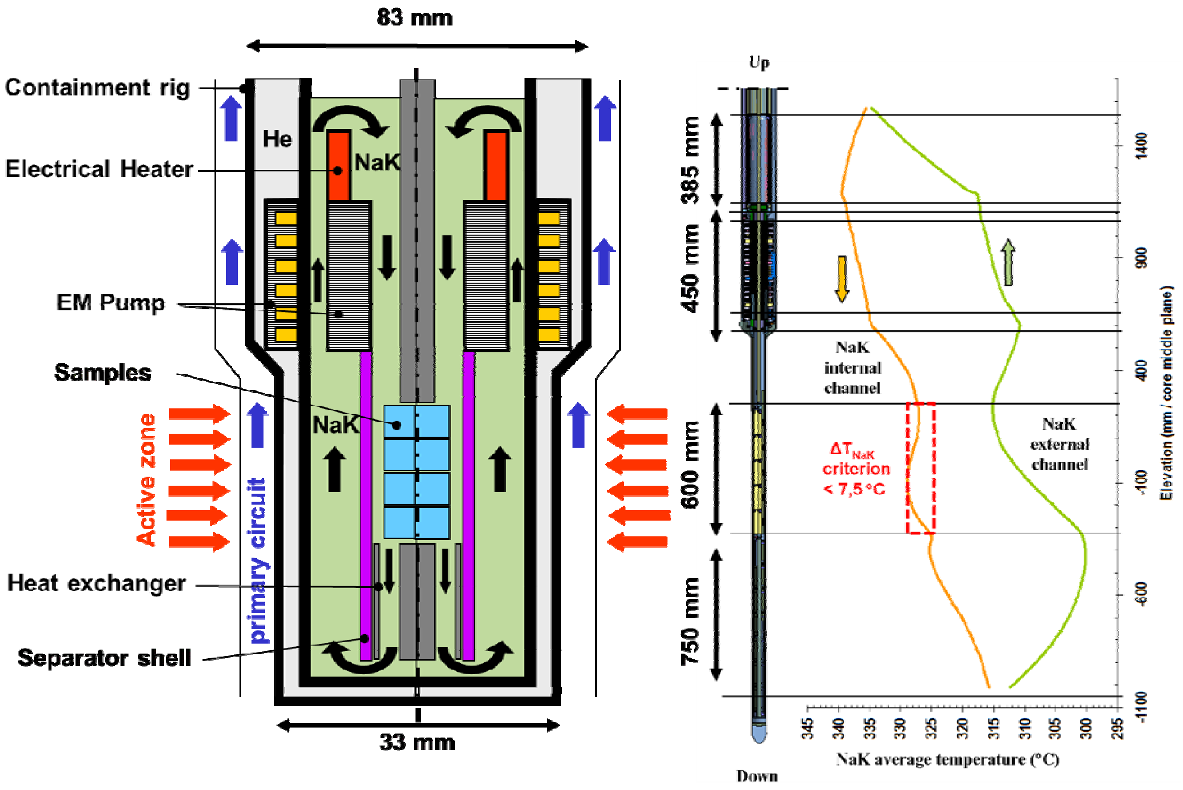

Fig. 7 CALIPSO functional sketch.

## 4.2 OCCITANE test device

In the field of pressure vessel steels of NPPs, irradiations are carried out to justify the safety of this 2nd containment barrier and to improve its lifetime. Then CEA is designing a hosting system so named OCCITANE (Out-of-Core Capsule for Irradiation Testing of Ageing by Neutrons), which will allows irradiations in an inert gas at least from 230 to 300°C.It will be implemented in the JHR reflector and reach damage rate around 100 mdpa/year (E >1 MeV). The associated instrumentation will include at least thermocouples and activation foils as close as possible to the samples.

OCCITANE is based on IRMA device of OSIRIS. The ongoing design studies consist mainly in decreasing thermal gradient in the sample area (see Fig. 8) and in integrating the capsule to the JHR environment.

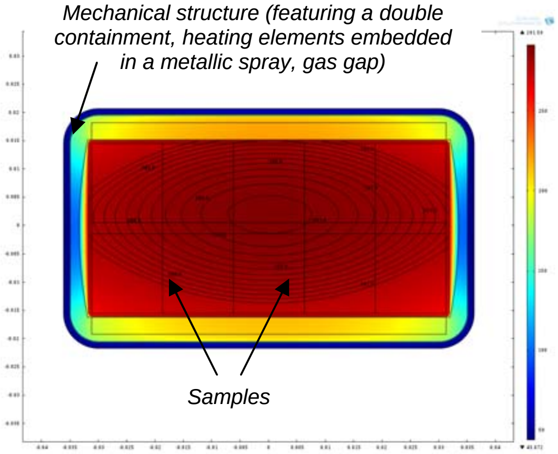

Fig. 8 Calculated temperature map in the OCCITANE device (core Mid-plane, gamma heating: 0.6 W/g)

## 4.3 CLOE test device

Due to ageing of the NPPs, stainless steel core components undergo increasing radiation doses, which enhance their susceptibility to local corrosion phenomena, known as irradiation-assisted stress corrosion cracking (IASCC). Cold laboratories can study and model SCC phenomena; but to really be representative of LWR environments, these studies require integral tests in MTR to take into account irradiation effects (radiation dose and flux). To answer to these industrial needs, DAE (India) and CEA have launched the design of a LWR corrosion loop (so-called CLOE), likely located in the JHR reflector, close to the tank. Then CLOE will reproduce as close as possible the nominal environment of LWR reactors, including well known and well controlled water chemistry and will allow to apply a mechanical loading of the specimens during the experiment (see Fig. 9).

This test device will be made of a double wall pressure flask (cylindrical shape) containing an irradiation rig which will carry the samples and all measurement sensors for experimental and safety purpose. This in-pile part will be connected through under-water pipes to experimental components such as pumps, heat exchangers or water tanks located in an experimental cubicle.

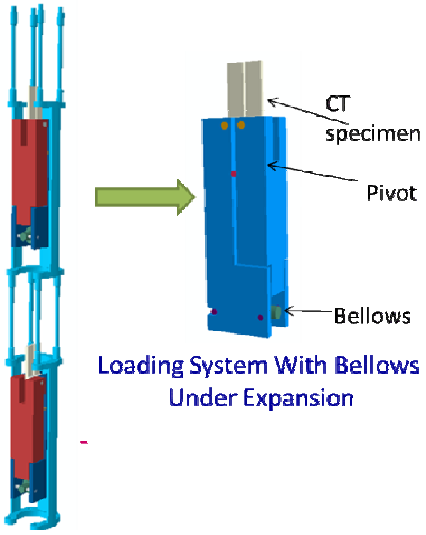

Fig. 9 View of CLOE sample holder

## 4.4 LORELEI test device

The purpose of LORELEI device is investigating the behaviour (thermal-mechanical and radiological consequences) of LWR-type pre-irradiated fuel rods under “Loss Of Coolant Accident” conditions (ref. [4]). The thermal-hydraulic phenomena does not reproduce all phases of a realistic LOCA-type power reactor sequence (in particular the first clad temperature peak), but the thermal-mechanical conditions (clad temperature, clad over-pressure, steam environment) will be representative (see Fig. 10).

This equipment consists in an integrated water capsule that can be operated as a thermo-siphon able to cool and re-irradiate a single pre-irradiated fuel sample, and to produce a short half-life Fission Product (FP) inventory. For the first version of the test device, the re-irradiation power is low and adapted to the production of a detectable short half-life FP inventory (versus long half-life radionuclides already present in the fuel material). Next version will allow reproducing thermal conditions representative of current LWR power reactors and performing a re-irradiation of samples at higher power in order to simulate the effects of the local peak power ("core hot spot") and to produce a representative FP inventory and distribution at the accidental sequence start-up.

It is equipped with a gas injection able to rapidly empty the test device in order to simulate the dry-out phase of the fuel rod during LOCA transient. A neutron shielding can be used to flatten the axial neutron flux profile. An electrical heater implemented in the sample holder allows getting a homogeneous temperature azimutal distribution and acts as a dynamic thermal insulation in order to get representative adiabatic conditions (initial heat-up rate depending on customer request and typically ranging from 10 up to 20°C/s).

The high temperature phase (up to about 1200°C) will be monitored by adjusting the rod nuclear power with the displacement system. During this phase, the electrical heater will be switched-off in order to increase heat losses and to prevent any temperature escalation (e.g. due to steam – zirconium reaction).

At last, low temperature water can be re-injected in the device to simulate the quenching process.

This device, designed in collaboration with IAEC (Israel), allows investigating ballooning and burst of the fuel cladding (the inner pressure of the fuel rod can be monitored to that purpose), clad corrosion phenomena (oxidation and hydriding), thermal-mechanical behaviour, quenching, post-quench behaviour and fission product release. To that purpose, the device will be connected to a fission product laboratory.

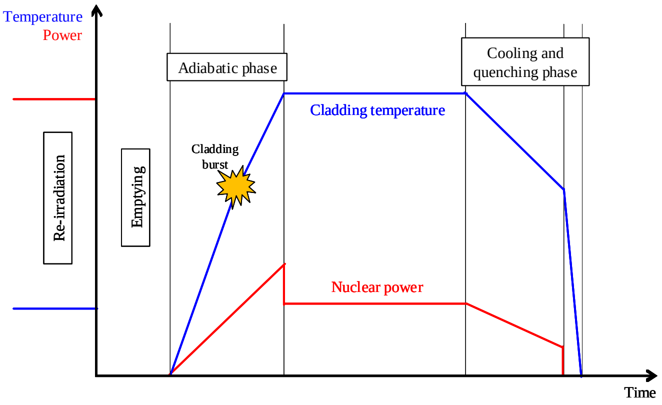

Fig. 10 Phases of the LOCA sequence

## 5. Conclusion

The Jules Horowitz reactor, which is under construction at the CEA/Cadarache centre (France) with a target of commission by end 2017, will be a major European user facility for sustaining the international irradiation capacity from the end of this decade and for the next 50 years.

This paper gives an overview of the JHR experimental irradiation capacity, and presents in particular the main material and fuel hosting systems under design and development. Only some of them will be available at the JHR start-up.

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