The MADISON experimental hosting system in the future Jules Horowitz Reactor

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The future **Jules Horowitz Reactor**, under construction in Cadarache (France), and scheduled for operation in 2014, will perform experimental irradiations of material and fuel for utilities and research institutes in the nuclear industry. The experiments will aim at **characterizing the behaviour** of material and fuel under neutron flux and will participate in the **qualification of industrial** products before using in Nuclear power plants. The experimental programs will be performed in experimental hosting systems able to reproduce the environment of power reactors (neutron flux, thermal-hydraulics, chemistry…).

CEA is designing a first set of hosting systems, that will be available for the start up of the reactor, and that anticipates the future experimental needs. Among the equipments dedicated to investigation on fuel products, the **MADISON device ("*M*ultirod *A*daptable *D*evice for *I*rradiation of experimental fuel *S*ample *O*perating in *N*ormal conditions")** will allow **irradiation of several LWR fuel rods (of PWR or BWR type) under representative normal conditions**. It will allow adapting the experimental environment (neutron flux, thermal-hydraulics, water chemistry), required for an experiment. It is designed in collaboration with **IFE** team (Institute For Energy Technology in Norway), operating the **Halden boiling water reactor**, and includes most state-of-the-art technologies and instrumentation from this institute. It will allow performing experiments of high precision (follow up of fuel power, primary fluid thermal-hydraulics and chemical conditions) and can use most systems available in the JHR to perform post-irradiation testing and examination on samples.

This document presents the MADISON hosting system in the JHR facility. After a short reminder of the context, it will describe the objective of this equipment in the first panel of hosting systems. Then the present design of this system will be presented. At last, the main performances and the time schedule of the first cycle will be presented.

Context and objectives of MADISON device

The JHR facility

The JHR is a 100MW tank pool reactor that has several experimental locations located inside the reactor core (very close to the reactor fuel with high fast neutron flux), and outside the reactor tank (with high thermal neutron flux). These experimental locations allow the insertion of experimental hosting systems, housing experimental samples, to be tested under neutron flux.
The reactor core is surrounded by beryllium blocks that aim at reflecting the neutrons and increase the neutron flux in the reactor. Some radial water channels are implemented through the beryllium with **displacement systems** allowing the precise positioning of experimental devices from the reactor tank.
The JHR facility will be equipped with several equipments that can be used in support to an experimental program [1]:

- **Hot cells** in the nuclear auxiliary building that will allow the (un)mounting and examination of irradiated samples (several type of examination instruments will be available)

- Non Destructive Benches (gammagraphy, X tomography and Neutron imaging systems) that allow a precise examination of the samples and that will be installed in the reactor pool and in one storage pools and hot cells

- Laboratories for various uses (more details are presented in another paper in this conference [2]): water chemistry, fission products…

In the reactor building, the reactor pool is surrounded by several **cubicles** that allow implementing Instrumentation and control systems and heavy components in order to control the environment of experimental samples. Each experimental device situated in the reactor pool is linked to this cubicle by a system of fluid pipes and cables.
All the systems described in the present section are presented in Figure 1.

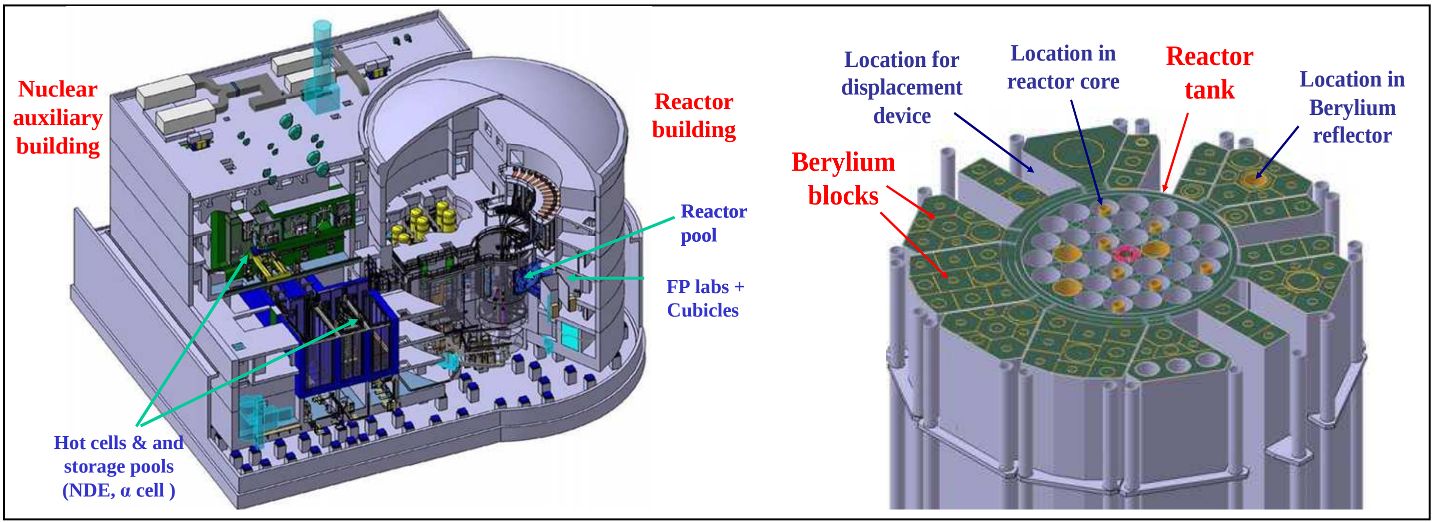

Figure 1 : View of the main systems in the JHR facility (left picture) and view of the reactor core with experimental locations (right picture)

MADISON device in the JHR facility

The in-pile part of MADISON device will be implemented on a displacement system in the beryllium reflector in order to control the neutron flux on the experimental samples.
Its design will allow using all Non destructive Examination benches available in the JHR facility to perform examination on the samples. In the reactor pool, the examination will be possible through the structures of the experimental device. In hot cells, the examination will be possible after unloading the sample from its sample holder. The design will target examination of the samples as rapidly as possible after the end of the irradiation.
The design of the experimental device will allow performing rapid (un)mounting in hot cells.

MADISON hosting system among the first panel of hosting system

In the nuclear industry, the utilities and research institutes need experimental facilities for the **characterization** of material and fuels (to determine thermal and mechanical properties in function of burn-up, to assess fission gas release, to assess chemical behaviour…) and for their **qualification** in conditions representative of power reactors (behavior in normal operating condition as well as in incidental or accidental conditions) (see [3]).

The panel of experimental hosting systems available in the JHR facility must allow investigating fuel behaviour in all type of situation that the fuel can face in power reactor. This requires the possibility to reproduce the environment and the use conditions of power reactors (Neutron flux, thermal-hydraulics, chemistry, burn up…) and to reproduce the transient situation that a fuel product can face in power reactor.

In order to satisfy these needs, CEA is developing three types of hosting systems corresponding to the grade of operating condition:

- The **MADISON** hosting system "**M**ulti-rod **A**daptable **D**evice for **I**rradiations of experimental fuel **S**amples **O**perating in **N**ormal conditions" will allow investigating the comparative behavior of LWR fuel rods (both PWR and BWR samples) in normal working situations that may not lead to an expected clad failure. The experiments targeted in the device will aim at investigating the evolution of the fuel properties (microstructure, fission gas release,…) in function of the burn-up and the Linear Heat Generation Rate (LHGR). Other experiments such as *slow power variations* representative of slow transient phenomena in power reactors or *long-term irradiations* (up to 3 years) are also targeted. They will allow investigating clad corrosion under irradiation or crack initiation and propagation.
- The **ADELINE** hosting system will perform experiments corresponding to "up to limits" situations that may lead to a clad failure or allow quantifying margins to safety criteria. This typically corresponds to power ramp transients (up to 600 W/(cm.min)), to lift off phenomena, to irradiation of non leak-tight fuel samples, or very high linear power experiments (up to 800 W/cm).
- The **LORELEI** hosting system will perform experiments corresponding to accidental situations that may lead to limited fuel damage. This typically corresponds to Loss of coolant accident situation.

Basic design of the experimental device

General description of the hosting system

The device is made of an **in-pile part** and a **loop system** (see Figure 2).

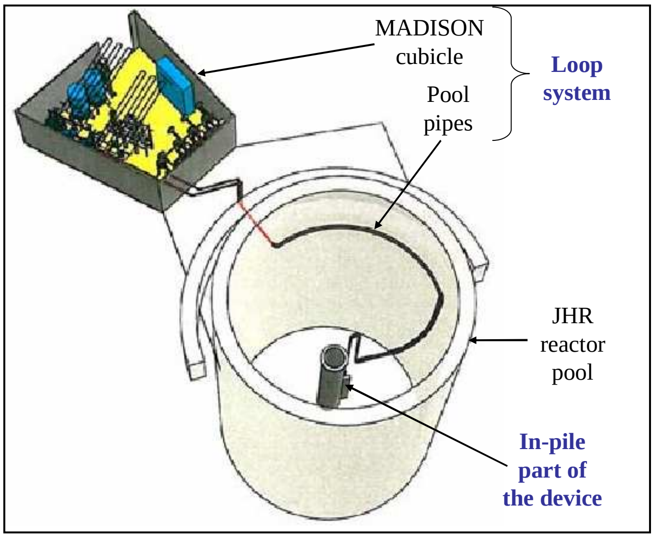

Figure 2 : View of the main systems of MADISON device (based on first IFE design)

The in-pile part will be installed in a reflector position of the JHR reactor on one of the displacement systems. It will be made of a *pressure flask* of cylindrical shape that will maintain the high pressurized fluids (typically 155 bars for PWR experiments and 73 bars for BWR) and will house the *irradiation rig* which will carry up to 4 experimental fuel rods (for the standard version of the irradiation rig), all measurement sensors for experimental and safety purpose and a moderating exchanger necessary for steam condensation in case of BWR experiments (see Figure 3).

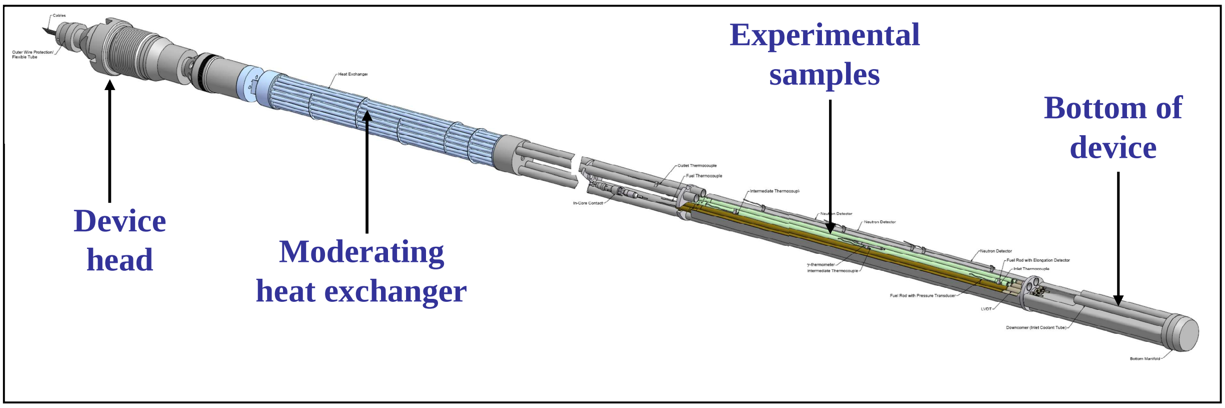

Figure 3 : Schematic view of a possible design of MADISON irradiation rig (based on first IFE design)

This in-pile part will be connected to a *loop system* providing the adequate thermal hydraulics (temperature, pressure, velocity) and chemical conditions that are representative of power reactors (PWR or BWR, depending on the experiment). It will be made of heavy components (pumps, heat exchangers, pressurisation system,…), installed out of the reactor pool, in an *experimental cubicle* of the reactor building (see Figure 4). The water flow will be sent to the in-pile part through *under-water pipes*. Instrumentation located on the irradiation rig is also connected to the out-of-pile part with cables.

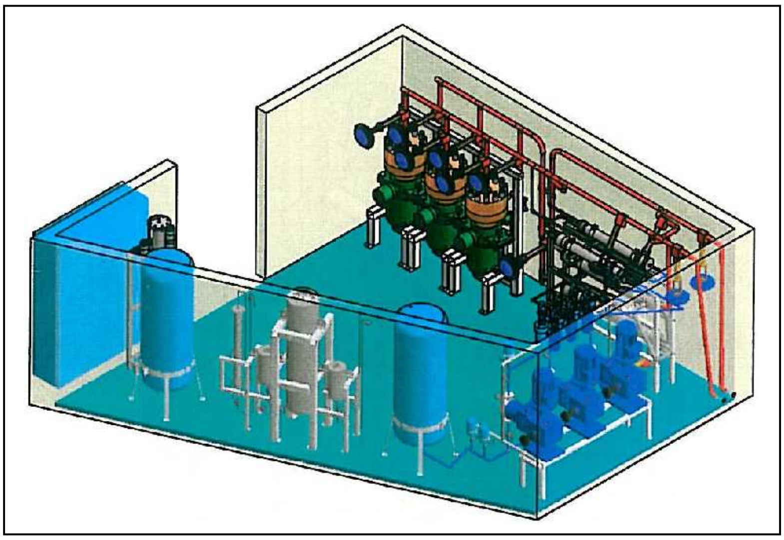

Figure 4 : First implementation of the experimental cubicle for MADISON loop system (based on first IFE design)

Hosting capacity

In order to satisfy customer needs, the design of the hosting system will be versatile in order to adapt to a large panel of irradiation rigs.

CEA plans to design a first standard rig able to hold **4 instrumented experimental fuel rods** at the same time (PWR or BWR samples). A good **homogeneity of the linear power** of the 4 samples is targeted (If the 4 samples are identical, a maximum 3% heterogeneity is targeted), with a maximum linear power of **400 W/cm**. An important request in the design of this rig is the possibility to (un)load irradiated fuel samples and their instrumentation from the irradiation rig in JHR fuel cells.

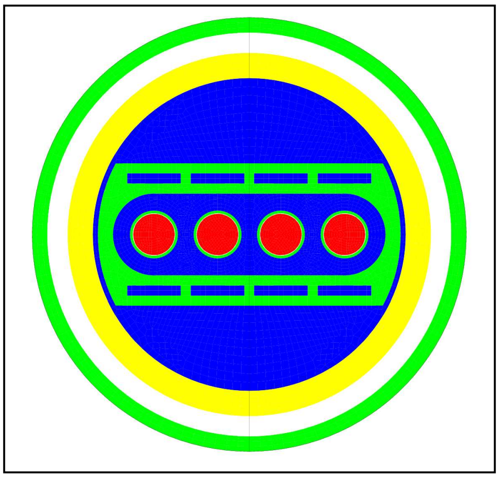

Figure 5 : View of the first version of the sample holder with fuel samples in the pressure flask (PWR geometry).

For specifics experimental program, the hosting system will be able to adapt to other kind of irradiation rigs such as:

- For an experiment requiring more experimental samples, a **high embarking capacity** rig able to hold up to **8 samples** (standard or reduced fuel stack length) at the same times can be accepted in the hosting system.
- For an experiment requiring more **instrumentation** or rods larger in diameter, a low embarking capacity rig (typically one or two samples) can be accepted in the hosting system. For such kind of experiments, the thermal-hydraulics conditions in the experimental device can be adapted to specific instrumentation (reduced velocity and/or pressure for fragile instrumentation).

Experimental purpose of MADISON device

Among the different JHR devices dedicated to experiments on LWR fuel samples, the MADISON device will allow investigating the behaviour of LWR fuel rods (both PWR "Pressurized Water Reactor" and BWR "Boiling Water Reactor" samples) in normal working situations that may not lead to an expected clad failure.

Experimental samples

MADISON experimental device will be adapted to all kind of **PWR** and **BWR** fuels that are (or will be) currently used in the nuclear industry by international utilities. The products can be **UO2** or **MOX** type (of clad outer diameter lower than 12,3 mm and less than 60 cm height) with possibly some additive or burnable poison. The enrichment acceptable will be the one currently used in power reactors (higher enrichments will be accepted for experimental new products). Irradiated fuels will be accepted with a maximum burn up of 120 GWd/t.

Very innovative fuel samples (regarding clad or fuel), can be tested in MADISON device. Their introduction will be conditional on a specific qualification process or through in pile selection with short samples of the product with its associated clad in order to be confident that the experiment may not lead to a clad failure.

Type of experiments

The following type of experiments gives examples of the MADISON capabilities:

- *Type 1 experiments:* Such experiments will focus on the fuel behaviour. It corresponds to investigation on the fuel evolution in function of burn up. Such experiments will allow characterizing fuel properties (mechanical properties, microstructures, fission gas release,…), it will allow to perform comparisons of different fuel microstructures or perform re-irradiation of fuel samples before other tests (ramp tests for example). For these type 1 experiments, the MADISON device will reproduce the correct **Fuel linear power**, on **Fuel temperature**, on **Clad temperature** (to investigate fuel clad interaction) and **Water loop pressure**. On the contrary, the environment parameters are of secondary importance for such experimental program: Water flow velocity, Coolant void fraction, Coolant temperature and Coolant chemical composition do not need to be representative of power reactor (but the values must be well adapted to have the adequate clad temperature)

- *Type 2 experiments:* Such experiments will focus on the clad behaviour. It corresponds to investigations on clad evolution in function with burn up. These experiments will allow characterising clad corrosion, creep phenomena, crud deposits or cracks initiation. For these type 2 experiments, the MADISON device will be representative of **Clad temperature**, of **Coolant temperature**, of **Coolant pressure**, of **Coolant void fraction** and of **Coolant chemistry**. On the contrary, fluid velocity in the test section, fuel temperature and linear power are of secondary importance and are less representative.

- *Type 3 experiments:* These experiments will target an acceleration in burn up aging of the fuel sample. The principle of this kind of experiments is generating a power density in the fuel sample superior to the nominal one. The design of experimental fuel samples in this precise case is specific, in order to have a fuel test section smaller than usual fuel rod (typically, a fuel rod outer diameter of 7 mm can be used). For these type 3 experiments, the MADISON device will be representative of **Clad temperature**, of **Fuel temperature**, of **Liquid pressure**, and of **Linear power**. On the contrary, fluid velocity in the test section, fluid temperature and void fraction do not need to be representative.

- *Type 4 experiments:* These experiments will be specific to the sample holder with a carrying capacity of one or two rods. They will allow to perform highly instrumented experiments. For these specific experiments, the pressure of the loop device will be different from usual values of power reactors (typically 130 bars) and the fluid velocity will be reduced in order to allow implantation of fragile instrumentation. For these type 4 experiments, the MADISON device will be representative of **Clad temperature**, of **Fuel temperature**, of **Fuel linear power**. On the contrary, fluid velocity in the test section, fluid temperature and fluid void fraction do not need to be representative.

Possible measurements

The irradiation rig will be equipped with instrumentation providing adequate measurements for the characterization and qualification of experimental fuel samples. A standard instrumentation is proposed on the standard irradiation rig, but one can adapt this instrumentation to specific customer needs.
Some of the sensors are installed on the experimental samples (that can be (un)mounted in fuel cells), and other instrumentation are installed in the loop system (that are fixed on the irradiation rig).

Instrumentation on the fuel samples

For the standard irradiation rig under development, CEA is planning to install 2 sensors on each fuel samples:

- Fuel central temperature

- Clad elongation thanks to LVDT sensors situated in the bottom of the irradiation rig

For specific customer needs, other instrumentation can be installed on the fuel sample:

- Clad temperature

- Fission gas internal pressure

- Fuel stack elongation

Instrumentation on the main water loop

For all type of irradiation rig, CEA is planning to install the following sensors:

- Coolant temperature in the close environment of the rod (at different elevations in the test section)

- Water loop pressure in the test section

- Main **water flow**

- Neutron flux measurements (thermal and fast) in the immediate surrounding of the rod, with no disturbance of the neutron flux on the sample. The Linear Heat Generation Rate (LHGR) on the fuel samples can be calculated from these measurements.

- Gamma heating measurement in the core mid-plane

- Thermal balance will be performed on-line, based on the heating of the main water flow between upstream and downstream from fuel samples and based on the water flow measurement. This thermal balance will allow determining the total power generated by the fuel sample (no distinction between each rod). A correction will be performed to account for gamma heating in water and in the structures. A 5% precision of the evaluation of fuel power is expected by CEA. This thermal balance will be performed on-line and continuously.

- Total activity in the main water loop will be monitored

- Chemical composition of the main water loop will be controled continuously to ensure that the chemical composition is adequate.

Status of the project

The main objective of the MADISON project is developing a hosting system available for first experiments for the start up of the JHR. As a consequence, the schedule of the project is based on this milestone.

CEA and IFE performed between June 2008 and March 2010 a **feasibility study** aiming at demonstrating the possibility to adapt IFE technologies to JHR (regarding geometrical constraints and regulation standards). The two institutes concluded on the feasibility of the experimental device and agreed on the feasibility to design and build the hosting system before first operation of the JHR.

The two institutes are now preparing the future phases of the project:

- A **detailed design phase** (to take place from beginning of 2011 to end 2012) that will aim at precisely designing the components of the hosting system. This phase must also define the manufacturing process of all these equipments and propose relevant manufacturers. In addition, CEA targets to perform a safety analysis based on the final design of the equipment, and targets to obtain agreement from the safety authority at the end of this phase.

- A **manufacturing phase** (to take place from beginning of 2013 to end of 2014) that will aim at building all components of the system and assemble the hosting system in the JHR building. All the manufacturing and building process must be based on the processes defined in the previous phase.

Conclusion and outlook of the MADISON project

Building a new research reactor such as JHR is a long and complex project. Its main interest is performing experimental irradiations for the nuclear industry. As a consequence, the design and manufacturing of experimental device, in parallel of building the reactor, is of primary importance and the success of the project is linked to the success of experimental device design.

CEA is proposing a first panel of experimental devices that must be available for the JHR start up and must comply with the needs of utilities and research institutes. Among the equipments dedicated to experimentation on LWR fuel samples, the MADISON device will participate in the characterisation and the qualification of the products. It will reproduce the environments (neutron flux, thermal-hydraulics, water chemistry) of power reactors (PWR or BWR, depending on the customer needs), and will allow testing the samples under conditions corresponding to normal operation of power reactors (no clad failure expected).

CEA will continue working with IFE-Halden on this project, considering the long experience of this institute in the design, manufacturing and exploitation of water loops, as well as the sound collaborative basis established so far. In addition, the experimental device includes most instrumentation systems of high precision developed by this institute.

The two institutes are confident in the feasibility to adapt IFE technology to JHR and are confident in the feasibility to build the hosting system before start up of the reactor and want to start as rapidly as possible the detailed design and the manufacturing.

At last, since this equipment will be used to fulfil industrial partner requests, it is very important for CEA to precisely focus on industrial needs. Consequently, CEA welcomes, even in early phases of the project, utilities or research institutes to express their future needs and to participate in the definition of the experimental capacity, in its detailed design and manufacturing.

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