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The ADELINE irradiation loop in the Jules Horowitz MTR: Testing a LWR fuel rod up to the limits with a high quality level experimental process

S.GAILLOT [(a)], D.PARRAT [(b)], G.LAFFONT [(a)], C.GARNIER [(a)], C.GONNIER [(c)]

Nuclear Energy Commission (CEA), Nuclear Energy Division

[a] CEA, DEN, DTN, *CEA Cadarache, BP1, F-13108 Saint Paul lez Durance. FRANCE.*
[b] CEA, DEN, DEC, *CEA Cadarache, BP1, F-13108 Saint Paul lez Durance. FRANCE.*
[c] CEA, DEN, DER, *CEA Cadarache, BP1, F-13108 Saint Paul lez Durance. FRANCE.*

Abstract

Checking the behaviour of a LWR fuel rod up to limits in normal and incidental conditions encountered in a power reactor is a key step toward the licensing of the industrial product. As the requested experimental conditions are often not technically possible or allowed in a power plant (in particular the rod failure is either an objective or a risk), it is essential to be able to perform this kind of test in experimental reactors. For that aim, the experimental LWR ADELINE loop has started in 2009 its detailed design phase, and will be able to reproduce various experimental irradiation scenarios with experimental fresh or irradiated fuel rods, such as:

- Soliciting or complex linear heat generation rate time histories (until 500 W. cm^{-1} with a fresh fuel sample with an enrichment of 1% ^{235}U),
- Power ramp tests (power ramp rate up to 660 W. $cm^{-1}.min^{-1}$),
- Permanent irradiation in a failed mode (on-line monitoring and purification of the fission products and actinides released in the coolant),
- Fuel centre melting conditions approach,
- Internal over-pressurization (“lift-off”).

After a short reminder of the experimental service offer of the Jules Horowitz Reactor, this paper is firstly focused on the performances requested by the scientific teams for this kind of tests, then on the technical description of the ADELINE irradiation loop and the associated experimental process.

1. Introduction

The Jules Horowitz (JHR) Material Testing Reactor will be operated from 2014 as an international user’s facility on the CEA Cadarache site (south-east of France - see.fig.1) in the field of materials and fuels behavior studies under neutron flux and also for medical applications with radio-isotopes production. To perform these types of irradiations, the JHR facility is designed to be flexible and adaptable to various requests in very large domains concerning type of samples (fuel or materials), neutron flux and spectrum, type of coolants and large thermal hydraulics conditions (LWR, Gen IV,…). A more detailed presentation of the project status is given in ref [1].

Fig.1. Overview of the JHR site (spring 2009)

2. JHR main performances at 100 MW

The main specific features of the JHR related to its experimental capability will be (cf. ref [2]):
- A high neutron fast flux within the core up to 1.10^{15}n.cm^{-2}.s^{-1} (perturbed flux above 0.1MeV), and a high neutron thermal flux in the reflector (non perturbed flux up to 5.10^{14} n.cm^{-2}.s^{-1}) (see fig.2).
- High quality power ramp experiments up to 600W.cm^{-1}.min^{-1} on one of the six displacement systems located around the core (see fig.3).

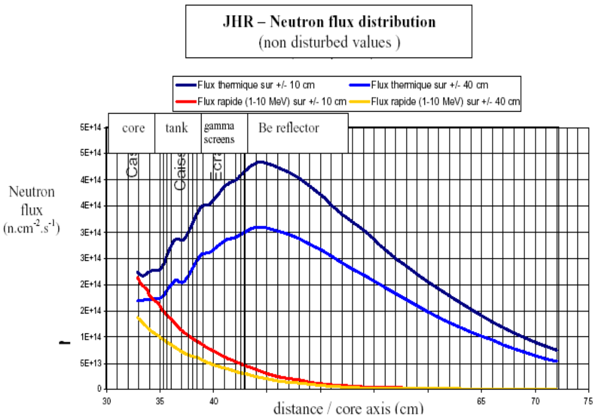

Fig.2. JHR radial neutron fluxes distribution

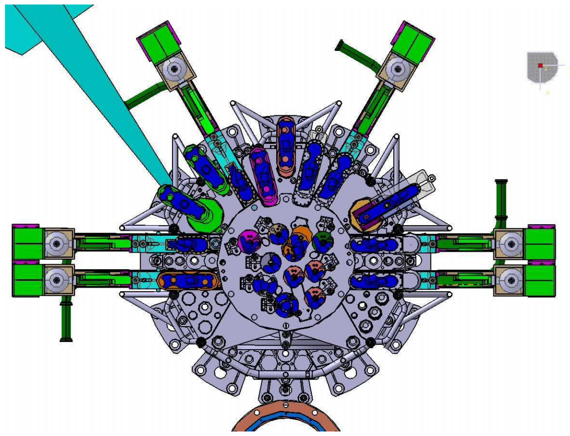

Fig.3. Overview of the core equipped with displacement systems

- Several experimental laboratories among which
  i) a fission product analysis laboratory,
  ii) a radiochemistry laboratory,
  iii) a dosimetry laboratory.
- A set of hot cells, with a dedicated alpha cell for recovery and management of failed fuels,
- Examinations capabilities which allow performing final checks before irradiation, post irradiation follow-up controls with a short delay and non-destructive examinations in dedicated hot cells.

3. Objectives of the ADELINE irradiation loop

The experimental LWR ADELINE loop development which is currently in its design phase focused on critical components studies will be able to reproduce various experimental irradiation scenarios with experimental fresh or pre-irradiated fuel rods, such as:

- Soliciting or complex linear heat generation rate (LHGR) time histories (until 500 W.cm^{-1} with a fresh fuel sample with an enrichment of 1% ^{235}U),
- Power ramp tests (power ramp rate up to 660 W.cm^{-1}.min^{-1} minimum),
- Permanent irradiation in a failed mode, with on-line monitoring and purification of the fission products and actinides released in the coolant,
- Fuel centre melting conditions approach,
- Rod internal over-pressurization (“lift-off”),
- Rod internal free volumes gas sweeping.

The interest of this experimental offer regarding the scientific needs and the fuel industrial development process is presented more in details in ref [3,4].

3.1. Feedback from previous experimental tests

A significant experience feedback is available on fuel power ramp tests or soliciting tests carried out in several MTRs in France (OSIRIS, SILOE) and abroad (BR2, HFR, R2, HBWR,…).

For the definition of future tests within an experiment quality increase process, the following main experimental challenges have to be overcome and integrated in the ADELINE loop design:

- Capability to reproduce correctly the power ramp kinetics and the stable upper plateau with high accuracy objective <10W.cm^{-1} (to be compared to the targeted LHGR value),
- Capability to analyze fission product release by device coolant on-line monitoring or by rod gas sampling,

- Possibility to unload the failed rod after the test thanks to specific equipments (e.g. tight connection to an alpha type cell).

3.2. ADELINE typical experimental transient proposal

The experimental protocol proposed as an exercise for the ADELINE basic design studies aimed at reproducing the phases of a fuel rod irradiation capable of resulting in its clad failure. The scenario included a post-failure irradiation phase. The typical phases in question are listed below (see fig.4):

Phase 1: Standard irradiation of a leaktight rod
Aim: study of the fission gas release = f (LHGR),
Fissile power plateaux between 50 and 400 W.cm^{-1},

Phase 2: Power transient
Transition from 50 to 100 W.cm^{-1} with a minimum power variation rate of 200 W.cm^{-1}.min^{-1},
Transition from 100 to 500W.cm^{-1} with a continuous rate of 660 W.cm^{-1}.min^{-1},
Maintain at 500W.cm^{-1} for 24h maximum,
The rod is supposed to become un-tight,
Rapid recoil of the device and transfer to the gamma spectrometry bench with less than 3h delay,

Phase 3: Irradiation in a failed rod mode
Different power plateaux between 50 and 400 W.cm^{-1},
Quantitative monitoring of the FP release in the coolant thanks to the FP laboratory by means of on-line gamma spectrometry and by sampling (delayed gamma and alpha spectrometry) and also through the on-line monitoring of delayed neutrons emitters.

Phase 4: Post-irradiation phase
Inter-cycle checking on the gamma spectrometry bench (with less than 72h delay),
Examination on the neutron radiography bench,
Transfer to alpha cell to recover the sample,
Insertion in a container and then in a transport cask for sending to a hot cell laboratory.

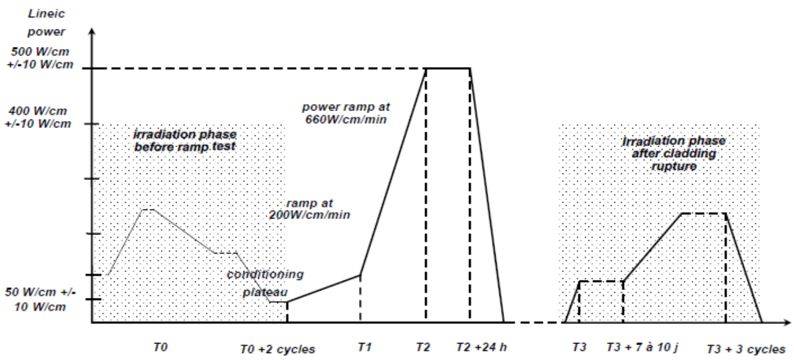

Fig 4. Typical experimental scenario

4. Current design studies for ADELINE type tests in JHR

4.1 Description of the sample

The sample considered for the experiment will be a UO_2 or MOx single fuel rod with PWR (diameter 9.5 mm) with a 200 to 600 mm long fissile stack and either being fresh or pre-irradiated up to 120GW.d/t.
The sample will be instrumented with a fuel centerline thermocouple and a cladding thermocouple. Moreover two capillary tubes connected to the top and the bottom free volumes of the rod will be used to sweep the gases (fission product and He) released by the fuel and to route them to the fission product laboratory in the JHR experimentation area (called CEDE).The instrumented sample is maintained in the test section through a sample holder (see fig.5).
Current studies concern instrumentation and fluid tightness connectors allowing to load and unload the instrumented fuel sample in the hot cells.

In order to increase the flexibility of the device, studies are also performed on the internal structures design regarding the possibility to take into account BWR rods samples (diameter up to 12.3mm).

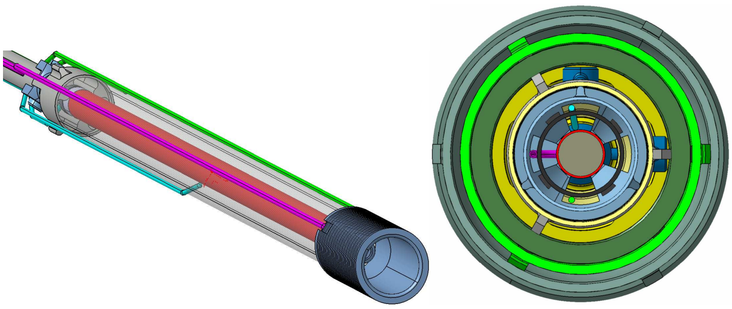

Fig.5. View of the sample holder and the test section

4.2 Description of the loop

The loop is composed of two parts:

- An in-pile section subjected to the flux, the low and high extensions, the instrumentation lines, the device head, the head extension, the fluid connectors, FP line and electrical equipment, flexible connections, the pool experimental and the Fission Products penetrations (see fig.6).

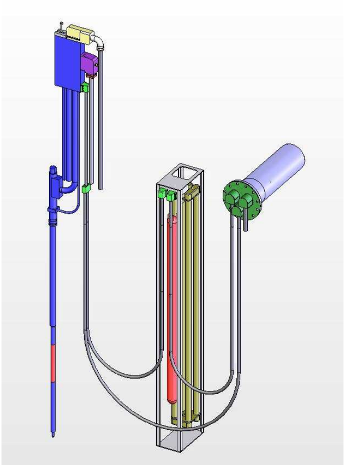

Fig.6. View of the irradiation device

(in-pile section exchangers and flexible connections)

- A grounded section including the fluid circuit, connections to fixed parts of the facility (fluids, utility fluids, utility waste, ventilation and electrical equipments), and I&C cabinets.

- **In-pile section:**

This part is composed of the following components (see fig.7):
- The double containment (DE),
- The instrumentation holder (PI) containing the environment sensors and the so-called “jet pump” flow amplification system,
- The sample holder (PE) including the instrumented test rod to be tested,
- The device head integrated electric heater and leak tight connectors (fluids and electrics).

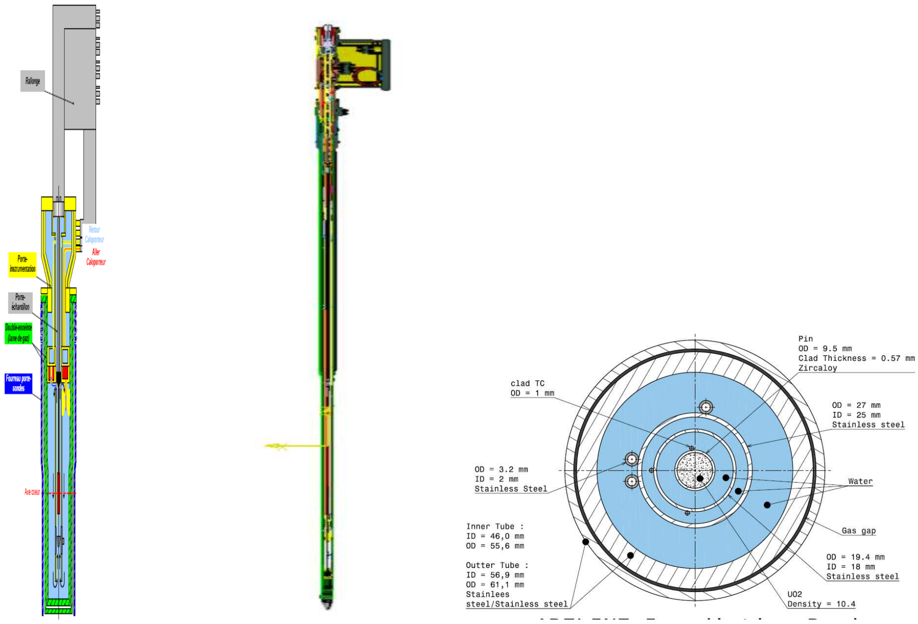

Fig.7. Schematic schemes of the in-pile section

of irradiation loop (axial and radial sections)

The internal structures and the process are regulated thermally by the fluid in the loop.

The fluid is injected from the out-of-pile section by circulation pumps operating simultaneously to obtain an overall flow rate of 140 g/s (called "inducing flow rate").

The fluid flows through a flow rate injection module used to re-entrain part of the flow in the test line and thus amplify the inducing flow rate. The amplification factor is around 4 to 5, resulting in a "useful" flow rate in the test channel of 570 g/s.

The fluid exiting the device transits towards the out-of-pile section via an underwater flexible metallic line (about 16 m long), heat exchangers and a penetration through the pool (see fig.8).

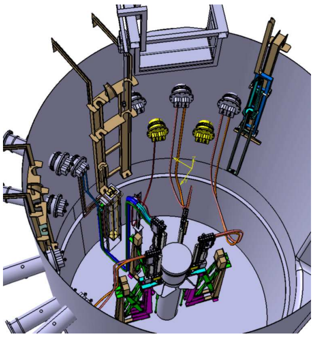

Fig.8. Overview of the underwater lines

Current studies are performed on the jet pumps thermal hydraulics (TH) behavior taking into account feedback from OSIRIS experimental results (especially from ISABELLE device).

For the BWR application, TH exploratory calculations are under progress to test the capability of the ADELINE type loop to work at these conditions (or approaching).

- **Out-of pile section:**

In principle, this part will be located in a 30 m² metallic liner covered cubicle on level –2 in the CEDE area. It includes the fluid circuit and the equipment needed to reproduce the thermal hydraulic conditions of the in-pile section (see fig.9). The filtering systems and the chemical & conditioning modules for the coolant (hydrogenation) are also located in this cubicle. Under normal operating conditions, the cubicle is ventilated and equipped with filtration modules.

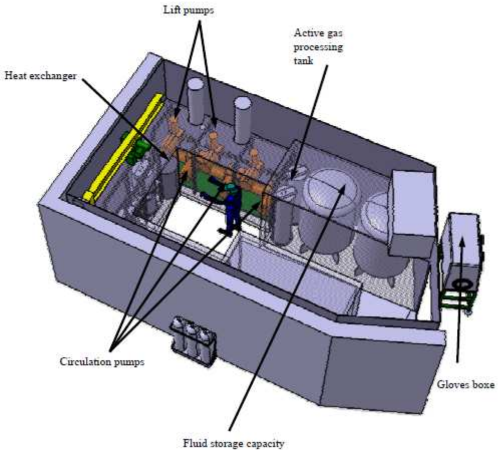

Fig.9. View of the ADELINE experimental cubicle

The experimental loop operates at 160 bar thanks to **a pressurization module** placed upstream of the circulation pumps (see fig.10).

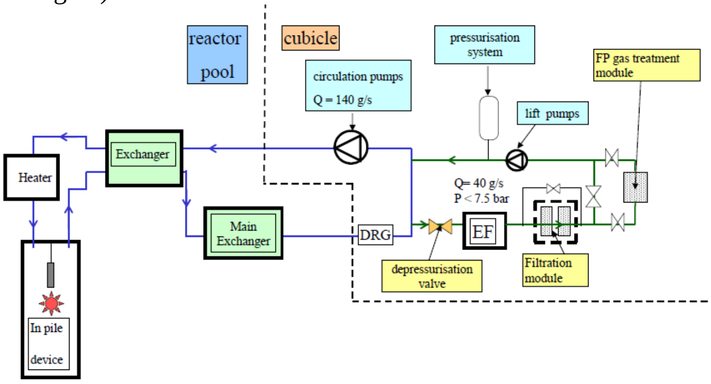

Fig.10. Schematic diagram of the loop

The inducing flow rate in the loop is guaranteed **by circulation pumps** with the following characteristics:
- Normal operation phase: Q=140g/s with a ΔP of 25 to 35 bar,
  Coolant temperature = between 50 and 100°C,
- Thermal balance phase: Q= 30g/s (specific and temporary operating phase for sample LHGR determination).

A low pressure system is installed in parallel of a part of the main loop. It mainly includes the FP filtration and purification systems, the loop chemistry and coolant conditioning modules. This system is located downstream of a pressure reducer that lowers the pressure to less than 8.5 bar.

The current studies on the loop concern the analyses of different architectures allowing to limit the number of components (mainly exchangers) and the possibility to use standards components (as gas accumulator for the pressurization system).

4.3 Test driving using a displacement system

The device will be loaded on a displacement system located on the reflector of the core (see fig.11). This system can move to or from the core tank. It allows implementing simply and quickly linear power variations on the sample, and reaching representative power level and FP inventory during conditioning phase before a soliciting test (see.fig.12).

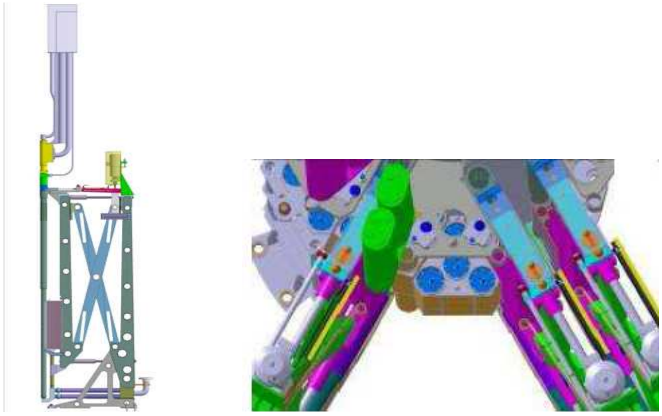

Fig.11. Displacement systems

and example of location in the JHR reflector

The maximum speed of withdrawal is 50 mm/s. The total stroke of the displacement systems is about 350 mm. Such a concept is convenient for the operating (easy to handle, even during the operating cycle of the core) and for the safety (the safe back position and the off normal conditions of the device are not directly coupled to the core operations).

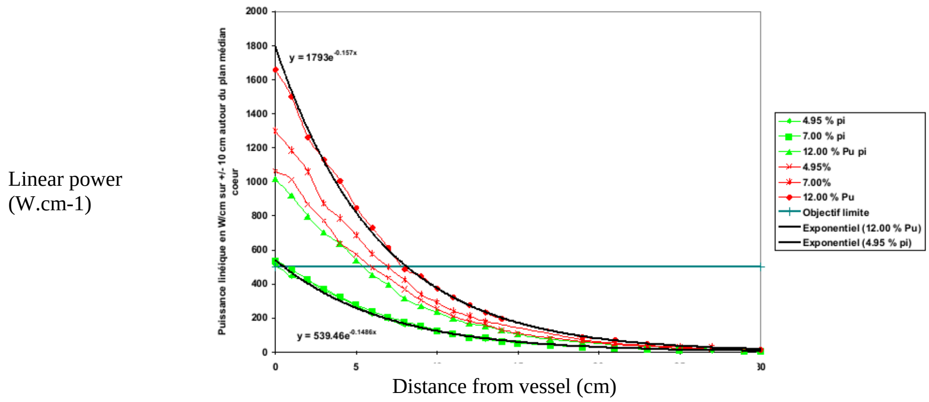

Fig.12. Example of power evolution versus displacements and fuel enrichment

on displacement system (parametric calculations)

4.4 Recovery and conditioning to the JHR alpha cell.

After the experimental transient and examination on the underwater NDE benches, the sample will be recovered in the hot cell. Depending of the risk of contamination (case of a failed or damaged rod), the sample can be unloaded in a specific alpha cell. In this case, the head of the device is specially designed to transfer the sample in the hot cell with tightness connection (see. fig.13).

Current studies allow to precise the feasibility of these operations using specific tools which are under developments.

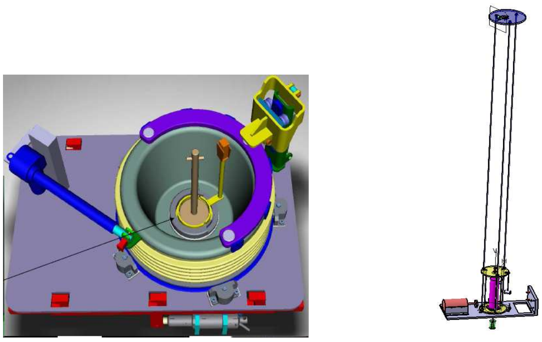

Fig.13. transfer door in the alpha hot cell and sample unloading tool

5. Non destructive examination benches [4].

The JHR experimental process includes also non-destructive examination (NDE) stands (see fig.14) aiming at improving the experiment quality through NDE on full devices or sample holders by:

- Initial check of the experimental load status just before the beginning of irradiation (after transportation, mounting in JHR hot cell or insertion in the device),
- Adjustment of the experimental protocol after a first irradiation run at low power (sample evolution, power adjustment…),
- On the spot monitoring of the sample state after a test on the close-by gamma-X tomography stand located in the reactor pool and with limited handlings (e.g. geometrical changes after an off-normal transient, quantification of short half-life fission product distribution…).

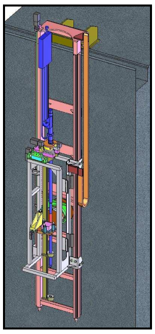

Fig.14. Description

of the underwater X ray and gamma systems

Full device NDE can also be performed on an underwater neutron imaging bench installed on the reactor pool floor.

6. Conclusion.

The current ADELINE studies allow investigating the phenomenological aspects of a rod behavior and the FP releases under power ramps tests or solicitation scenarios mainly in PWR conditions. Nevertheless, the current engineering phases explore different evolutions in the design of the loop allowing to increase the experimental offer (for instance with BWR TH approaching conditions or with simplified design).

The next steps of development of the ADELINE device will correspond to the detailed studies phase and its manufacture. The objective is to have this type of loop available for the JHR start-up (with eventually, at the first exploitation period, experimental tests with low risks of clad failures).

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