SUSTAINING MATERIAL TESTING CAPACITY IN FRANCE: FROM OSIRIS TO JHR

S. MARTIN
French Alternative Energies and Atomic Energy Commission (CEA),
Saclay,
France

G. BIGNAN
French Alternative Energies and Atomic Energy Commission (CEA),
Cadarache,
France

Abstract

Since 1966 the OSIRIS reactor located at Saclay Centre, near Paris, is participating to French and international Research and Development irradiation programs in the field of nuclear fuel and materials. CEA is operating OSIRIS to support industry and public organizations by strengthening knowledge in several fields such as plant-life management (study of pressure vessel steel ageing) or high burn-up LWR fuel qualification (study of pellet-clad interaction). However, OSIRIS, as most of existing MTRs in Europe, is over 40 years old. A safety and performance assessment has shown that even with a major refurbishment, OSIRIS would not allow guaranteeing the availability of the irradiation experimental capacity during additional decades. A new high performance MTR, operated in a European and international framework, is necessary to meet the needs of industry and public organizations (Research Centers, Safety Authorities…). This is the scope of the Jules Horowitz Reactor (JHR), under construction at the CEA Cadarache Centre (start of operation foreseen in 2016). The JHR design (reactor and experimental devices) takes benefit from the large amount of experience from OSIRIS as well as from other European MTR and will be for some decades a key international facility supplying services to the nuclear community. This paper presents the status of the OSIRIS and JHR reactors featuring their experimental capacities. It describes the main irradiation devices and the actions carried out to take into account OSIRIS feed-back. OSIRIS teams are dealing with design, manufacturing follow-up, safety studies, preparation, and irradiation follow-up, results analysis. The first transfer of know how is from ISABELLE 1 loop to ADELINE loop. The aim of these two loops is to determine LWR fuel limits while undergoing power ramp tests until clad failure. A close collaboration between Saclay and Cadarache teams is established to validate design options of ADELINE loop. The second transfer of know how, presented in this paper, relates to device used for material studies (it is named CHOUCA in OSIRIS and MICA in JHR). This paper focus especially on these two major devices, on neutronic and photonic reactor measurements, and on the transfer of know how from OSIRIS to JHR.

1. INTRODUCTION

OSIRIS reactor is participating to French and international Research and Development irradiation programs in the field of nuclear fuel and materials. CEA is operating OSIRIS to support industry and public organizations (Research Centres, Safety Authorities, …) by strengthening knowledge in several fields such as plant-life management (study of pressure vessel steel ageing) or LWR fuel qualification.

However, OSIRIS, as most of existing MTRs in Europe, is over 40 years old. A new high performance MTR, operated in a European and international framework, called Jules Horowitz Reactor (JHR) [1], is under construction at the CEA Cadarache Centre (start of operation foreseen in 2016). It will enable to sustain a material testing capacity in France.

The JHR design (reactor and experimental devices) takes benefit from the large amount of experience from OSIRIS. This paper describes the main irradiation devices and the actions carried out to take into account OSIRIS feed-back. Close exchanges between OSIRIS and JHR teams are done on the different kinds of devices but also on general themes such as command-control, safety analysis, and nuclear instrumentation. This article presents theses exchanges in particular about irradiation loops for fuel testing, devices for materials testing and neutronic/photonic reactor measurements.

2. IRRADIATION LOOPS FOR FUEL TESTING

The ISABELLE1 loop, set up at the periphery of the OSIRIS reactor, enables to test new fuel rods (with new clad material, new pellet size, or new type of fuel). The device is qualified to realize power ramps with a very good accuracy of the target's linear heat rate.

2.1. Power ramps objectives

The aim of power ramps is to determine the limit of fuel rod in class 1 and 2 incidental transients encountered in a power reactor. Different fuel rods are tested (with fresh fuel and high burn up) until clad failure. These tests are necessary to establish safety reports before the licensing of an industrial product, or a new kind of core loading (with high burn-up for example) by determination of the technological limit (maximal strain on cladding with no failure). The phenomenon is known as clad-pellet interaction: clad failure by stress corrosion due to pressure from pellets on cladding and corrosive fission products release during transient.

The ramp speed and plateau durations are formally set by the customer. The conditioning plateau is necessary to recover fuel's thermo-mechanical state similar to his life in power reactor.

Experiment results enable also to validate fuel's behavior modelling, especially study of pellet-clad interaction.

2.2. ISABELLE1 loop description

The ISABELLE1 loop represents PWR conditions (pressure, temperature, water chemical characteristics). The loop (Fig. 1) is composed of two parts:

— An in-pile part with the sample-holder inside a pressure tube (150 bar);
— An out-pile part in a bunker to pressurize water.

Experiments are carried out mostly on pre-irradiated UO_2 or MOX fuel rods in PWR conditions (and possibly BWR) up to 90 GWd/t.

Power variation is done by moving the device perpendicularly to OSIRIS core, slaved to neutron flux to guarantee the speed, and stopped according to thermal power to guarantee the target.

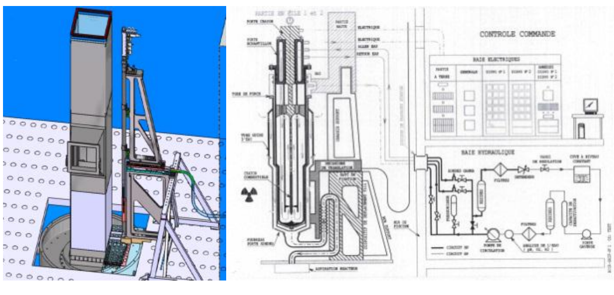


FIG. 1. ISABELLE 1 LOOP.

There is an on-line thermal balance with real time calculator and temperature, flow rate measurements. The target accuracy of upper plateau power is below10 $W.cm^{-1}$. Maximum linear heat rate is 600 W/cm.

A neutron balance is made by means of silver and cobalt self-powered neutron detectors (SPND), with an anticipatory algorithm.

Expansion of the rod is monitored by means of LVDT (Linear Voltage Differential Transformer) elongation sensor.

The on-line detection of clad failure is monitored by several means : a system measuring gamma activity, a delayed neutron detector, and a gamma spectrometry. Non destructive examinations enable to check pellets restructuring and precise neutron flux profile during the ramp.

2.3. ISABELLE1 qualification

Thermal power calculation has been validated by ETALISA experiment in ISABELLE1 loop (1992). Measurement of thermal balance has been compared to three separate measures of fission power : dosimetry, gamma spectrometry and neodymium isotopes proportioning. Gamma heating related to the fuel rod was measured by calorimetry.

Results of the different methods were corroborating. Uncertainties of linear heat power determination were evaluated at 5,8 % within 2 □ standard deviation.

From 1993 an important data base has been constituted: more than 60 ramps have been realized in ISABELLE1 loop.

2.4. ADELINE design [2]

ADELINE device, will comprise a sample holder (which contains possibly instrumented fuel rod) and also an instrumentation holder (which contains the thermocouples for thermal balance). The precise position of instrumentation will be defined using OSIRIS sample holders feed-back.

The sample can be instrumented with a fuel centerline thermocouple and back-pressure sensor (to analyze fission products and helium release kinetics). This type of instrumented fuel rods has been used for several experiments in OSIRIS using GRIFFONOS loop.

The objectives are also to make more ramps per cycle avoiding connecting/reconnecting phases and hot cells transfer: the loading and unloading of the sample holder underwater is in designing stage. This should also reduce delays before nondestructive examination.

The know-how of OSIRIS teams contributes to validate the design of ADELINE loop, taking into account easy device handling, connecting/reconnecting and also minimizing thermal leaks and pressure losses, increasing heat exchangers efficiency, reducing time of cladding failure detection so improving the loop operation.

Likewise ISABELLE1, 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. This enables to have smaller pipes and pumps in the out-of pile part. The jet pumps thermal hydraulics behavior is studied taking into account feedback from OSIRIS experimental results.

3. DEVICES FOR MATERIALS TESTING

3.1. CHOUCA, one of the main irradiation devices of OSIRIS reactor

The CHOUCA systems are devices mainly dedicated to irradiation of materials in the core of OSIRIS reactor (Fig. 2). We can divide them into 3 families:

- Passive capsules in which only measurements of the neutron flux and the temperature are made. Some periodic measurement can be performed on the irradiated specimens in dedicated hot labs outside of the reactor;
- Capsules in which the samples are submitted to stress or strain under irradiation;
- Metrology capsules, which are used to measure the dimensional changes of the samples in situ.

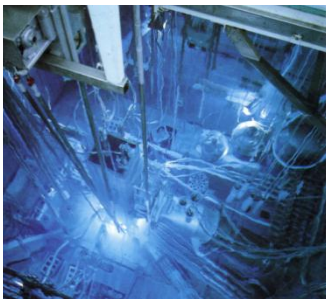


FIG. 2. OSIRIS core with CHOUCA devices inside.

The experiments carried out in CHOUCA systems are typically related to fuel cladding reactors' internal structures and neutron-absorbing materials.

This device has an useful diameter of 24 mm with a height under flux of 600 mm. It is designed according to a fast neutron flux (E > 1 MeV) up to $2.10^{18} n.m^{-2}.s^{-1}$ and a gamma heating up to 13 $W.g^{-1}$. The medium around the specimens is NaK and the usual operating temperature ranges from 250 to 400°C, adjusted to ± 5°C.

The temperature measurement is obtained by 12 thermocouples on the CHOUCA rig and 18 on the sample-holders. Activation foils are used for dosimetry to access the neutron fluence received by the samples.

3.2. From OSIRIS to JHR

The successor of the CHOUCA device in JHR is named MICA. The main characteristics of the MICA are similar to those of the CHOUCA (useful diameter around 24 mm, height under flux around 600 mm, NaK around the specimens and usual operating temperatures from 250 to 400°C, with possible extension to 600°C).

The global design of the MICA is based on CHOUCA's with an out of pile part for power supply and monitoring of the system, under water connection lines for electrical power and instrumentation and an in core part for supporting the instrumentation and the specimens in a static medium (NaK).

The MICA device is also designed in order to improve the quality of the experimental results, to be able to perform irradiation at higher temperature, and to manage highly instrumented irradiations.

JHR and OSIRIS teams are working together to take into account the OSIRIS feed-back for the design of JHR devices (meetings, creation of a common database for the documents related to the CHOUCA/MICA, transfer of know-how during process operation). For instance a close collaboration between the 2 teams was recently organized to test under gamma flux in an OSIRIS facility some pressure sensors that will be placed in the future MICA device.

Among all the different topics to deal with, the common JHR/OSIRIS teams will have to improve thermal performances of the MICA device, to optimize the location of the thermocouples on the future sample-holders, to optimize the design of the device in order to reduce thermal gradients on samples, to simplify hot lab operations and to be able to receive highly instrumented sample holder.

3.3. Evolution of the MICA device

JHR teams are working today on a future innovative evolution of the MICA device. Instead of using a stagnant liquid metal like NaK, the future CALIPSO [3] loop will perform a better control of the temperature around the samples by having the liquid metal flowing. The detailed design (Fig. 3) of this innovative device has been made concerning its geometry and its main components such as the electromagnetic pump, the electrical heater and the heat exchanger. The manufacturing of an out-of-pile prototype is under way. This prototype will be used to qualify the performance of the main components and to validate the thermal assessment of such a test device toward its licensing for irradiation in the Jules Horowitz Reactor.

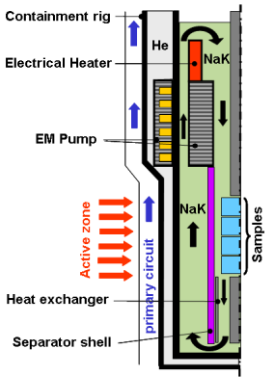


FIG. 3. Operating principle of CALIPSO loop.

3.4. An example of collaboration

The MELODIE experiment [4], in collaboration with VTT Technical Research Centre of Finland, is a practical example of a future experiment that will take place in a MICA device in JHR. Moreover, MELODIE which is now under construction (Fig. 4) will be tested next year in OSIRIS reactor.

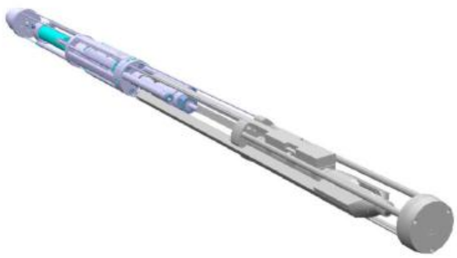


FIG. 4. The lower instrumented part of MELODIE sample-holder.

MELODIE, (MEchanical LOading Device for Irradiation Experiments), is planned as a 2-year in-core irradiation in OSIRIS reactor, aiming to assess the capabilities of an innovative sample holder for creep behavior study of advanced PWR fuel cladding. This experiment will allow to pilot biaxial stresses on samples and to monitor corresponding axial and radial deformations.

In a second step, MELODIE will take into account the feedback of irradiation in OSIRIS reactor to evolve in an improved version to be later implemented in the JHR MICA device.

Besides the scientific interest of a fast neutron flux as high as possible, the choice of the "hottest" locations in OSIRIS core is also dictated by the fact that MELODIE is intended to be used in JHR reactor, whose specific nuclear heating is still higher in the central locations. To be able to accommodate a much instrumented experiment like MELODIE is one of the challenges that the future MICA device will have to overcome in JHR. The MELODIE experiment is quite complicated and exotic for a CHOUCA device, should become a more classical experiment for the future JHR's MICA.

4. NEUTRONIC AND PHOTONIC REACTOR MEASUREMENTS

4.1. OSIRIS experience

4.1.1. OSIRIS' need for photonic and neutronic measurements

Many locally made probes for thermal neutron flux and gamma heating measurements have been developed for OSIRIS reactor monitoring. They have been used very frequently to characterize experimental locations inside or in the periphery of the core. The corresponding data are indeed required for safety assessment of new experiments. They are also necessary to choose irradiation locations and to design new irradiation devices to meet customers' requirements (samples temperature, thermal and fast neutron fluxes…).

4.1.2. CALMOS device

Following different generations of improved calorimeters, the last one for in-core measurements, CALMOS, brings very interesting progresses [5, 6]. This innovative device enables to perform both gamma heating and thermal neutron measurements. Thanks to a mobile probe, measurements can be performed at any axial position along the core height, or above. Furthermore, calorimetric measuring cells (sample and reference cells) are located one above the other and not side by side as for traditional calorimeters. The main advantage of such a configuration is a shorter diameter and a more pointwise measurement, limiting any radial gradient effect. Another key advantage of this system is that, when not in operation, the probe can be secured above the core in order to limit its ageing. It can also been noticed that the sheath structure surrounding the calorimeter, has been designed to be representative of a typical OSIRIS device used for in-core experiments. Gamma heating measurements are then really representative of energy deposit inside samples.

The R&D program started in 2002. Design and manufacturing of the device required a long development until its completion in 2011. Thermal simulations using Finite Element Cast3M code were performed to determine positions of constitutive elements and main dimensions. Two mock-ups of the probe were manufactured and tested in ISIS and OSIRIS pools to choose material references and to measure relevant characteristics (sensitivity, linearity, stabilisation time constant). A diagram of the final probe is presented on Fig. 5.

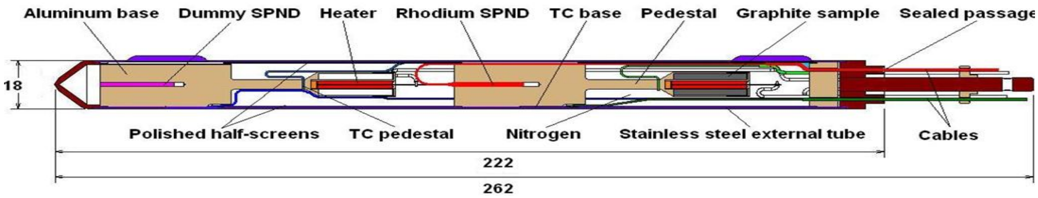
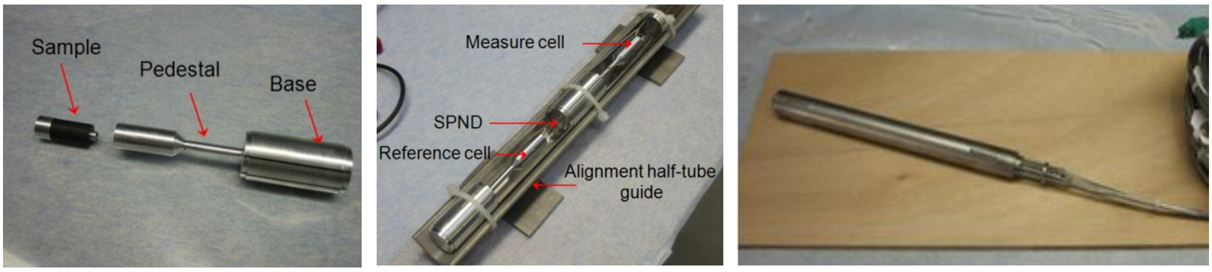


FIG. 5. Diagram of the calorimetric probe.

A mock-up of the whole device (equipped with a dummy calorimetric probe fixed on the moving system) was also manufactured and tested in order to check the probe displacement system. This mock-up was also tested, inside a bench representative of OSIRIS in-core thermo hydraulic conditions, to measure water flows inside the structure of the CALMOS device. These values are indeed necessary inputs for thermal calculations required for the safety demonstration report.

At the present time, this development is coming to an end. The final probe has been manufactured, tested and calibrated. A picture of the final calorimetric probe is shown on Fig.6. The whole system (probe associated with the moving system) has been manufactured and functional tests (under no irradiation conditions) have successfully been performed. First in-core qualification measurements inside OSIRIS reactor are scheduled in November 2011.



(a) (b) (c)

FIG. 6. Pictures of the final CALMOS calorimetric probe manufacturing (a) cell assembly, (b) probe assembly, (c) probe finalized.

4.2. Collaboration between OSIRIS and JHR on photonic and neutronic measurements devices

4.2.1. The JHR context

The JHR MTR reactor should have an even greater need for photonic/neutronic measurements than OSIRIS. Indeed, gamma heating being higher (up to around 20 $W/g_{graphite}$ versus a maximum of 12-13$W/g_{graphite}$ for Osiris conditions), accurate calorimetric measurements will be required to limit excessive thermal constraints on the future irradiation JHR experimental devices. Secondly, as no neutronic mock-up of the JHR core will be available (OSIRIS reactor has its own mock-up, the ISIS reactor), simulations will play a key role in the core management. This will therefore require previous codes validation and to do so, many comparisons between calculations and corresponding neutronic measurements.

4.2.2. CARMEN device

The longstanding nuclear measurement know-how of OSIRIS teams is therefore very useful for JHR ones. Looking for the same advantages highlighted by the CALMOS calorimeter, the concept of a mobile probe equipped with different sensors has been selected as one of the future equipments of the JHR reactor. The first step of this so-called CARMEN research and development project is to manufacture two different mock-ups, a neutronic probe and a photonic one [7]. The neutronic probe associates a Rhodium SPND and a ^{235}U fission chamber dedicated to thermal neutron flux measurement, and a ^{242}Pu fission chamber dedicated to fast neutron flux measurement. In addition, an ionisation chamber without fissile deposit will allow correcting the data. The photonic probe associates Bismuth SPND, a gamma thermometer, an ionisation chamber without fissile deposit and a calorimetric probe to measure gamma heating (drawn from CALMOS). All these sensors will allow characterizing the gamma field either in terms of photonic fluxes or in terms of gamma heating per mass unit.

These probes will soon be tested in the periphery of the OSIRIS core. A positioning system will be used in order to locate successively all sensors at the same level with regard to the core mid-plane. Measurements campaign will be completed with activation dosimetry data. All these results will enable to compare measurements in order to select the most appropriate detectors to equip the final CARMEN device. This comparison of different sensors will be performed within the framework of a PhD thesis.

5. FINAL REMARKS & CONCLUSIONS

Exchanges between JHR and OSIRIS teams are helpful to take into account OSIRIS feed-back for new devices design, and to improve quality, capacities and also innovation of material or fuel experiments. JHR outlooks enable CEA to continue major programs in OSIRIS reactor or start new ones with its high-performance devices. Continuity of irradiation programs will be guaranteed by OSIRIS devices operating till the second half of this decade and JHR devices starting operation in the same period (a joint program called JHIP [1] is being elaborated). Some long experiments, such as on pressure vessel steels, started in OSIRIS will have to be transferred and completed in JHR reactor.

The preparation of JHR experimental capacities benefits from the large know-how of OSIRIS and a strong interaction (cross-checking, calibration...) between existing experimental devices in OSIRIS and new ones in JHR is foreseen to maintain high quality experiments for the end-users of JHR.

REFERENCES

[1] BIGNAN, G. “The Jules Horowitz Reactor : A new European MTR (Material Testing Reactor) open to international collaboration : Update description and focus on the modern safety approach” Proceedings of the International Conference on Research Reactors: Safe Operation and Effective Utilization, 11–15 November 2011, Rabat, IAEA, Vienna (2012).

[2] GAILLOT, S., “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,” IGORR, Beijing, 2009.

[3] MOULIN, D., “Thermal assessment of the CALIPSO irradiation de vice for the Jules Horowitz Reactor” DEN/CAD/DTN/STPA/LCIT/ NT/2010/N°056.

[4] GUIMBAL, P., “ Status of the MELODIE experiment, an advanced device for online biaxal study of the irradiation creep of LWR cladding,” RRFM’11 Rome, 2011.

[5] CARCREFF, H., Patent N° FR 1060068, (2010).

[6] CARCREFF, H., “CALMOS : Innovative device for the measurement of nuclear heating in Material Testing Reactors,” submitted to ASTM for the ISRD 14 congress.

[7] FOURMENTEL, D., “Combined analysis of neutron and photon flux measurements for the Jules Horowitz Reactor core mapping,” ANNIMA, Ghent, 2011.