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A complete dosimetry experimental program in support to the core characterization and to the power calibration of the CABRI reactor

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Abstract– **CABRI is an experimental pulse reactor operated by CEA at the Cadarache research center. Since 1978 the experimental programs have aimed at studying the fuel behavior under Reactivity Initiated Accident (RIA) conditions. Since 2003, it has been refurbished in order to be able to provide RIA and LOCA (Loss Of Coolant Accident) experiments in prototypical PWR conditions (155bar, 300°C). This project lied within a broader scope including an overall facility refurbishment and a safety review. The global modification is conducted by the CEA project team. It is funded by IRSN, which is conducting the CIP experimental program, in the framework of the OECD/NEA project CIP. It is financed in the framework of an international collaboration.**

During the reactor restart, commissioning tests are realized for all equipment, systems and circuits of the reactor. In particular neutronics and power commissioning tests will be performed respectively in 2015 and 2016.

This paper focuses on the design of a complete and original dosimetry program that was built in support to the CABRI core characterization and to the power calibration.

Each one of the above experimental goals will be fully described, as well as the target uncertainties and the forecasted experimental techniques and data treatment.

I. INTRODUCTION

CABRI is an experimental pulse reactor operated by CEA at the Cadarache research center. Since 1978 the experimental programs have aimed at studying the fuel behavior under Reactivity Initiated Accident (RIA) conditions. Since 2003, it has been refurbished in order to be able to provide RIA and LOCA (Loss Of Coolant Accident) experiments in prototypical PWR conditions (155bar, 300°C). This project lied within a broader scope including an overall facility refurbishment and a safety review. The global modification is conducted by the CEA project team. It is funded by the French Institute of Nuclear Radiation protection and Safety (IRSN), which is conducting the CIP experimental program, in the framework of the OECD/NEA project CIP. It is financed in the framework of an international collaboration.

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This paper focuses on the design of a complete and original dosimetry program that was built in support to the CABRI core characterization and to the power calibration.

Cobalt and gold disk and wire dosimeters will be used for:

- determining precisely the radial and axial flux profiles vs. energy, inside the CABRI driver core and inside the central cell in which test fuel pin is inserted,
- calibrating the power of the CABRI core and hence the CABRI experimental chambers used for recording power transients,
- calibrating the energy deposit during power transients,
- measuring the coupling factor between the driver core and the test fuel pin,
- contributing to the measurement of CABRI kinetics parameters (prompt neutrons lifetime and effective fraction of delayed neutrons),
- validating the neutronics calculations performed in support to the safety studies and to the design of the CIP experiments.

Each one of the above experimental goals will be fully described, as well as the target uncertainties and the forecasted experimental techniques and data treatment.

II. CABRI COMMISSIONING TESTS

A. *Description of the CABRI reactor*

Cabri is a pool-type reactor, with a core made of 1487 stainless steel clad fuel rods with 6% ^{235}U enrichment. The reactor is able to reach a 25MW steady state power level. The reactivity is controlled via a system of 6 control and safety rods made of 23 hafnium pins for each (see Fig. 1).

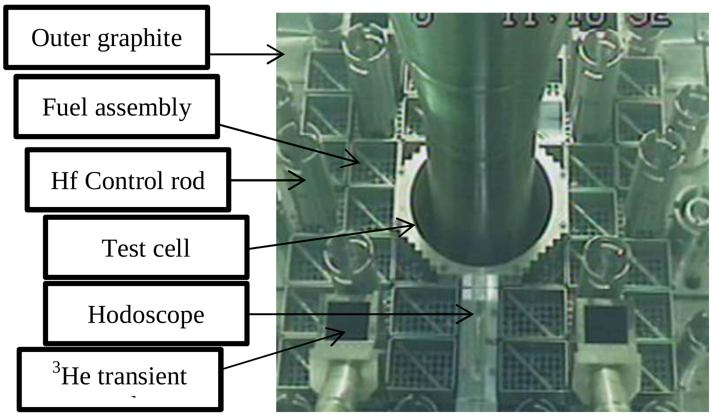

Fig. 1. CABRI core

The key feature of CABRI reactor is its reactivity injection system [1]. This device allows the very fast depressurization into a discharge tank of the ^{3}He (strong neutron absorber) previously introduced inside 96 tubes (so called "transient rods") located among the CABRI fuel rods. The rapid absorber depressurization translates into an equivalent reactivity injection possibly reaching 4$ within a few 10ms. The power consequently bursts from 100 kW up to ~20GW (cf. Fig. 2) in a few ms and decreases just as fast due to the Doppler effect and other delayed reactivity feedbacks. The total energy deposit in the tested rod is adjusted by dropping the control and safety rods after the power transient.

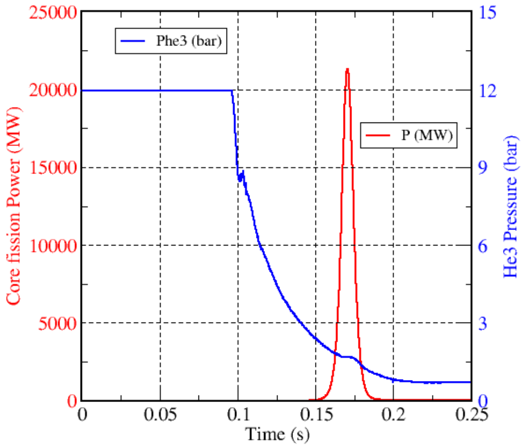

Fig. 2. Typical CABRI ^{3}He Pressure and core power shapes during a RIA transient

B. *Status of the CABRI recommissioning*

Since 2003 the CABRI facility has been refurbished and upgraded in order to fit with new safety rules imposed by the French regulators and with the setup of a pressurized water loop in the center of the reactor.

Seismic reinforcements have been carried out as for the reactor building, the reactor pool and the primary cooling system.

Several modifications and upgrades have also been achieved on equipment and circuits such as the pressurized water loop vessel and lines, the transport cask, the core vessel, the ventilation, the safety and control rods, the transient rods and the primary cooling system.

After which the commissioning tests were successfully performed on equipment and circuits to demonstrate their good functioning prior to the 1st CIP RIA test and to fit with new safety rules imposed by the French regulators. Those commissioning tests mostly dealt with the reloading of the driver core, the primary cooling system, the control and safety rods [2] and the Helium-3 transient rod system [1]. The commissioning tests on the pressurized water loop are this date still in progress.

C. *Focus on the neutronics commission tests*

The neutronics commission tests aim at precisely characterizing the neutronics parameters of the CABRI core [3] (see Table I): reactivity effects, power distributions and kinetic parameters. They are carried out at low power (< 100 kW), in natural convection and at ambient temperature.

TABLE I. NEUTRONICS PARAMETERS, MEASUREMENT TECHNIQUES AND TARGET UNCERTAINTIES FOR NEUTRONICS COMMISSIONING TESTS

Neutronics parameters	**Measurement technique**	**Target uncertainty (1σ)**
Critical height	Critical state	± 1mm
Integral reactivity worth of control and safety rods	MSA/MSM & « *rod drop* »	± 4%
Differential reactivity worth of control and safety rods	Doubling time	± 1%
Core power distribution	Dosimetry	± 2%
Isothermal temperature coefficient	Critical state	± 1 pcm/°C
Reactivity effects inside the water loop	Critical state	± 5%
Axial flux profile	Dosimetry	± 2%
Core stacking reactivity worth	Critical state	± 5%
Effective fraction of delayed neutrons	Rossi and Feynman-α methods	± 3%
Effective prompt neutron lifetime		± 3%
Axial distribution and integral of fission rate in the core	Dosimetry	± 2%
Reactivity worth of the ^{3}He transient rods	Critical state	± 5%
Integral reactivity worth of control and safety rods	MSA/MSM & « *rod drop* »	± 4%
Differential reactivity worth of control and safety rods	Doubling time	± 1%

These tests are designed to demonstrate the ability of the CABRI core to achieve target performances towards testing and safety margins while controlling at best the associated uncertainties. Another goal is to validate the preliminary neutronics calculations performed for the design of the safety and the performances of the CABRI core.

D. *Focus on the power commission tests*

The power commission tests are essentially made of two parts.

The first part is performed using the CABRI reactor at a steady state power up to 25MW. The main goal is to precisely calibrate the core power through heat balances measurements. Hence it is also used for calibrating the operation and experimental neutron detectors (compensated boron chambers) vs. power.

The second part aims at testing the global functioning of the CABRI facility with all circuits underway (transient rods, pressurized water loop, control and safety rods, primary cooling system). The final goal is to perform so-called "startup tests", i.e. to demonstrate the ability of CABRI to provide accurate power transients of different shapes (in terms of maximum power and Full Width at Half Maximum (FWHM) duration).

III. CONTRIBUTION OF THE DOSIMETRY PROGRAM

In addition to the instrumentation and experimental techniques usually used for standard commissioning tests (see Table I), a complete and complementary dosimetry experimental program has been added in support to the CABRI core characterization and to the power calibration.

A. *Dosimeters and dedicated equipment*

2 types and 2 natures of dosimeters will be used for the CABRI tests. Depending on their location in the core the shape of dosimeters (disk or wire) was chosen. The use of cobalt (^{59}Co) and gold (^{197}Au) dosimeters will allow providing information on both thermal and epithermal neutron energy spectra using the method described in [4].

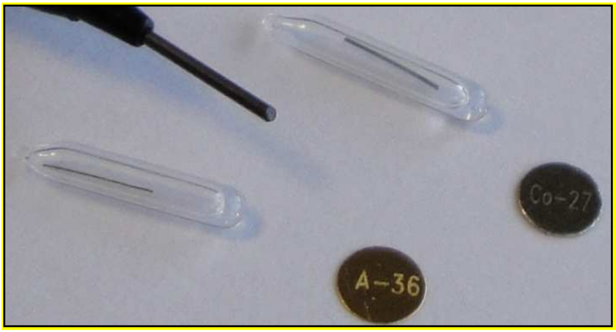

Fig. 3. Example of cobalt wire dosimeter (under quartz) and of cobalt and gold disk dosimeters

Sizing of dosimeters (mass, diameter, wire or disk) was conducted taking into account the following criteria and design elements:

- The target irradiation conditions (duration and power),
- The spatial cluttering specific to each measurement position,
- An activity high enough for measurements (>1Bq) but less than 1MBq at the end of irradiation to facilitate handling and transport,
- Calculated neutron capture rates of ^{59}Co and ^{197}Au at the different positions of dosimeters. Those calculations were performed using a 3D and real geometry model of CABRI [6] [7] with the TRIPOLI-4 French Monte Carlo code [5] and the JEFF3.1.1 nuclear data library [8],
- The minimization of neutronic self-shielding due to the strong resonances of ^{59}Co and ^{197}Au (see Fig. 4), by reducing the dosimeters thickness and diameter as much as possible.

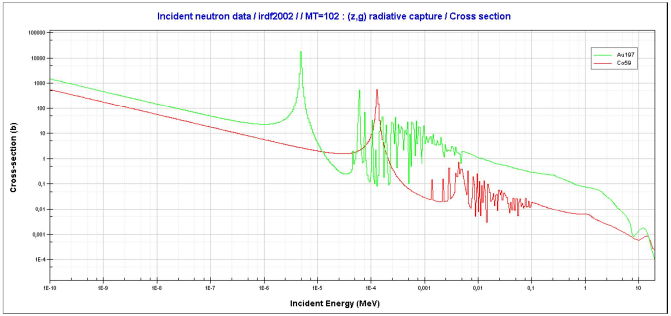

Fig. 4. (n,γ) cross sections of ^{59}Co and ^{197}Au [8].

Disk dosimeters are supported by an aluminum holder (see Fig. 5 and Fig. 7) which are themselves supported by the hodoscope device and hence positioned between fuel assemblies near the core center (see Fig. 6 and Fig. 7).

Wire dosimeters are included inside tubes (see Fig. 5) which will be positioned at 3 locations: in the center of the test cell, inside a dummy assembly (see Fig. 6) and outside of the graphite reflector surrounding the core. Each tube is made of 5 gold wires and 5 cobalt wires equally alternated and positioned symmetrically as regard to the mid plan of the core.

All equipment to handle the aluminum holders and tubes (~80cm high) has been specifically manufactured at CEA Cadarache, as well as a dedicated bench for removing dosimeters after the irradiations.

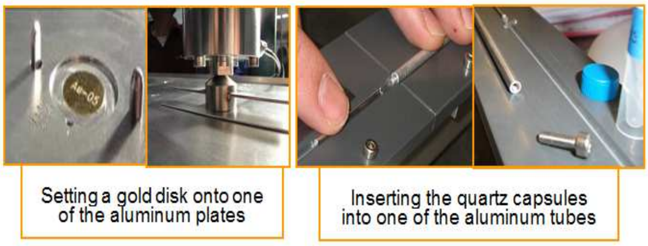

Fig. 5. Setting of disks on aluminum holders and insertion of wires in aluminum tubes

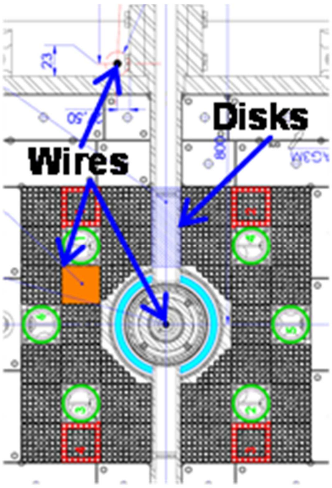

Fig. 6. Position of wire and disk dosimeters inside the CABRI core (transient rods in red, control rods in green, dummy assembly in orange)

In the end a total set of 220 dosimeters was designed and manufactured for CABRI commissioning tests. After the tests and shipment, the final spectrometry measurements will be performed at the MADERE platform of CEA Cadarache [9] on measurement benches equipped with HPGe detectors.

The following chapters will detail the design and measurements performed with the different dosimeters and will establish the link and the complementarity with the other measurements of commission tests.

B. *Support to the validation of neutronics calculations*

The predictive neutronics calculations of the CABRI core were performed using the TRIPOLI-4 calculation scheme described in section III. This calculation scheme was as much as possible validated with regard to past experiments with a sodium loop in the center of the CABRI core. However, only integral parameters (multiplication factor, reactivity worth of control rods and of transient rods) were studied because of the lack of local experimental results. Moreover, the validation on integral parameters has to be checked with the water loop in the center of CABRI.

Hence it is crucial to be able to accurately measure fine power distributions inside the CABRI core. It is also valuable to have more information on the neutron spectrum inside the core. To do that, several dosimetry measurements will be achieved at low power (<100kW) during the neutronics commission tests:

- A relative reaction rates distribution will be measured along the hodoscope channel with thin disks of gold and cobalt (4mm or 10mm of diameter). It will provide a total of 60 dosimetry irradiations corresponding to 5 radial and 10 axial locations (see Fig. 7). As the hodoscope channel can be considered as a void layer between subassemblies, those measurements will give axial and radial local distributions in a neutron spectrum representative of the CABRI core.
- A relative reaction rate axial distribution in the center of the test cell.
- 4 relative reaction rate axial distributions at the 4 corners of the dummy assembly, rather close to the control rods that will be at their critical position

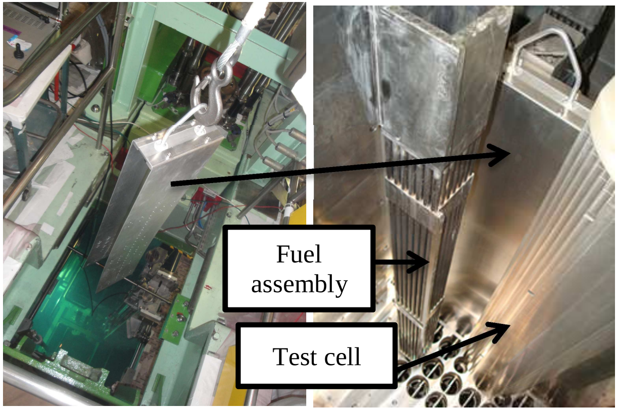

Fig. 7. Insertion of the dosimeter aluminum holder inside the CABRI core (left) and positioning upon the hodoscope device (right)

The ratio of ^{59}Co and ^{197}Au reaction rates of dosimeters irradiated in the center of the test cell and inside the dummy assembly will also be compared with the calculated ratio. This will contribute to validate the calculation of the coupling factor, defined as the ratio between the driver core power and the test fuel pin power.

C. *Support to the measurement of safety parameters*

Kinetics parameters (β = effective fraction of delayed neutrons and Λ = prompt neutrons lifetime) are crucial parameters for the control of the reactor. They allow to determining the Nordheim curve of a reactor.

Cross power spectral density measurements [10] [11] will be achieved during the neutronics commissioning tests. β and Λ will be inferred using the following equations:

$$\beta^2 = \frac{2D}{F}\,\frac{V_{01}V_{02}}{CPSD}\,\frac{1}{(1+|\rho_\$|)^2} \quad \text{and} \quad \Lambda = \frac{\beta}{2\pi f_c}$$

Where: CPSD is the cross power spectral density between V_{01} and V_{02} (signals of the two fission chambers positioned inside the dummy assembly), D is the Diven factor, $\rho_\$$ is the core reactivity in dollars, f_c is the break frequency of CPSD and F is the total number of fissions in the core per unit of time.

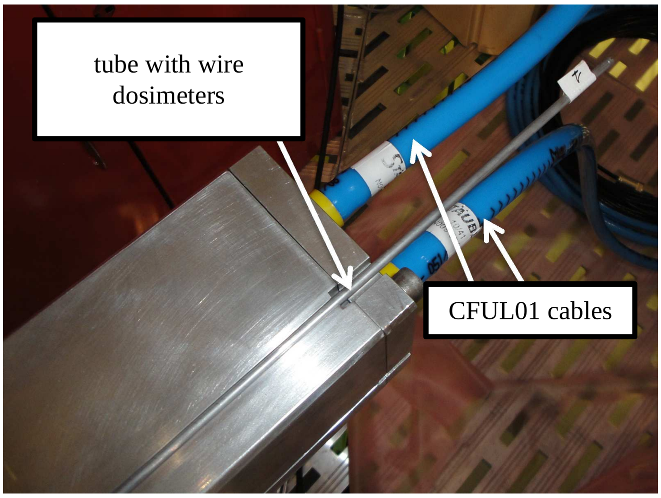

Fig. 8. View of the dummy assembly

The determination of F will be performed using the measured activities of cobalt and gold wires places at each corner of the dummy assembly and knowing (by calculations) their radiative capture rate per unit of flux.

D. *Support to an enhanced control of the power and of the energy deposit during transient tests*

The accurate measurement of the absolute power and hence of the total energy deposit during transients is crucial.

The measurement of the core power is carried out using a heat balance method. During steady states of power, this method consists in measuring the primary coolant heating for an accurate monitored flow rate. In the end the current delivered by experimental neutron detectors is calibrated vs. the power measured by heat balance. However this calibration is only possible until a 25MW power that is the maximum deliverable power level that can be obtained for a steady state operation of CABRI. An uncertainty around 3% (1σ) is expected.

In order to check that this calibration is still reliable during power transient (up to 25GW), and hence that the linearity of experimental neutron detectors is good between 25MW and 25GW, we will compare the activities of ^{59}Co and ^{197}Au dosimeters generated during heat balance measurements and during power transients. This will be carried out during power commissioning tests, using a same position of wire dosimeters (outside of the graphite reflector surrounding the core, see Fig. 6) and targeting a same injected energy in the driver core (270MJ) for both measurements. In the end this will help to minimize the experimental uncertainty on absolute power measurements and to strengthen the estimation of the uncertainty on the energy deposit during power transients (see Fig. 9).

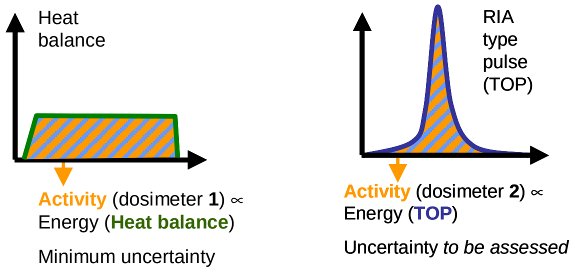

Fig. 9. High power neutron detectors calibration

Moreover the axial power distribution measured with the hodoscope device will be controlled by comparison with the axial reaction rate distribution measured by dosimetry in the center of the test cell.

IV. CONCLUSION

This paper shows the high interest to carry out complementary dosimetry measurements during the neutronics and the power commissioning tests of the CABRI reactor.

This original approach will provide a strengthened validation of neutronics calculations, and an enhanced control of the power and of the energy deposit during RIA power transients. It will also contribute to the measurement of CABRI kinetic parameters and hence to the control of those crucial safety parameters.

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