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Analysis of the dosimetry campaign performed during the CABRI commissioning tests

J. Lecerf¹, Y. Garnier¹, JP. Hudelot¹, JM. Girard², C. Domergue², L. Gaubert³, M. Maillot³, C. Manenc⁴, S. Mirotta⁴

johann.lecerf@cea.fr

¹ CEA, DEN, CAD/DER/SRES/LPRE, Cadarache, F-13108 Saint-Paul-lez-Durance, France

² CEA, DEN, CAD/DER/SPEX/LDCI, Cadarache, F-13108 Saint-Paul-lez-Durance, France

³ CEA, DEN, CAD/DER/SPRC/LPN, Cadarache, F-13108 Saint-Paul-lez-Durance, France

⁴ IRSN, PSN-RES/SEREX/L2EP, Cadarache, F-13108 Saint-Paul-Lez-Durance, France

Abstract– CABRI is an experimental pulse reactor operated by CEA at the Cadarache research center and funded by the French Nuclear Safety and Radioprotection Institute (IRSN).

For the purpose of the CABRI International Program (CIP), operated and managed by IRSN under an OECD/NEA framework it has been refurbished since 2003 to be able to provide experiments in prototypical PWR conditions (155 bar, 300 °C) in order to study the fuel behavior under Reactivity Initiated Accident (RIA) conditions.

This paper first reminds the design and the goals of the dosimetry program that was built in support of the commissioning tests performed for the reactor restart and requalification.

Then it focuses on the irradiation conditions for each dosimeter and presents the measurement results.

Finally, an analysis of the dosimetry campaign including measurement-calculation comparisons is presented.

I. INTRODUCTION

CABRI is an experimental pulse reactor operated by CEA and funded by the French Nuclear Safety and Radioprotection Institute (IRSN), 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 (155 bar, 300 °C). This project is part of a broader scope including an overall facility refurbishment and a safety review. The global modification has been conducted by the CEA project team and funded by IRSN, which is operating and managing the CIP experimental program (CABRI International Program), in the framework of the OECD/NEA agreement.

During the reactor restart, commissioning tests have to be realized for all equipment, systems and circuits of the reactor. In particular neutronics commissioning tests have been performed in 2015 and 2016.

This paper focuses on the analysis of the results of the complete and original dosimetry program that was built in support of the CABRI core characterization.

Cobalt and gold disk and wire dosimeters have been used for:

- determining precisely the radial and axial flux profiles inside the CABRI driver core and inside the central cell in which test fuel pin can be inserted,
- validating the neutronics calculations performed to support the safety studies, to design the CIP experiments and to calculate the coupling factor between the driver core and the test fuel pin,
- contributing to the measurement of CABRI kinetics parameters (prompt neutrons generation time and effective fraction of delayed neutrons).

Each one of the above experimental goals will be described, as well as the target uncertainties.

II. CABRI REACTOR AND COMMISSIONING TESTS

A. Description of the CABRI reactor

CABRI is a pool-type reactor, with a core made of 1487 UO₂ fuel rods with a 6 % ²³⁵U enrichment with stainless steel clads. The reactor is able to reach a 25 MW 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). The core is cooled by a forced water flow of 3215 m³.h⁻¹ when the core power is upper than 100 kW and by natural convection with the pool water otherwise [1].

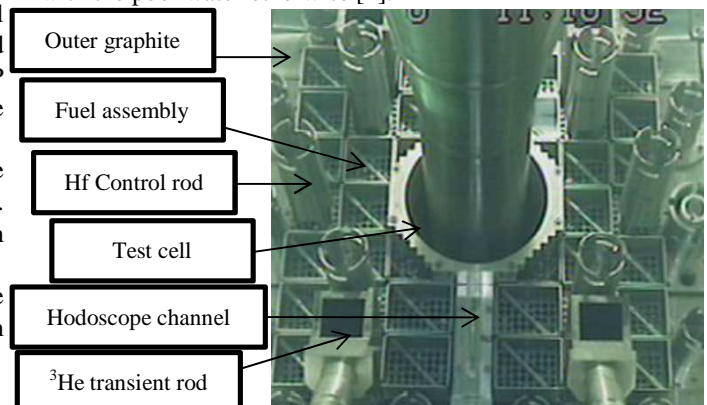


Fig. 1. Core of CABRI

The key feature of CABRI reactor is its reactivity injection system [2]. This device allows the very fast depressurization of the ^3He (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 3.9 $\$$ within a few 10 ms. The power consequently bursts from 100 kW up to ~ 20 GW (see Fig. 2) in a few ms and decreases just as fast due mainly to the Doppler effect. The total energy deposit in the tested rod is adjusted by dropping the control and safety rods after the power transient.

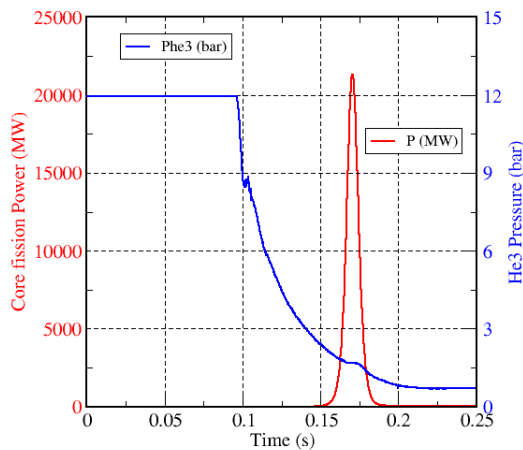


Fig. 2. Typical CABRI ^3He Pressure and core power shapes during a RIA transient

The other specificity of the CABRI core is the Hodoscope, a unique online fuel motion monitoring system. A channel crosses vertically the core in order to lead the fast neutrons emerging from the test rod to a bank of 306 sensors: 153 fission chambers and proton recoil counters located by pair behind a collimator composed of 153 measurement channels (3 columns of 51 rows). The Hodoscope device, an IRSN experimental equipment, is specifically designed to track the axial test fuel displacement during power transients.

B. Focus on the neutronics commissioning tests

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

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

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

These tests are designed to demonstrate the ability of the core of CABRI to provide appropriate testing conditions and safety margins while controlling the associated uncertainties in the best possible way. Another goal is to validate the preliminary neutronics calculations performed for the design of the safety and the performances of the core of CABRI.

III. DESIGN OF THE DOSIMETRY PROGRAM

In addition to the instrumentation and experimental techniques generally used for standard commissioning tests, a complete and complementary dosimetry experimental program has been designed in support of the characterization and the power calibration [4] of the core of CABRI.

Two types and two natures of dosimeters have been used for the CABRI commissioning tests. Depending on their location in the core the shape of dosimeters (disk or wire) was chosen (see Fig. 3). The use of cobalt and gold dosimeters enables to provide information on both thermal and epithermal neutron energy spectra depending on the (n,γ) cross sections of ^{59}Co and ^{197}Au .

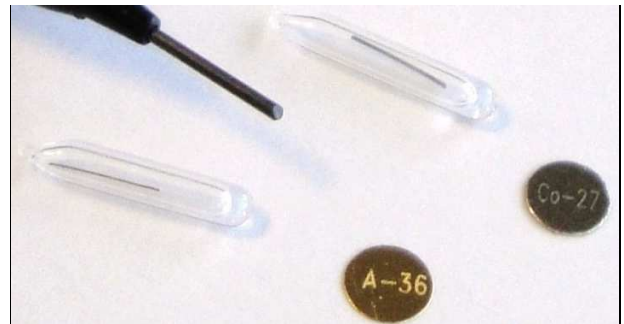


Fig. 3. Example of cobalt wire dosimeter (under quartz bulb) and of cobalt and gold disk dosimeters

Disk dosimeters are supported by two aluminum plates, which are themselves located along the irradiation channel of the Hodoscope device, and hence positioned between fuel assemblies near the core center (see Fig. 4).

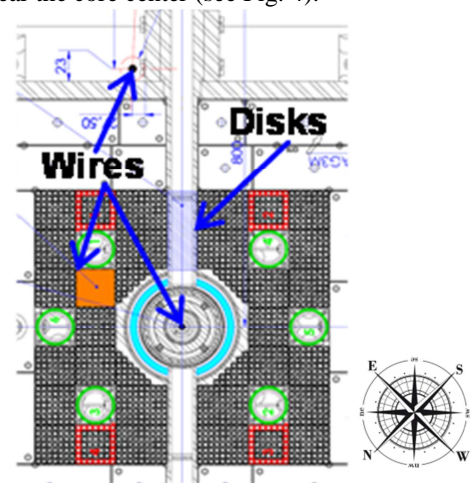


Fig. 4. Position of wire and disk dosimeters inside the core of CABRI (transient rods in red, control rods in green, dummy assembly in orange)

Wire dosimeters (thin wires in sealed quartz bulbs) are included inside tubes which are positioned at 3 locations: in the center of the test cell, inside a dummy assembly and outside of the core against the graphite reflector (see Fig. 4).

In the end a total set of 120 dosimeters was designed and manufactured for CABRI neutronics commissioning tests. After the tests, the dosimeters were recovered and shipped to the MADERE platform of CEA Cadarache [5] for performing spectrometry measurements on measurement benches equipped with High Purity Germanium (HPGe) detectors.

Calculations of neutron capture rates of ^{59}Co and ^{197}Au at the different positions of dosimeters were performed using a 3D and real geometry model of CABRI with the TRIPOLI-4 French Monte Carlo code [6] and the JEFF3.1.1 nuclear data library. Note that the calculations are then normalized in such a way that the power deduced from all the calculated activities on the dosimeters is equal to the experimental power deduced from measured activities. This makes it possible to obtain an indication on the dispersion of the C/E deviations.

These calculations were preliminary used to define the mass of each dosimeter, with respect to the foreseen irradiation level and duration.

The following chapters will detail the irradiation conditions performed with the different dosimeters and will present the results of the dosimetry campaign.

IV. HODOSCOPE DOSIMETRY

A. Objectives and design of Hodoscope dosimeters

The main objectives of this irradiation were:

- to obtain detailed reaction rates distribution and comparisons with calculations,
- to check out of North East/South West symmetry (red encapsulated dosimeters on Fig. 5),
- to provide information on both thermal and epithermal neutron energy spectra,
- to contribute to the calibration of the power of CABRI core.

Disk dosimeters used are described in Table II and Table III. A total of 60 dosimeters corresponding to 5 radial and 16 axial locations have been irradiated in the core of CABRI at a power of ~2.5 kW during one hour.

The position of the dosimeters on the aluminum plates is shown in Fig. 5. The position of the plates in the core of CABRI is defined in Fig. 4.

TABLE II. DOSIMETERS OF THE SOUTH WEST PLATE

Nature	Number	Type	Thickness
Co	15	Disk Ø 4 mm	0.125 mm
	3	Disk Ø 10 mm	0.125 mm
Au	6	Disk Ø 4 mm	0.05 mm

TABLE III. DOSIMETERS OF THE NORTH EAST PLATE

Nature	Number	Type	Thickness
Co	4	Disk Ø 4 mm	0.125 mm
Au	25	Disk Ø 4 mm	0.05 mm
	7	Disk Ø 10 mm	0.10 mm

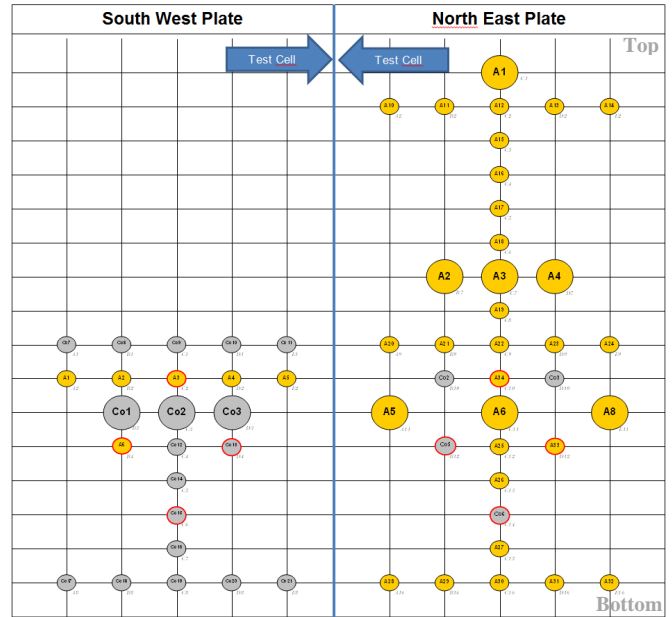


Fig. 5. Position of disk dosimeters on aluminum plates

B. Main results of Hodoscope dosimetry campaign

This section presents the measurement and calculation results obtained during the Hodoscope dosimetry campaign.

Axial distributions measured and associated calculations are compared on Fig. 6 and Fig. 7. A good agreement of the results is obtained.

10 mm diameter disk are indicated in green in the figures. The results of those dosimeters are substantially lower than the 4 mm diameter dosimeters ones, due to differences in neutron self-shielding effects (variation in diameter and thickness of dosimeters).

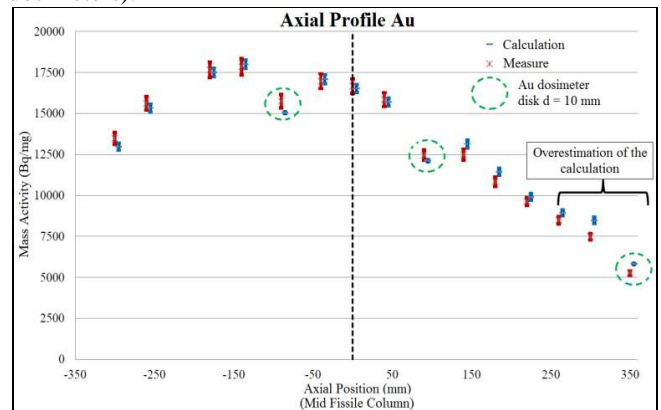


Fig. 6. Au dosimeters of the North East plate – axial mass activity distributions – measurements and calculations

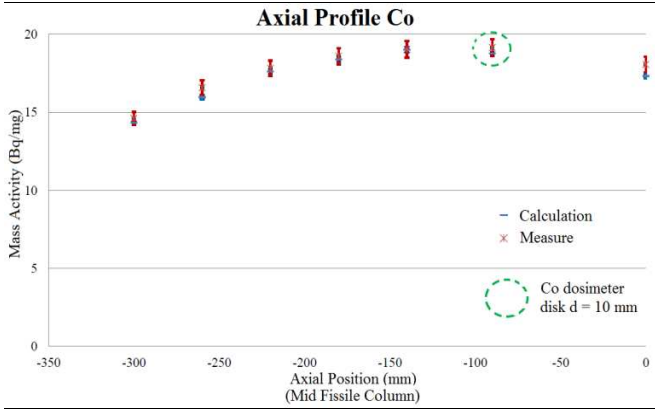


Fig. 7. Co dosimeters of the South West plate – axial mass activity distributions – measurements and calculations

Measured radial distributions are shown on Fig. 8 for Au dosimeters and Fig. 9 for Co dosimeters. As the distance from the test cell (center of the core of CABRI) increases, the dosimeter activity decreases slightly.

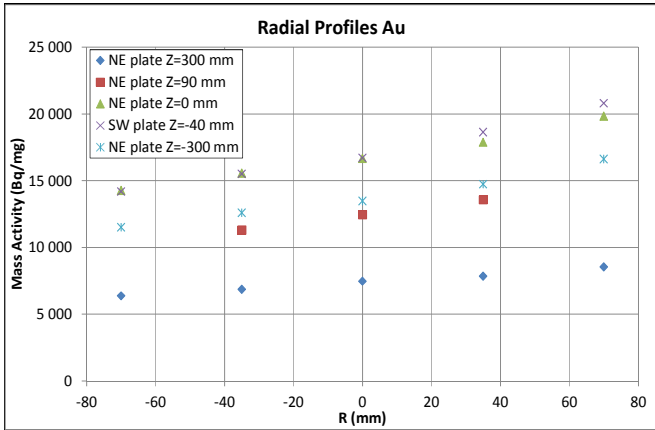


Fig. 8. Au dosimeters - radial mass activity distributions - measurements

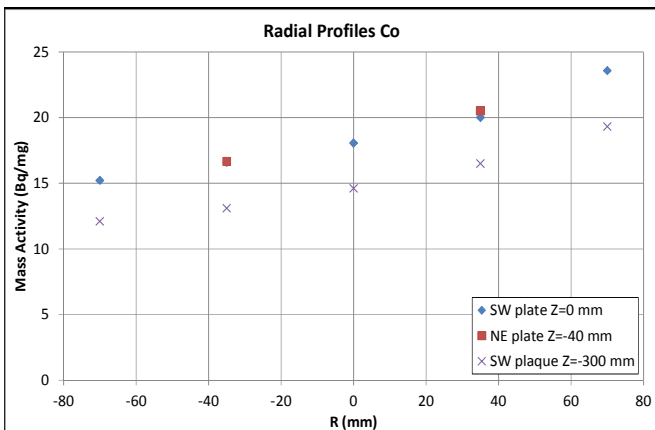


Fig. 9. Co dosimeters - radial mass activity distributions - measurements

North East/South West symmetry is checked. Activity differences between symmetric dosimeters are less than measurement uncertainties (see Table IV).

TABLE IV. HODOSCOPE - SYMMETRIC DOSIMETERS

		Dosimeter	Mass Activity (Bq/mg)	Measurement uncertainties k=2 (%)	$\Delta_{NE/SW}$ (%)
1	NE	NE-Au-34	1.697E+04	2.7%	1.6%
	SW	SW-Au-03	1.670E+04	2.6%	
2	NE	NE-Co-05	2.198E+01	2.8%	2.8%
	SW	SW-Co-13	2.136E+01	2.9%	
3	NE	NE-Au-33	1.638E+04	2.7%	1.8%
	SW	SW-Au-06	1.668E+04	2.6%	
4	NE	NE-Co-06	1.791E+01	2.8%	0.5%
	SW	SW-Co-15	1.782E+01	2.8%	

V. CENTER OF THE TEST CELL

A. Objectives and design of test cell dosimeters

Two irradiation campaigns have been performed: one with the test cell in air and one with the test cell filled with water. The dosimeters were centered in the test cell at the driver core elevation.

The main objectives were:

- to obtain a relative reaction rate axial distribution in the center of the test cell,
- to validate neutronics calculations used to predict the coupling factor between the test fuel and the driver core of CABRI,
- to compare the mass activity axial distributions of the dosimeters to the axial profile measured with the Hodoscope device.

Wire dosimeters used are described in Table IV and their positions inside the aluminum tube are illustrated in Fig. 10.

Each tube is made of 5 gold wires and 5 cobalt wires equally alternated and positioned symmetrically as regard to the mid plane of the core.

A total of 20 dosimeters have been irradiated in the core of CABRI during one hour at a power of ~2.5 kW for dosimeters placed in the case of the cell filled with air and during one hour at a power of ~25 kW in the case of the cell filled with water.

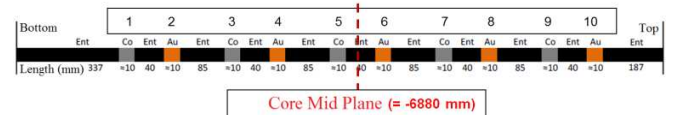


Fig. 10. Position of wire dosimeters inside the aluminum tube

B. Main results of test cell dosimeters

The axial profiles for Au and Co dosimeters are shown on Fig. 11 for the test cell filled with air and Fig.12 for the test cell filled with water.

The axial profiles obtained by dosimeter activity measurements in the center of the test cell are compared with the axial power distribution measured with the Hodoscope system. Note that the hodoscope device has been designed to measure fast neutrons (greater than ~600 keV) coming from the core and the test rod, and it is very precise (statistical uncertainty less than 1%) at high power levels (i.e. during power transients, reaching more than 20 GW).

In Fig. 11 and Fig. 12 it is possible to see a great according between dosimetry and hodoscope measurements. That means a constant ratio between thermal flux and fast neutron flux in steady state conditions. Hodoscope results present high uncertainties because of low power plateau.

Table V gives dosimetry measurement – TRIPOLI-4 calculation relative errors and uncertainties. The axial profiles measured and calculated are presented on Fig. 13 and Fig .14.

TABLE V. RELATIVE ERRORS AND ASSOCIATED UNCERTAINTIES FOR AU (ORANGE) AND CO (GREY) DOSIMETERS – TEST CELL WATER AND AIR

Axial location (mm)	Test Cell - Water		Test Cell - Air	
	(C/E-1) (%)	Associated uncertainties (k=2) (%)	(C/E-1) (%)	Associated uncertainties (k=2) (%)
-315	-4,5	2,8	-4	2,9
-265	-5,5	3,4	1,7	4,6
-170	-3,7	2,8	-4,7	2,9
-120	-3,4	3,5	2,6	3,7
-25	0,7	2,8	-1,5	2,9
25	-2,1	3,4	0,3	3,7
120	4,2	2,8	-0,3	2,9
170	4,6	3,6	3,4	3,9
265	6,6	2,9	0,2	3
315	5,9	4	9,6	5

Most of the time, the relative deviations between measurements and calculations are consistent with the associated uncertainty that is the composed of the experimental uncertainty and of the statistical uncertainties of the TRIPOLI-4 calculations. The highest deviations are observed for extreme positions of the dosimeter holder, i.e. for the lowest mass activities. A general trend is a slight overestimation of all reaction rates calculated in the upper part of the core (above mid plane) and a slight underestimation in the lower part.

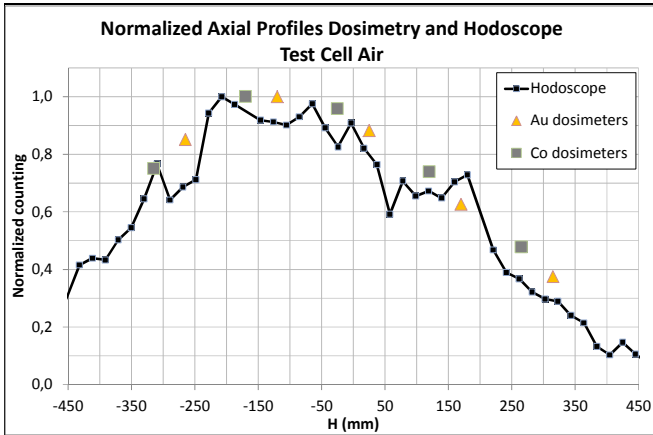


Fig. 11. Au and Co axial profiles measurements for test cell in air dosimeters and Hodoscope axial profile

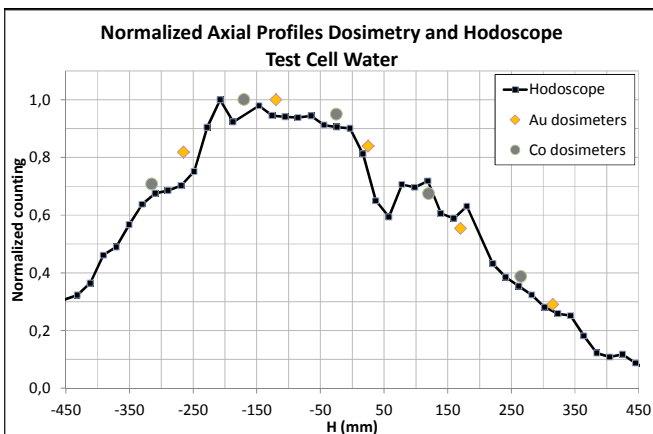


Fig. 12. Au and Co axial profiles measurements for test cell in water dosimeters and Hodoscope axial profile

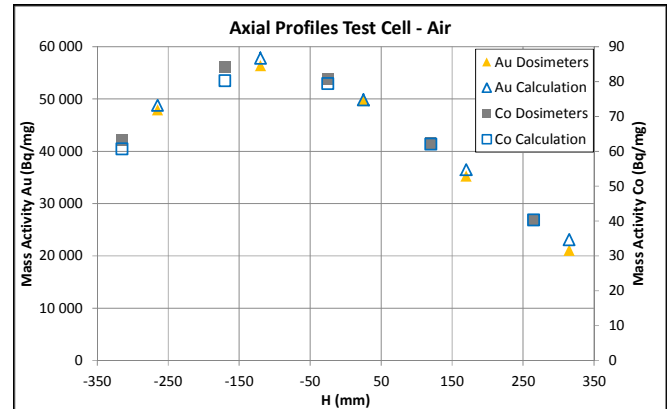


Fig. 13. Au and Co axial profiles measurements and calculations for test cell in air

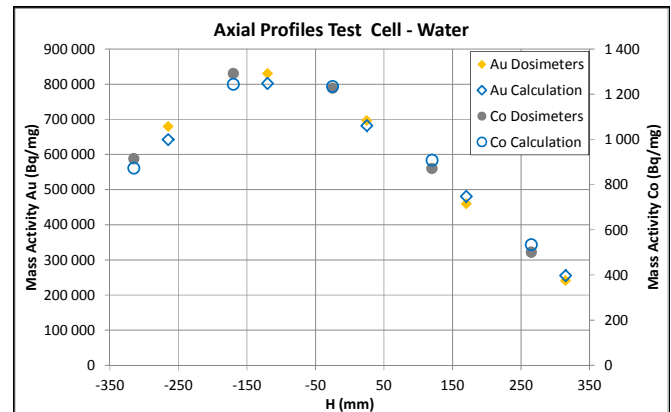


Fig. 14. Au and Co axial profiles measurements and calculations for test cell in water

VI. DUMMY ASSEMBLY CORNERS

A. Objectives and design of the dosimeters located at the 4 corners of the dummy assembly

The main objectives of this irradiation were:

- to obtain 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 positions,
- to determine F (total number of fissions in the core per unit of time) using the measured activities of cobalt and gold wires placed at each corner of the dummy assembly. This factor is used in the analysis of the measurements to obtain the kinetics parameters (β = effective fraction of delayed neutrons and Λ = prompt neutron generation time),
- to validate neutronics calculations regarding the 4 relative reaction rate axial distributions and the coupling factor (with the dummy assembly in place of fuel assembly).

The dosimeters used are the same as for the cell dosimetry (see § V. and Fig. 10).

A total of 40 dosimeters have been irradiated in the core of CABRI during 5 consecutive 1-hour power steps (about 3, 95, 340, 1200 and 4900 W).

B. Main results of the dosimeters located at the 4 corners of the dummy assembly

The axial profiles for Au and Co dosimeters of the 4 tubes are shown on Fig. 15.

The upper part of the axial distributions of the tubes 1, 2 and 4 are impacted by the position of the safety and control rods (critical position at 425 mm in this case). Tube 3, positioned in the corner of the dummy assembly closest to the test cell is less affected.

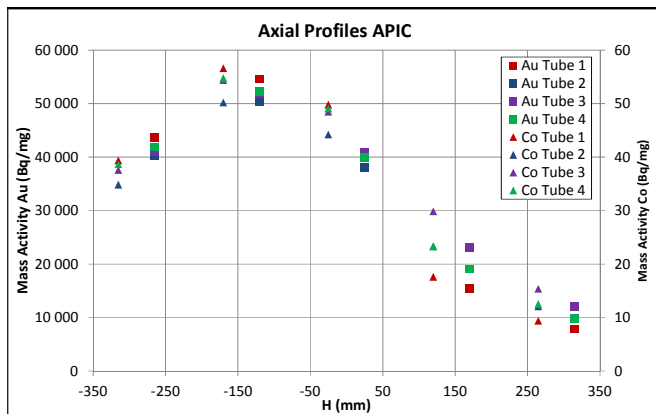


Fig. 15. Au and Co axial reaction rate distributions for the 4 tubes of the dummy assembly

VII. CONCLUSION

This paper presents the results of the dosimetry campaign performed during the commissioning tests of the CABRI reactor.

A total of 120 dosimeters have been irradiated and measured by gamma spectrometry at the MADERE platform of CEA Cadarache. Measurement to calculation comparisons are presented and show a very good consistency. This provides a strengthened validation of neutronics calculations of the driver core of CABRI.

The objectives of the dosimetry program built in support of the commissioning tests were reached.

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