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## Reactivity Initiated Accident transient testing on irradiated fuel rods in PWR conditions: the CABRI International Program

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### Abstract

The CABRI International Program (CIP) tests irradiated UO<sub>2</sub> or MOX fuels submitted to Reactivity Initiated Accidents (RIA) representative power pulses in prototypical PWR thermal-hydraulic conditions. CIP is managed by The Institut de Radioprotection et de Sûreté Nucléaire (IRSN) within a OECD/NEA framework. Experiments are conducted in the CABRI reactor operated by CEA.

For CIP, CABRI benefits from a new pressurized water loop. An important refurbishment program enhanced the facility safety and upgraded the experimental equipment such as the non-destructive examination bench IRIS and the Hodoscope on-line fuel motion monitoring system. Specific test devices with appropriate innovative instrumentation follow the test rod behavior during the transient.

The successful first test in the pressurized water loop demonstrated the CABRI capability to perform fully instrumented RIA tests in PWR conditions and to provide highly valuable results for RIA phenomena modelling (boiling crisis, post-failure events), for code validation, and for assessing PWR safety criteria.

### Highlights

- The CABRI international Program (CIP) tests industrial irradiated fuel rods in a circulating test loop ensuring prototypical PWR conditions.
- The CABRI reactor provides experimental conditions and power pulses representative of PWR RIA transients.
- A complete instrumentation is available: online fuel motion monitoring system (Hodoscope), instrumented test device, pre-test and post-test non-destructive examination (IRIS).
- Results will help modelling, code qualification and validation, and provide a new technical basis for PWR fuel safety criteria assessment for RIA conditions.

## Keywords

CIP

CABRI

RIA

IRIS

Hodoscope

## Abbreviations

ASN: (French) Nuclear Safety Authority

ATF: Accident Tolerant Fuel

CEA: Commissariat à l'Energie Atomique et aux Energies Alternatives (France)

CIP: CABRI International Program

DNB: Departure of Nucleate Boiling

FC: Fission Chamber

FCI: Fuel Coolant Interaction

FWHM: Full Width at Half Maximum

HZP: Hot Zero Power

IET: Integral Effect Test

IRIS: Installation for Radiography, Imaging and Spectrometry

IRSN: Institut de Radioprotection et de Sécurité Nucléaire (France)

LECA: Laboratory for Examination of Active Fuel (CEA, France)

LOCA: Loss Of Coolant Accident

LVDT: Linear Voltage Differential Transducer

MTR: Material Testing Reactor

NSRR: Nuclear Safety Research Reactor

OECD/NEA: Nuclear Energy Agency at the Organization for Economic Cooperation and Development

PBF: Power Burst Facility

PR: Proton Recoil counter

PWL: Pressurized Water Loop

PWR: Pressurized Water Reactor

RIA: Reactivity Initiated Accident

TRF: Transient Reactor Facility

TSO: Technical Safety Organization

## 1. Introduction

On April 16, 2018, the CABRI International Program (CIP) entered his experimental phase in the new pressurized water loop configuration with the triggering of the CIPQ test. CIP is an international research program, led by the Institut de Radioprotection et de Sûreté Nucléaire (IRSN, the French Technical Safety Organization) under an OECD/NEA framework. CIP is dedicated to the study of the behavior of fuel rods submitted to a Reactivity Initiated Accident (RIA) under typical Pressurized Water Reactor (PWR) conditions. Its main goals are to enhance the understanding of RIA phenomena and to provide new technical basis and data for the safety evaluation and modelling of such accident. In regard with these objectives, a series of tests is planned in the CABRI facility, varying the nature of the fuel (MOX or UO<sub>2</sub>), the burn-up, the initial internal rod pressure, the fuel microstructure, the cladding material, or the injected energy.

CIP tests are conducted within the CABRI transient reactor facility (TRF) operated by the French “Commissariat à l’Energie Atomique et aux Energies Alternatives” (CEA) in Cadarache. For the purpose of the CIP program, the CABRI facility refurbishment, funded by IRSN, has led to some very important upgrades. Besides the safety-related goals (new seismic constraints, post-Fukushima safety surveys), the major modification has consisted in the replacement of the old experimental sodium loop by a pressurized water loop, capable of reaching PWR conditions in terms of pressure, temperature and flowrate around the test rod.

A specific test device has been designed by IRSN to accommodate and center the test rod in the in-pile test cell. This device is instrumented with sensors developed specifically for the needs of the CIP program, monitoring both the pressurized water loop and the test rod, as well for the steady-state as for the transient phases of the test. The on-line behavior of the rod during the test is also monitored with the Hodoscope, a specific fuel motion monitoring system. The initial and final states of the rod are characterized through X-ray imaging and gamma-spectrometry in the IRIS non-destructive examination facility within the CABRI reactor hall. Post-mortem characterization is completed by hot cell non-destructive and destructive examinations performed in the LECA facility of CEA.

The CIP program goals and the RIA safety assessment objectives (high burn-up effects, fuel microstructure, boiling crisis occurrence...) are introduced in section 2. Further, the CABRI refurbishment, the new Cabri pressurized water loop and the facility capabilities regarding RIA testing are described in section 3. Finally, the new or enhanced major experimental components, such as IRIS, the Hodoscope, and the instrumented test devices are presented in section 4.

## 2. The CABRI International Program

### 2.1. The needs for nuclear fuel safety R&D

Historically, the safety criteria defined concerning Reactivity Initiated Accidents (RIA) were inherited from transient tests performed on fresh fuel or on low burn-up fuel (< 33 GWd/t) in SPERT (Special Power Excursion Reactor Test) and PBF (Power Burst Facility) [1], and in NSRR (Nuclear Safety Research Reactor) [2]. The evolutions of fuel management strategies led to increase the end-of-life burn-up, while fuel and cladding evolutions (MOX compared to UO<sub>2</sub>, new cladding materials) also brought new considerations. The CABRI REP-Na program, started in 1993 [3] [4], was devoted to



RIA testing on irradiated fuel rods, with a medium or high burn-up. REP-Na tests were conducted within CABRI, with prototypical power pulses characteristics and at a representative temperature, but in a sodium loop. In parallel, NSRR experiments also began on irradiated fuel, but in static water conditions.

CABRI REP-Na and NSRR brought some unexpected results with failure thresholds at lower energy deposition than expected, and evidenced the role of hydrides in the risk of rupture, the contribution of fission gases at the grain boundaries or the importance of oxide layer spalling. It was therefore decided to launch a new test program on irradiated fuel rod in a representative pressurized water loop: the CIP program. Contrary to REP-Na who focused on the PCMI (Pellet-Cladding Mechanical Interaction) phase of the RIA transient, CIP would then take into account the heat transfer mechanisms with the appropriate coolant, and thus address both the PCMI phase and the boiling phase (Figure 1): DNB (Departure of Nucleate Boiling) and post-DNB events, such as the boiling crisis behavior, the critical heat flux, ballooning effects, or post-failure phenomena as Fuel Coolant Interaction (FCI). REP-Na focused on the PCMI (Pellet-Cladding Mechanical Interaction) phase of the RIA transient because of the use of sodium as coolant. Neither the post-adiabatic phenomena nor the Fuel Coolant Interaction (FCI) could then be addressed. CIP will take into account the heat transfer mechanisms with the appropriate coolant, and thus address both the PCMI phase and the boiling phase (Figure 1): DNB (Departure of Nucleate Boiling) and post-DNB events, such as the boiling crisis behavior, the critical heat flux, the clad to coolant heat transfer, ballooning effects, or post-failure phenomena as FCI. The boiling crisis for rodlets unfailed during the PCMI phase and the mechanical interaction energy between the fuel and the water in case of fuel ejection are of special interest.

The demonstration of the absence or limitation of fuel dispersal in the primary coolant after clad ballooning and burst during boiling crisis is required to ensure adequate core coolability. CIP is thus intended on filling some gaps identified in RIA experimentation [5] [6], providing a relevant technical basis for the modelling of RIA and code validation, and for assessing revised or new safety criteria for reactivity initiated accidents [7] [8], notably in France [9] [10].

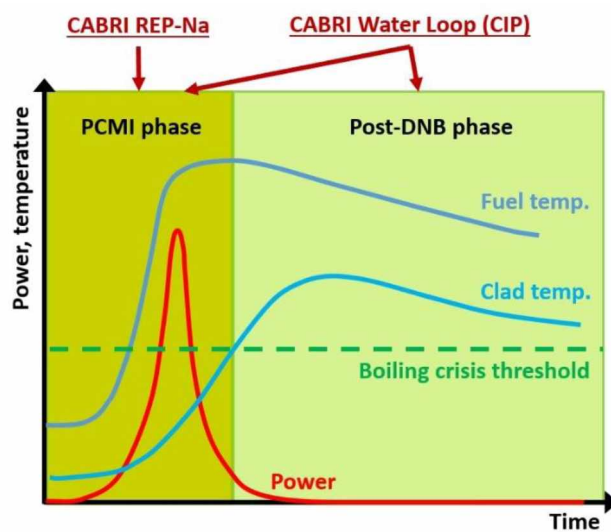


Figure 1: RIA phases and CIP objectives

## 2.2. Organization of the project

The CABRI International Program is an international investigation program on high burn-up fuel under RIA conditions in PWR Reactors. CIP lies within an OECD/NEA Project, whose operating agent is IRSN. An Umbrella Agreement defines the general objectives of the program, the indicative costs, the project organization (role of the partners, terms and rights, intellectual property...). The mode and scope of the participation and financial contribution of each signatory is defined in a bilateral agreement signed between this signatory and IRSN. The technical and scientific recommendations are debated within a Technical Advisory Group, and a Steering Committee endorses the decisions.

CIP gathers 15 organizations from 12 countries. These include Safety Authorities and Technical Safety Organizations (CSN in Spain, JAEA in Japan, NRC in the US, GRS in Germany...) power supply companies (EDF, EPRI), industrial partners, research centers.

Experiments are conducted within the CABRI facility, owned and operated by CEA. But a decree gives priority to IRSN to use the reactor for its research programs on fuel safety. The refurbishment and operation of the reactor are totally funded by IRSN. The experimental program is directed by IRSN, which also makes use of its own experimental equipment implemented in the facility.

## 2.3. Test Matrix

The project began in March 2000. The CIP program was originally intended to assess fission gas dynamics, fuel fragmentation, clad failure criterion, DNB and post-DNB understanding and modelling, fuel ejection and subsequent fuel-coolant interaction. With years, other goals were added, or are still in debate. The test matrix includes high burn-up, fuel microstructure and new cladding material effects, boiling crisis and post-failure phenomena, end of life internal pressure.

The current CIP test matrix (Table 1), resulting from active and continuous discussion between the project partners, comprises 12 tests. Two of them have been performed in the sodium loop: in 2002, CIP0-1 and CIP0-2 were carried out using fuel of very high burn-up with Zirlo<sup>®</sup> and M5<sup>™</sup> claddings. They acted as transition tests and entry data for further test and post-test measurements. Destructive post irradiation examinations in 2004 investigated, in particular, the effect of hydrogen on cladding properties [11].

After the facility renovation and upgrade phase (2003-2015), followed by the commissioning tests (up to 2017), the CIPQ experimental phase was launched. On April 16, 2018, the CIPQ test was the first to be carried out in the new pressurized water loop. The next test CIP1-2B is important for comparison to CIP0-2 performed in the Na loop, and for addressing high burn-up and M5 cladding. Then CIP3-1R will specifically be devoted to post-failure events thanks to an experimental sequence that shall lead to the rod failure. Mixt Oxide (MOX) fuel tests CIP4-1P and CIP4-1P-HP should follow, tackling in particular the end-of-life internal pressure effect. The following tests have been decided, but the last ones may still be modified according to the results from the first ones. IRSN and CEA are now in a position to perform two tests per year, where rodlets for the first five tests are already prepared and duly characterized.

Test	CIP0-2	CIP0-1	CIPQ	CIP1-2B	CIP3-1R	CIP4-1P	CIP4-1P-HP	CIP4-2	CIP3-3	CIP-X	CIP-Y	CIP-Z
<b>fuel type</b>	UO <sub>2</sub>	UO <sub>2</sub>	MOX	UO <sub>2</sub>	UO <sub>2</sub>	MOX	MOX	MOX	UO <sub>2</sub>	UO <sub>2</sub>	To be defined (Cr-doped UO <sub>2</sub> ?)	To be defined
<b>burn-up GWD/tU</b>	77	75	47	70	70	65	65	60	65	To be defined	To be defined	To be defined
<b>cladding</b>	M5	Zirlo	Zy-4	M5	Zirlo	M5	M5	Zy-4	Opt. Zirlo	M-MDA	To be defined	To be defined
<b>main goals</b>	Na loop ref. test	Na loop ref. test	WL qualification Boiling crisis	Boiling crisis Comparison with CIP0-2	Post-failure events	Internal pressure effect (50 and 90 bar at Room Temp) MOX behavior		Fuel micro-structure influence on clad loading Post-failure events	New cladding material Boiling crisis	New cladding material	Innovative fuel (Pre-ATF fuel)	PCI improved (inner liner...) cladding

Table 1: Current CIP Test Matrix

### 3. The CABRI Facility

CABRI is a Transient Reactor Facility (TRF) dedicated to Integral Effect Test (IET) in the nuclear fuel safety domain. Compared to the other transient test facilities around the world [12], CABRI is currently the only one to offer both PWR circulating conditions thanks to the pressurized water loop and representative transient pulses characteristics with its helium-3 (<sup>3</sup>He) system.

#### 3.1. General description

CABRI is a pool-type transient reactor. The core (Figure 2) is composed of 1487 UO<sub>2</sub> fuel rods with 6% <sup>235</sup>U enrichment and stainless steel cladding, arranged on a 7x7 fuel assembly pattern basis. The active part of the core is of relatively small dimensions: 60 (Length) x 60 (Width) x 80 (Height) centimeters. The reactivity is controlled by 6 bundles of 23 Hafnium Control and Safety rods each. The core is cooled by a forced circulation of water, at a 3200 m<sup>3</sup>/h flowrate. The CABRI core is able and authorized to be operated at a steady-state power up to 23.7 MW. It may also be operated at low power (below 100 kW) in natural convection mode, only exchanging heat with the surrounding pool water.



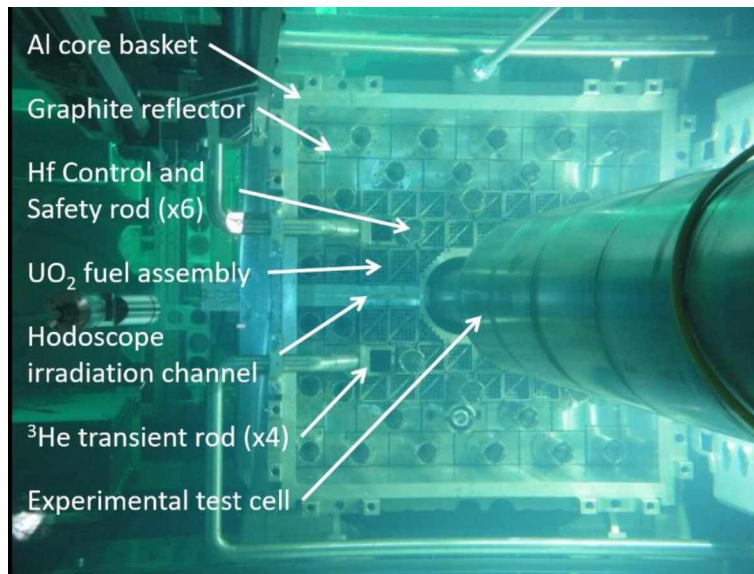


Figure 2: Cabri core

The postulated design-basis reactivity accident for PWR is initiated by the ejection of a control rod bundle following a control rod housing rupture. For simulating the subsequent neutronic transient, the key feature of the CABRI reactor is its helium-3 reactivity injection system [13], which generates the power transients starting from a max 100 kW initial power (HZIP - Hot Zero Power conditions). It is composed of 96 tubes located within the core, replacing the same number of fuel rods, grouped in 4 so-called “transient rods”. These transient rods can be pressurized at up to 15 bar of helium-3, a strong neutronic absorber gas. These rods are all linked and gather in a collector. The depressurization towards a 1000 L discharge tank is made through two discharge lines (low and high flow rates), each one being equipped with a fast-opening valve followed by a controlled valve. A specific control command application is operated from the remote control room. The helium-3 ejection leads to a reactivity injection (up to 3.9  $\beta$ ) in a short time (< 80 ms). The transient characteristics (Full Width at Half Maximum (FWHM), energy, power) depend on the sequence applied to the two fast-opening valves:

- Short FWHM (< 10 ms) and high power (up to 30 GW) transients are obtained by opening a unique fast valve (the high flowrate channel one),
- 20 to 80 ms FWHM high power transients (up to 10 GW) by successive and accurate opening of the two fast-opening valves.

Power transients are naturally counterbalanced in CABRI by neutronic feedback, mainly the Doppler effect. The core energy deposit, and subsequently the energy deposited in the test fuel, are adjusted by the scram order. Indeed, the Doppler feedback does not fully terminate the transient but only brings the reactor back to some dozens of MW, continuing then to deposit energy in the rod. The scram insertion of the control rods represents then a negative reactivity injection high enough for effectively terminating the transient and allowing the core to reach a zero power. Although the authorized domain of functioning of the CABRI reactor has been established and demonstrated during the commissioning tests, safety calculations are conducted before triggering any power transient to ensure that the CABRI core itself withstands the power pulse it generates.



### 3.2. Renovation and safety upgrade

The CABRI facility has already a long history. Construction started in 1962, allowing a first divergence in 1964. The Cabri core was first devoted to safety experiments related to Material Testing Reactors (MTR) such as OSIRIS [14]. A first deep modification was conducted in the years 1976-1978, with the replacement of the plate fuel element core by the current  $\text{UO}_2$  rod core, the installation of a sodium loop and of the Hodoscope. Experimental programs were then mainly dedicated to safety studies, first for fast neutron reactors [15], then for Pressurized Water Reactors (PWR).

Following the REP-Na results and for the purpose of the new CIP program, a complete refurbishment of the whole facility has been carried out from 2003 to 2015. The need was both to implement the new pressurized water loop and to enhance the global safety of the facility, so as to match up-to-date safety standards.

Concerning the facility, after dismantling the old sodium loop and related components, the seismic reinforcement was engaged for the buildings themselves, for the main heavy equipment such as the bridge crane, and for the core pool and storage pools. In parallel, the refurbishment, reinforcement and control of the whole driver core cooling circuit was realized, as well as the creation of a new waste management circuit, the replacement of the venting system, and the renovation of the helium-3 reactivity injection system with a new ordering and timing system. A new command-and-control system has been installed, while the electrical supply, the thunder protection and the fire protection were renewed. Complementary safety systems were also designed and installed, part of them as a consequence of the Fukushima accident feedback.

Following the installation of the new pressurized water loop, and given the new test device design, a new shielded handling device and a dedicated transportation cask have been designed, fabricated and qualified. The data acquisition systems of the main experimental sensors have also been renewed.

### 3.3. The new pressurized water loop

The design of the new experimental loop had to face both experimental and technical challenges: reach the thermal-hydraulic conditions equivalent to those of a PWR (temperature of 300°C, pressure of 155 bar, velocity of 4 m/s) [16], compactness (limited space within the core central zone for the in-pile test cell, and within the reactor hall for the loop components), neutron transparency for enhancing the power coupling between the driver core and the sample tested, and respect of a construction quality level equivalent to Level 1 of the RCC-M code (French Design and Construction Code for PWR). Secondary functions of the pressurized water loop (PWL) include removing the heat generated in the test rod, filtering the potential fuel debris issued from the tested rod failure during the transient and permitting a safe and controlled discharge of gaseous and liquid radiological waste.

The pressurized water loop (Figure 3) is divided in two main parts: the double-wall in-pile test cell in the center of the CABRI core and pool (acting as first and second barrier), and the PWL containment for housing the primary circulating pump, the pressurizer, the heating systems, the heat exchanger, the auxiliary circuits, the waste discharge tank and so on. The in-pile test cell is linked to

the distant container by circulating lines in a double-wall envelop circuit and a biological shielding. A submicronic filter is located on the return line upstream from the main pump. The in-pile test cell is made of Zircaloy-4 for neutronic optimization of the power coupling factor between the core and the tested rod. It is designed for positioning the test device in the center of the core.

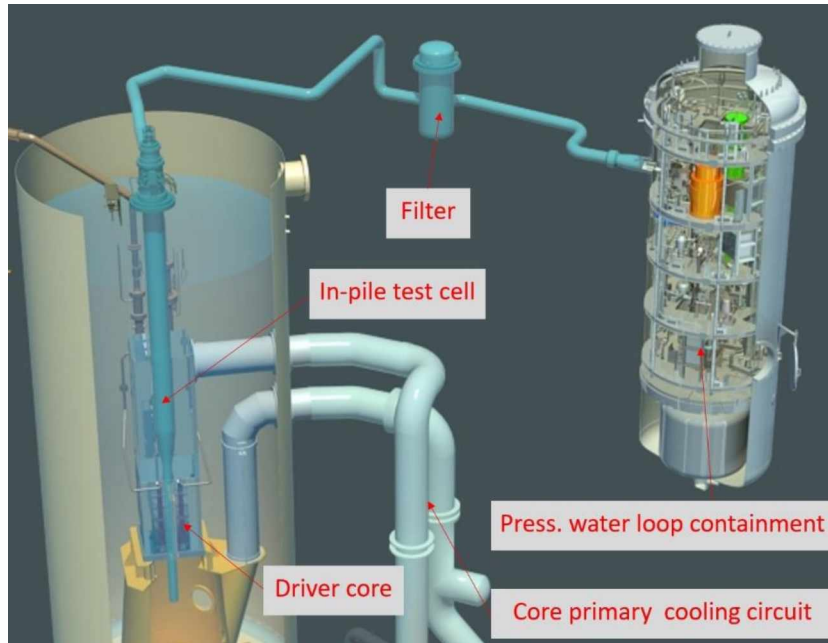


Figure 3: 3D view of the pressurized water loop

### 3.4. Commissioning Tests - Reactor restart

Following the refurbishment of the facility, commissioning tests were performed for qualification and approval of the renewed and modified components, circuits and systems of CABRI [17].

Preceded by unitary tests, they were organized in several test series. The commissioning tests addressed the different facility operation requirements, including Instrumentation & Control, reactor vessel (reinforcement, mechanical assembly, components tests), handling, docking & transfer systems, ventilation circuit, core circuits (notably transient rods and primary core cooling circuit). They were mainly conducted up to 2015. Tests regarding experimental needs included the experimental loop functioning, conduct and performances, and the characterization and qualification of the IRIS, Hodoscope [18] [19] and embedding facilities.

In 2015, the safety demonstration was completed and the authorization to restart was granted by the French regulator (ASN). From 2015 to 2017, the reactor restart was assessed by a complete neutronic characterization, and by power functioning tests, first in steady-state mode and then in transient mode. In particular, more than sixty power pulses of increased magnitude and of different FWHM were performed. All these qualification tests allowed to estimate the uncertainties on the acquisition data as well as on the elaborated quantities such as the core power or the coupling factor [20] [21].

Benefiting from this important commissioning test results database, the authorization of the CIP-Q test by the French regulator ASN was finally granted on 8 Feb. 2018 and the CIP-Q test was successfully performed on April 16, 2018.

## 4. Experimentation

### 4.1. Test devices

The specific objectives of the CIP required the design, fabrication and qualification of dedicated test devices and of an appropriate instrumentation, developed by IRSN.

The test device (Figure 4) ensures the accommodation and centering of the test rod within the in-pile test cell and the instrumentation housing. Its main dimensions are approx. 5 meters in length with a weight of 140 kg and an outer diameter in the range 72 to 140 millimeters. It allows the water circulation: inlet and outlet from and to the pressurized water loop, flowrate distribution between the test channel and the by-pass (for reaching the targeted velocity within the test channel). It is designed to withstand a potential pressure peak resulting from a fuel/water interaction in case of cladding failure and fuel ejection during the test. Furthermore, the upper part of the test device closes the in-pile test cell and therefore has to demonstrate its tightness as it is part of the first barrier. For enhancing neutron transparency in the core region, the central zone of the test device is made of Zircaloy. The others parts of the test device are made in stainless steel.

The test device is instrumented with 48 sensors, most of them specifically developed or adapted for the needs of the CIP program. They are devoted both for the pressurized water loop and for the test rod monitoring, as well for the steady-state phase as for the transient phase of the test. A minor part of the sensors was available off-the-shelf, requiring nevertheless an important work for their integration in the device. Sensors must indeed withstand high pressure and temperature, as well as high neutron flux, and present an adequate response time and precision while being small enough.

Measurements provided on the rod are the following:

- the axial clad expansion by a LVDT technology sensor (range  $\pm 10$  mm, with an uncertainty of  $\pm 0.04$  mm), developed with the Norwegian Institute for Energy Technology (IFE) and the Halden Reactor Project [22],
- the clad failure detection (timing and location) by a system composed of two high frequency microphones (50 to 500 kHz bandwidth, each signal split on 2 channels with 2 different gains, specific data processing),
- the detection of the onset of boiling near the clad surface, performed by a measurement system using ultrasonic waves (between one transmitter and three receiver sensors),
- the clad temperature with K-type thermocouples (enclosed grounded junction and restrained diameter for a limited time constant, with the usual range of 0-1370°C and a maximal uncertainty of  $\pm 4$  °C).

Instrumentation of the test channel includes:

- Water inlet and outlet temperature measurement;



- K-type thermocouples for the fluid temperature measurement in the test rod zone, held by an instrumented cage that centers the rod within the test channel;
- Flowrate sensors, both for steady-state conditions by two turbine flowmeters (range 0-2 m<sup>3</sup>/h, with an uncertainty about 0.05 m<sup>3</sup>/h) and for transient conditions by two target flowmeters (LVDT technology [22], range 0-8 m<sup>3</sup>/h);
- Pressure sensors for the static and dynamic pressures in the channel tube, upstream and downstream the rod (range 0-350 bar and an uncertainty about +/- 3 bars considering pressure variation);
- Pressure sensors measuring the bypass ring pressure drop and so the bypass flowrate.

All the signals coming from the test device are processed (amplification, filtering ...) and delivered to three acquisition systems, operating at a maximal rate ranging from 2 MHz (microphones) to 4 kHz (steady-state sensors), which also acquire signals coming from the facility (mainly the pressurized water loop and the core). Each one of these three systems is duplicated for ensuring redundancy during the test. The total number of channels recorded simultaneously is 264.

Almost all the test device sensors proved to work in a very satisfactory way during the CIPQ experiment, although some of the signals are still to be analyzed (e.g. the boiling detector signals, or the transient flowmeter ones, which require a specific post-test calibration). They gave consistent results between each other, as well as with the water loop sensors, the hodoscope on-line information and the post-test examinations with IRIS. This led to an increased confidence in the understanding of the test rod behavior during the experiment.

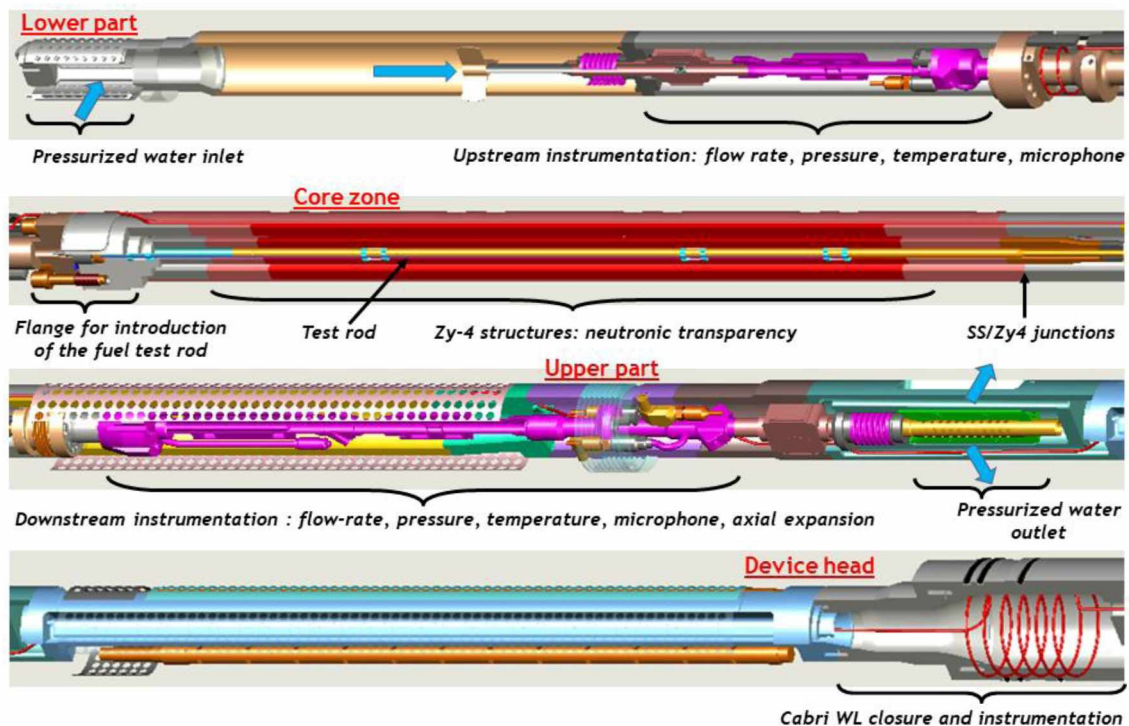


Figure 4: Test device description



#### 4.2. Hodoscope

The Hodoscope (Figure 5) is an on-line fuel motion monitoring system, based on the detection of fast neutrons emitted by the tested rod. Its central component is a massive stainless steel collimator of 3 m length and more than 5 ton weight, in which 153 line-of-sights are drilled. They define a 51 row by 3 column matrix of windows. For avoiding neutrons coming from the core, the latter has been split in two halves, separated by an irradiation channel giving a direct view to the test loop for the Hodoscope (see Figure 2).

Because of the wide power range of a CABRI experiment (from several kW to several GW), each line-of-sight is equipped with two detectors: a proton recoil proportional counter (PR), and a  $^{237}\text{Np}$  fission chamber (FC). PR sensors have a higher sensitivity and are therefore better suited for monitoring the low power part of the transient. Fission chambers follow the high power part of the transient. They proved to work in a satisfactory way up to 21 GW during the commissioning phase. No corrections are required up to  $\sim 5$  GW (see Figure 6), and a specific dead time correction algorithm is used to correct the linearity drift when the reactor power overpasses  $\sim 5$  GW.

For the CIP tests purpose, the Hodoscope acquires the initial and final state of the rod, before and after the transient, giving thus the fissile length and the axial power profile (form factor, see Figure 7). During the transient, it monitors the fuel behavior and motion of mm order (axial elongation, axial and radial displacement or relocation...) at up to 1 ms recording rate and eventually estimates the ejected and/or relocated fissile masses. The qualification of the new electronic modules and of the renovated command & control system has been validated during dedicated commissioning tests, together with the alignment operations [18] [19].

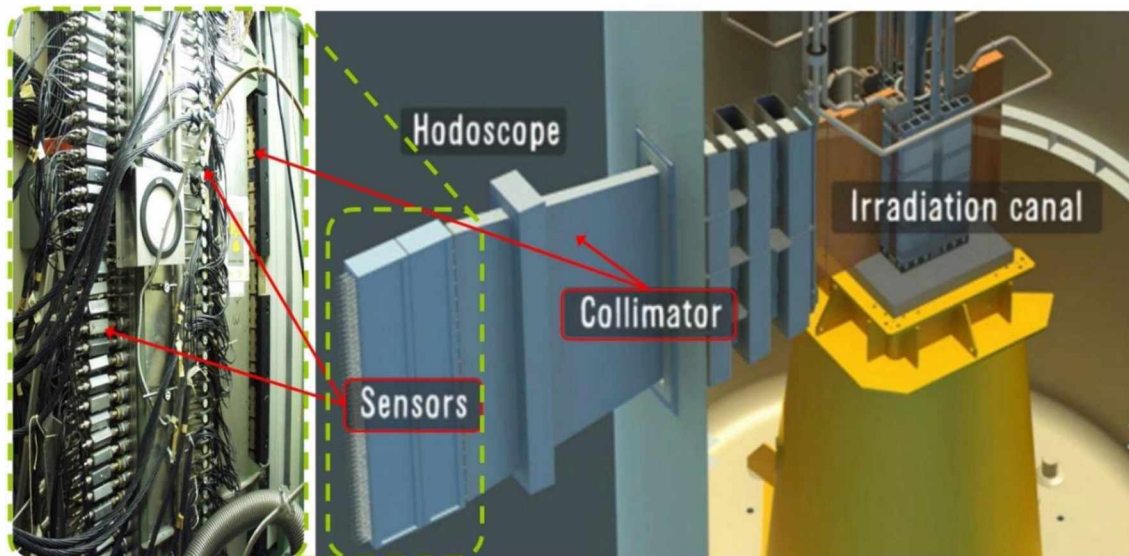


Figure 5: Hodoscope scheme

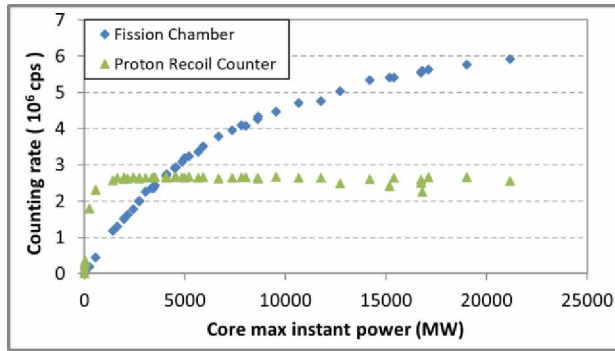


Figure 6: Raw counting rate recorded by FC and PR hodoscope detectors (at core peak power node level) as a function of the Cabri core maximum instant power

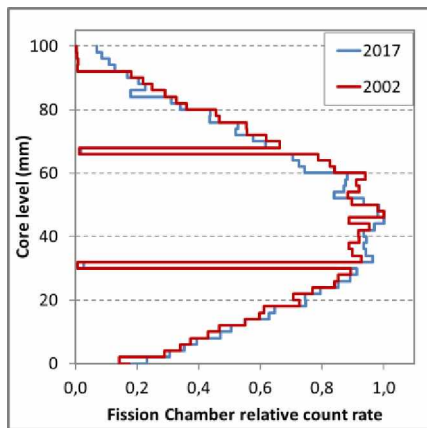


Figure 7: Fission chamber raw measurement of the axial power profile measured in steady state condition (center column detectors)

#### 4.3. IRIS

The IRIS facility (Installation for Radiography, Imaging and Spectrometry, Figure 8) is a non-destructive examination bench. It has been refurbished and adapted for the needs of CIP, in order to welcome the new test devices. IRIS can perform three types of examination:

- X-ray transmission radiography,
- X-ray transmission tomography,
- Quantitative gamma-scanning.

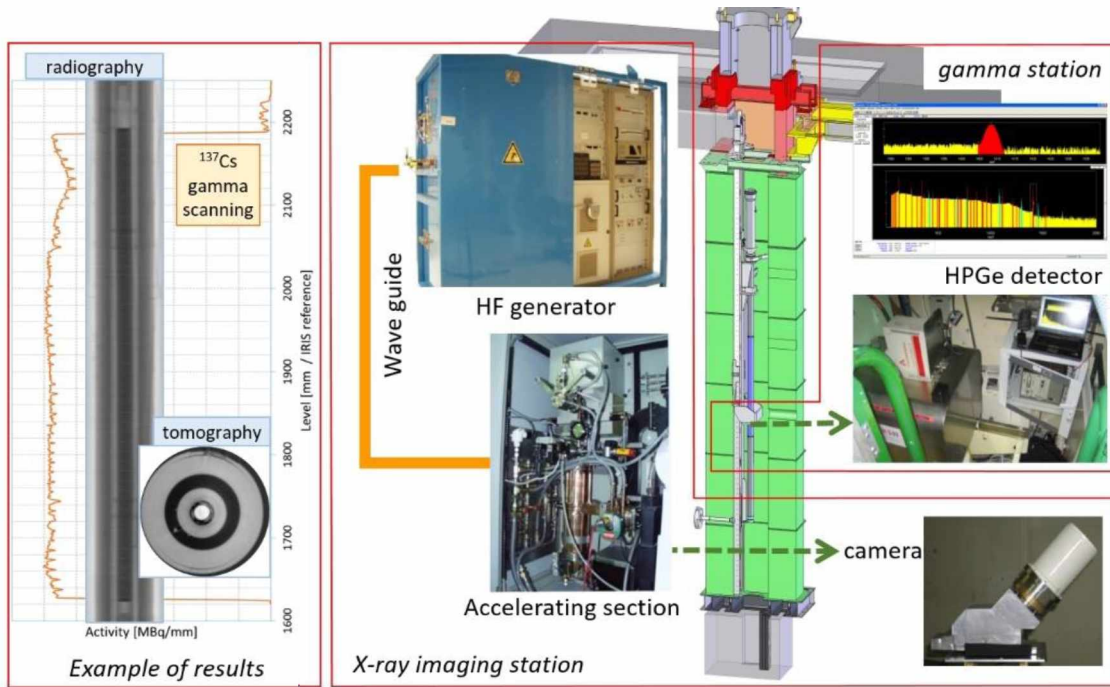


Figure 8: IRIS examination bench and measurement equipment

Located within the CABRI reactor building, the mechanical bench is installed in vertical position, for avoiding modifying the post-test final state of the rod, inside a concrete and iron radiological shielding. The test device is placed within a tightness sheath that is motorized in vertical translation and in rotation in front of two examination line-of-sights.

Quantitative gamma-scanning is performed with vertical translation in front of a 1 mm height collimation. The detector is a high purity Germanium detector, coupled to an acquisition system. The efficiency correction is made thanks to calibration measurements and efficiency function computation performed with the CAMELIAS tool [23] that was previously developed at the in-pile experimental laboratory of IRSN for the purpose of CABRI and PHEBUS [25] gamma-spectrometry stations. Another lab-made tool called CAPRICE is used for the batch calculation of the gamma spectra, acquired and processed with GENIE 2000 [24]. The spatial resolution is high enough to detect the inter-pellet spaces before the test. The total activity measured before the test (summed along the fuel stack for  $^{137}\text{Cs}$ , as well as for  $^{154}\text{Eu}$ ) is in agreement with neutronic calculations (depletion code).

X-ray radiographies and tomographies are carried out with a NMOS camera. The X-ray beam is generated by a high energy linear accelerator, at a max energy of 8 MeV (mean energy around 2.5 MeV), and with an equivalent dose rate of more than 10 Gy/min at 1 m. Radiographies are acquired by vertical translation of the device in front of the camera, equipped with a  $\sim 0.5$  mm entry slot collimator, while tomographies combine step-by-step rotation ( $0.4^\circ$  azimuthal step) at a given elevation. The spatial resolution of the reconstructed images is close to 200  $\mu\text{m}$ .

The coupled X-ray and gamma measurements allow thus to access the quantitative fission product distribution within the rod, and a post-test vs pre-test comparison of the state of the rod: fuel fragmentation or relocation, clad deformation and/or possible failures, fuel stack elongation...



#### 4.4. Test conduct

Once chosen by the program partners, the test rod is manufactured from a PWR irradiated fuel rod in a hot cell facility, according to the FABRICE process. The rod is cut to adapt its length to the CABRI core height, then equipped with hafnium pellets at both ends of the fuel stack, a spring at the upper end and two plugs. It is pressurized with an Argon/Helium mixture at an internal pressure level corresponding to the end-of-life state of a PWR rod before being sealed. Finally, the test rod is loaded within the test device, centered in the test channel thanks to an instrumented cage system.

The test sequence is defined by the experimenters for assessing the experimental objectives of a test defined by the CIP partners. Isothermal tests are conducted without any neutron reaction to check the hydraulic characteristics of the test loop and of the test device, and to check the instrumentation. Steady-state power plateaus at several megawatts are then performed to get by thermal balance on the test channel an experimental measurement of the coupling factor (defined as the ratio between the core power and the test rod power, which drives the energy deposit within the test fuel). This power coupling factor goes in CABRI from about 600 for a fresh  $\text{UO}_2$  fuel to more than 2000 for a high burn-up rod, either  $\text{UO}_2$  or MOX. Generally, MOX fuel rodlets present a lower power coupling factor than  $\text{UO}_2$  fuel rods. For accommodating this effect, the transient characteristics have to be tuned, notably by increasing the helium-3 pressure for enhancing the core energy deposit (note that the strong assumption is made that this coupling factor is constant during the transient).

Power plateaus also serve for the instrumentation and for the Hodoscope, which is aligned with the test rod in order to measure the axial power profile of the core, the fissile length of the tested rod, and also an indirect estimation of the coupling factor. The transient is finally triggered when all the required experimental conditions are met: the pressurized water loop at nominal conditions (155 bar, 280°C), transient rods pressurized, reactivity injection system ready for the test, core power stabilized at 100 kW. Low power plateaus (100 kW) of one hour are conducted before and after the test for getting with the Hodoscope the initial and final state of the fuel stack.

Pre-test and post-test characterizations of the test rod within the test device are performed within the IRIS facility. The test device is finally sent to the LECA hot cell facility of CEA in Cadarache for rod recovery, non-destructive and destructive examinations. In case of rod failure, the test device might be embedded within Wood metal alloy prior to its transfer.

## 5. Conclusion

Thanks to its unique features, notably the Hodoscope, the instrumented test device, the pressurized water loop and the helium-3 reactivity injection system, CABRI is a world unique Integral Effect Test facility offering RIA testing capabilities in representative PWR thermal-hydraulic conditions. The experimental equipment offers a complete set of measurement including on-line measurement for fuel behavior monitoring, cladding observation, recording of the test channel conditions and pre- and post-test non-destructive examinations thanks to the IRIS station.

The CIP program offers thus ideal conditions for testing real irradiated high burn-up fuel rods. The success of the first test in the new pressurized water loop demonstrated the capability to provide appropriate and improved testing conditions with controlled associated uncertainties. The valuable data coming from these tests will help the understanding of the RIA phenomena, in



particular the boiling crisis and post-failure events. CIP brings therefore an opportunity for testing new cladding materials and new fuel design, such as ATF (Accident Tolerant Fuel). It represents a priceless technical basis for the modelling of RIA and code validation, such as for the transient code SCANAIR developed by IRSN [26] [27].

After the qualification test CIPQ in 2018, two RIA tests are already planned in 2020. And in the future, the possibility to perform LOCA (Loss Of Coolant Accident) tests is already under investigation, the pressurized water loop having been developed for such a capability.

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