CARMEN MEASURING DEVICE FOR THE JULES HOROWITZ REACTOR: STATUS OF DEVELOPMENT

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Abstract

CARMEN is a multi-detector measuring device that will be able to acquire neutron and photon fluxes in different experimental locations down the full height of the Jules Horowitz Reactor (JHR) core. This reactor is presently under construction at the CEA Cadarache center in the south of France.
The unprecedented capabilities of CARMEN are expected to improve our knowledge of the JHR core, thus providing an optimized thermal design of the irradiation devices and better analysis of the experimental results. It will also be used for performance acceptance during the reactor start-up tests.
CARMEN will be equipped with state-of-the-art instrumentation, embedding a miniature ionization chamber to measure the gamma flux, two miniature fission chambers (U-235 and Pu-242 deposits) to measure the thermal and fast neutron flux, and a latest-generation differential calorimeter to measure nuclear heating.
This paper describes the development of the CARMEN device. Design optimization has made it possible to obtain a single design for the device that can be used both in the core and in the reflector.
Tests on a full-scale mock-up have validated the endurance of the internal motorized vertical displacement system for the measuring instrumentation.
The correct operation of this instrumentation under high flux will be tested in the BR2 reactor belonging to SCK-CEN (Belgium).

Keywords: Jules Horowitz Reactor, CARMEN, Calorimeter, Fission chamber, Ionization chamber, Neutron flux, Gamma heating, Gamma flux, Vertical displacement system

1. INTRODUCTION

1.1. JHR PROJECT

The Jules Horowitz Reactor (JHR) is a new material testing reactor (MTR) currently under construction at the CEA Cadarache research center, in the south of France. It will represent a major research infrastructure for scientific studies dealing with material and fuel behavior under irradiation. The reactor will perform research and development programs for the optimization of the present generation of nuclear power plants (NPPs), support the development of the next generation of NPPs and also offer irradiation possibilities for future reactors. The JHR will be fully optimized for testing materials and fuels under irradiation, in normal, incident and accident conditions [R1], [R2], [R3] and [R4]. The reactor will also be devoted to supplying radioisotopes for medical applications [R5], [R6], [R7] and [R8].

1.2. CARMEN OBJECTIVES

CARMEN is a multi-detector measuring device able to acquire the neutron and photon fluxes and the specific power deposited by nuclear heating over the full height of the core and in the different experimental locations of the JHR.

The unprecedented capabilities of CARMEN are expected to improve our knowledge of the irradiation conditions in the JHR experimental locations in order to:

- Refine the numerical models used to predict nuclear flux during operation [R9]
- Provide precise data to experimental users concerning the conditions of their irradiation experiment, for better analysis of their experimental results [R9]
- Give the input data necessary for the design calculation of a new device, both from the point of view of safety and performance expected
- Validate the performance during the reactor start-up tests.

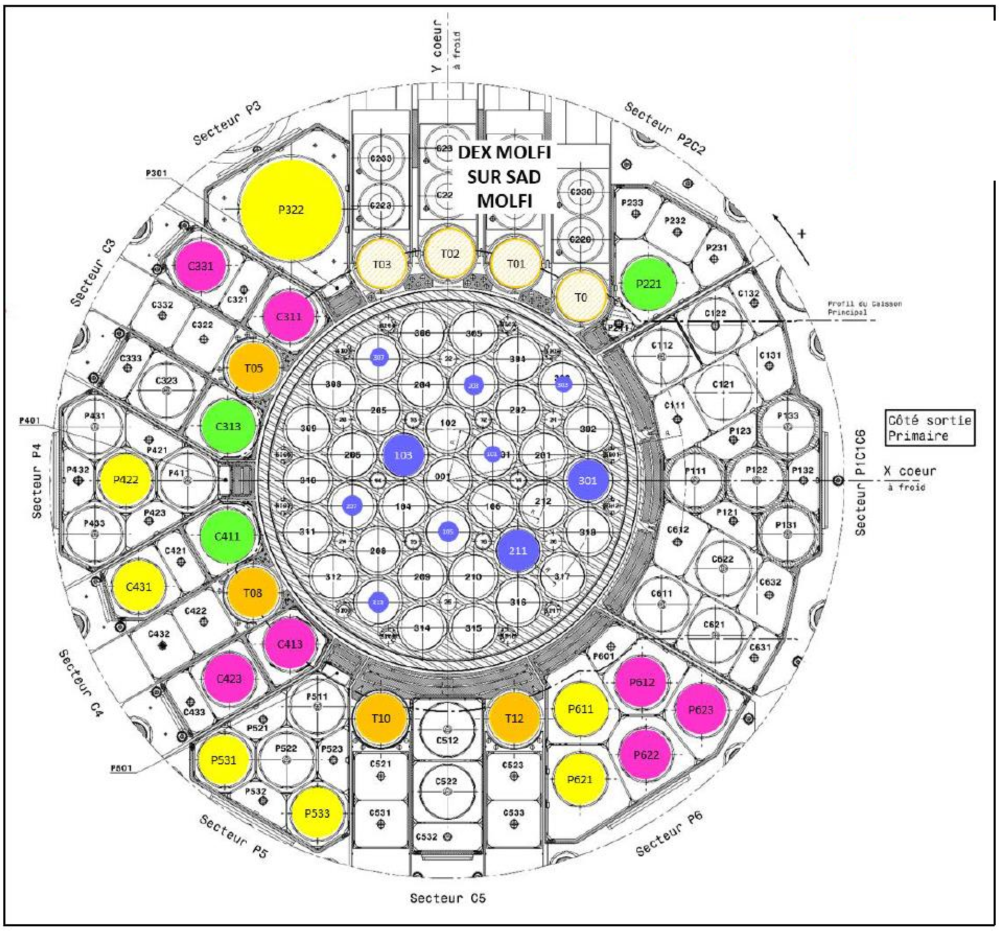
1.2.1. Different experimental locations to be characterized

In-core, the JHR has 10 experimental locations with high thermal and fast neutron fluxes (up to 5.10^{14} $n.cm^{-2}.s^{-1}$ (<0.625 eV) and up to 6.10^{14} $n.cm^{-2}.s^{-1}$ (>0.907 MeV)) and a high nuclear heating rate in aluminum (up to 20 W/g) at 100 MWth to satisfy current and future NPP needs:

- 7 locations inside a fuel element, with a small diameter of 33 mm
- 3 locations in empty fuel element spaces, with a large diameter of 86 mm.

In-reflector, the JHR has various experimental locations, with high thermal neutron flux (up to $3.5\ 10^{14}$ $n.cm^{-2}.s^{-1}$ (<0.625 eV)):

- 4 locations on displacement systems through the beryllium (Be) reflector, with a diameter of 100 mm, in order to simulate linear power histories for fuel samples
- 4 locations on displacement systems through the Be reflector, with a diameter of 100 mm, for radioisotope production
- 16 locations fixed in the Be reflector, with a diameter of 97 mm
- 1 location fixed in the Be reflector, with a large diameter of 200 mm.



	Location type	
In-core		7 inside a fuel element (device ∅ 33 mm)
		3 instead of a fuel element (device ∅ 86 mm)
In-reflector		4 on displacement system (device ∅ 100 mm)
		4 on displacement system (device ∅ 100 mm – radioisotope production)
		9 fixed on the Be reflector (device ∅ 97 mm – long devices)
		1 fixed on the Be reflector (device ∅ 200 mm – long device)
		7 fixed on the Be reflector (device ∅ 97 mm – short devices)

Figure 1: JHR experimental irradiation locations

The experimental locations in the core are accessible through the reactor vessel head (installation plane elevation: -5694 mm) which constitutes a leaktight barrier between the primary system and the pool water located above the reactor vessel.

The main experimental locations in the reflector (except those for short devices) are accessible at the level of the seismic support structure (installation plane elevation: -7085 mm).

It must be possible to insert the CARMEN device in these different experimental locations to carry out the expected measurments.

1.2.2. Measurements during reactor start-up tests

Core compliance with the initial requirements will be checked by start-up tests. These tests will verify that the measured values are in conformity with those taken into account in the reactor design and in nuclear safety studies in order to obtain administrative authorizations for operation.
In addition to two other measuring devices (MONITOR and DOSI), CARMEN will be used during this test phase at very low power (2 MW) and up to nominal power to carry out the complete acceptance of the facility's performance.

The characteristics of most experimental locations will need to be measured during this phase in a limited time, which is why three CARMEN devices will be used simultaneously to map the core. The motorization of the CARMEN measuring cell (see section 2.3) will be used to carry out rapid measurements in an automated way. The duration of the start-up tests can then be optimized. If one device fails, the two others will be sufficient to carry out the entire test program in an optimized time frame.

1.2.3. Measurements during reactor operation

During reactor operation, CARMEN will be used regularly to characterize an experimental location before or after an experiment or to refine the neutron calculation scheme. It is planned to use one CARMEN device nominally. In the event of failure, two back-up CARMEN devices will be available and can also be used in parallel with the main device on an *ad hoc* basis to optimize a measurement campaign, as is the case during the reactor start-up tests.

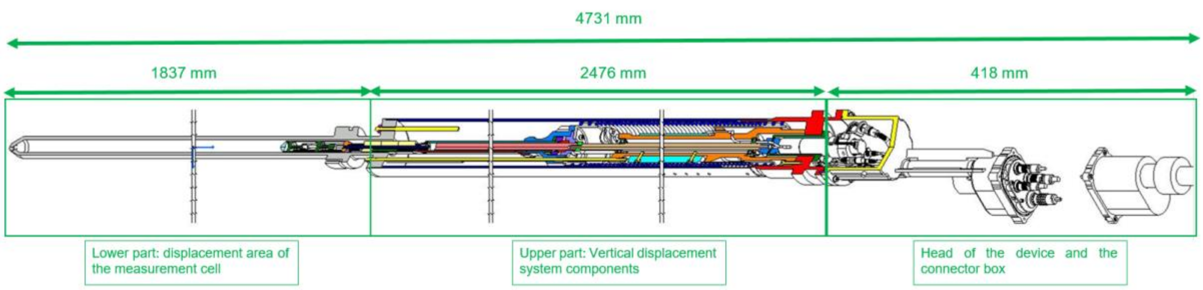
2. <u>CARMEN DESIGN</u>

The CARMEN device was designed based on feedback from the CALMOS device [R11], which was the first mobile calorimeter device used in the French reactor OSIRIS.

2.1. GLOBAL DESIGN

The in-pile part of the CARMEN device (4731 mm long) is composed of the following components:

- The lower part of the device (1837 mm long), which contains the measuring cell (see section 2.2), the measuring area (from – 500 mm to +500 mm on each side of the fuel mid-plane) and a withdrawal area (up to 500 mm) out of the neutron flux to prevent drift or decalibration of its sensors
- The upper part of the device (2476 mm long), which contains all the components necessary to carry out the translation kinematics. This is the vertical displacement system (see section 2.3)
- The red piece called “vessel head penetration” provides the installation plane for the devices in the experimental locations. It also ensures the seal with the reactor vessel head for those devices in the core
- The device head with its motorization box and internal connectors, which ensure the connection between the mineral insulated cables and more flexible cables with polymer insulation (see section 2.4)
- The connector box, which includes the external connectors and is connected to the device head by a stainless steel tube. The box is connected to a flexible hose (type corrugated stainless steel) ensuring the routing of underwater lines to the out-of-pile part of the device (see section 2.4).



<u>Figure 2: CARMEN device</u>

The following paragraphs detail these different parts and the mock-ups produced to support the design.

2.1.1. <u>A single design for all the experimental locations</u>

Given the different configurations of the experimental locations in the core and in the reflector, as well as their installation planes at different elevations, one dedicated core device and one dedicated reflector device were initially necessary.
The need for a back-up device in the event of failure and our objective of minimizing the number of CARMEN devices in operation led to further design optimization.
Our goal was to produce a single design that could be used in all of the different locations to be measured.

Adaptations were needed to bring the device as close as possible to the vessel when on a displacement system in the reflector. Thus, the connector box was offset from the axis of the device and the installation height of the device was offset with the respect to its installation height in the core.

The withdrawal area for the measurement cell is located in the lower part of the device in the reflector locations, while it is located above the measurement area in the core locations.

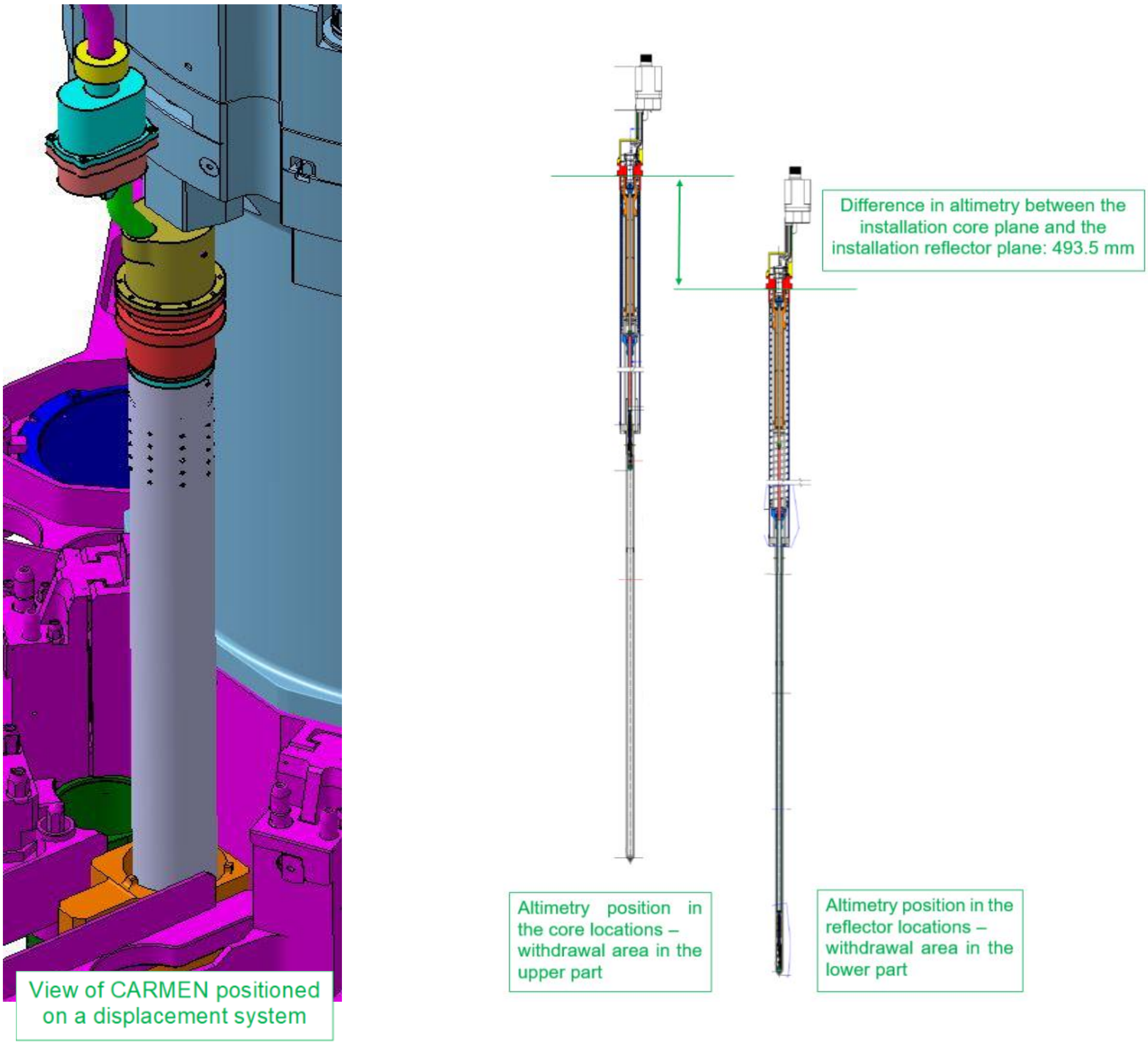


Figure 3: CARMEN design

2.2. MEASURING CELL

CARMEN's objective is to be able to measure the experimental locations with an accuracy of 10% at 2σ.

These measurements will first be carried out at 2 MW during start-up tests and at full power i.e. 100 MW for another test campaign. Thereafter, most measurements will be at nominal power i.e. 70 MW.

For this purpose, CARMEN will be equipped with state-of-the-art instrumentation, embedding:

- A miniature ionization chamber with an external diameter of 3 mm to measure the gamma flux
- Two miniature fission chambers with an external diameter of 3 mm (U-235 and Pu-242 deposits) to measure the thermal and fast neutron flux
- And a latest generation differential calorimeter made of aluminum and stainless steel with an external diameter of 19 mm and a height of 10 cm to measure nuclear heating (see section 2.2.1).

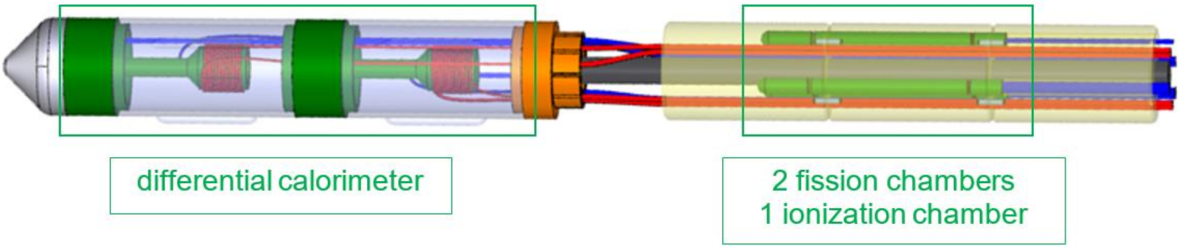


Figure 4: Measuring cell

The nuclear heating range to be measured in the aluminum will be quite large and will extend in the core from about 0.4 W/g at 2 MW to 20 W/g at 100 MW. In the reflector, the nuclear heating will be lower at 2 MW, around 40 mW/g.

The manufacturing of fission chambers (or ionization chamber) started several decades ago at Cadarache and more than 2300 chambers have been built since then.
Fabrication of the specific type used in CARMEN's measurement cell i.e. the "miniature fission chamber" started in 2008. Since then, 77 miniature fission chambers have been assembled at Cadarache. These fission chambers have been in use in French and international reactors for many years.
This product is hence considered as mature and does not require further development.

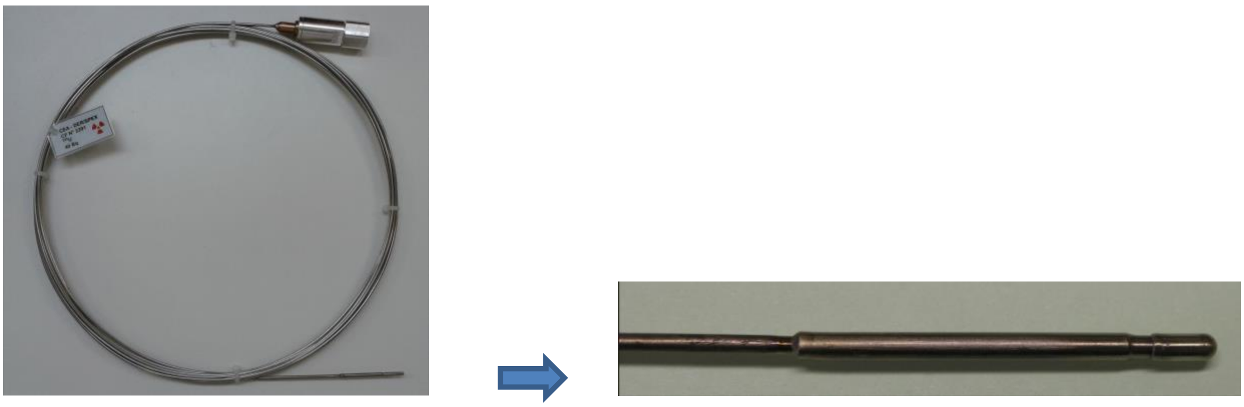


Figure 5: Miniature fission chamber

Development efforts on the measurement cell have therefore focused on the calorimeter.

2.2.1. Global design of the calorimeter

The CARMEN calorimeter is an upgrade of the CALMOS system which produced remarkable results in the OSIRIS reactor [R11]. CALMOS has provided a broad measurement range close to 4 decades, which makes it possible to adopt the use of a universal measurement cell with this type of calorimeter for all JHR locations and power levels.

The differential calorimeter consists of two aluminum specimens equipped with thermocouples positioned one above on the other; the measuring specimen is solid, while the reference specimen is hollow. The difference in mass is used to measure the energy deposited by nuclear radiation. The temperature rise in the measuring specimen is determined by calculating the difference in temperature between the two specimens having been successively positioned in a given axial position.

The self-calibration of the system is provided by the injection of electrical power generated by the heating resistors equipping the two specimens.

The CARMEN calorimeter will have an extended measurement range up to 20 W/g which will be optimal for high power in-core measurements (compared with 13 W/g for CALMOS). It will be suitable for in-core low-power measurements according to OSIRIS feedback. For use at low-power in the reflector, the ionization chamber in the CARMEN measurement cell extends the measurement range downwards because it is capable of measuring heating below 40 mW/g.

2.2.2. Improved calorimeter design with mock-ups

To establish the feasibility of manufacturing the upgraded CARMEN calorimeter, several studies have been awarded to two different companies with the know-how and experience in this type of instrumentation.

Mock-ups made it possible to validate the different stages of the manufacturing protocol.

Figure 6: Calorimeter mock-up before and after assembly

Thermal cycling tests at 350°C validated the homogeneity of the temperature in the winding.

The calorimeter underwent 200 thermal cycles in order to validate its behavior. The cycling consisted of a temperature rise of 2 minutes to reach a plateau of approximately 350°C for 4 minutes, and a 2-minute descent. A thermal camera was used to measure the temperature within the winding and the support. The calorimeter retained its insulation and resistivity during the tests.

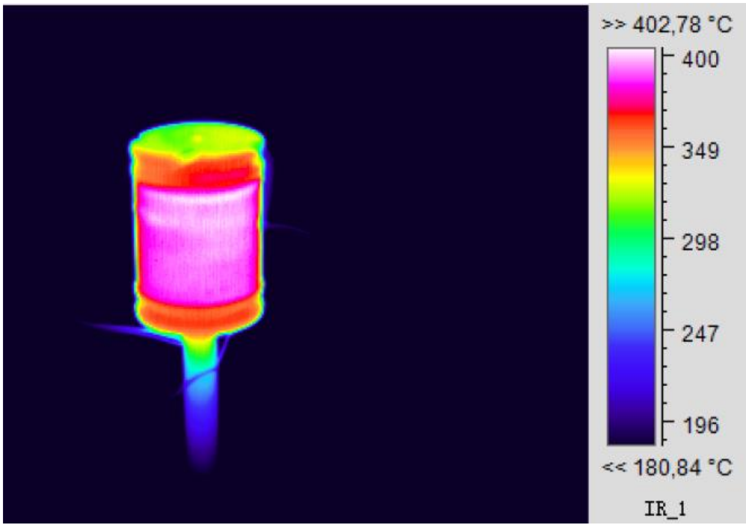


Figure 7: Thermal camera image during temperature stabilization at the landing

In order to compile feedback from previous mock-ups and the latest design developments, the production of a 3D printed model of the calorimeter made it possible to validate its overall manufacturability.

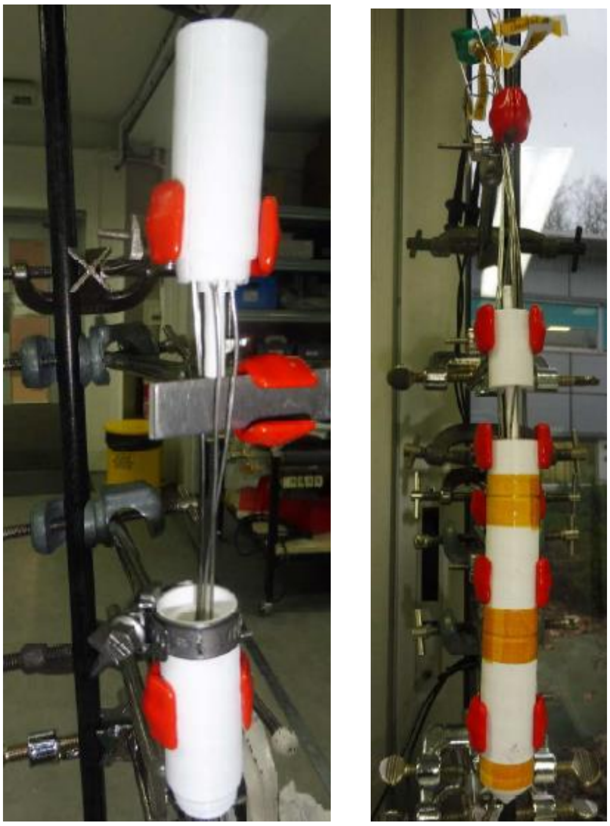


Figure 8: Assembly of the 3D model printed calorimeter

2.2.3. Validation of the calorimeter for high nuclear heating in BR2

The validation of the correct operation of the CARMEN measurement cell under high flux is considered to be an important issue, which is why irradiation in the BR2 reactor (SCK CEN, Belgium) is being prepared.

The BR2 version of the measurement cell will be similar to that used in the JHR. It will also include two platinum self-powered detectors (SPD) to monitor the photon flux, one on each side of the calorimeter in order to verify that its position is correct with respect to the maximum flux plane. Activation dosimeters will also be added to supplement the neutron measurements recorded by the fission chambers.
At the end of the experiment, the activation dosimeters will be recovered from the CARMEN device in the BR2's hot cell and sent to the CEA Cadarache center for their analysis.

The in-pile section of the device will be designed to be inserted in an in-fuel-element channel. The head will include a displacement system to move the measurement cell vertically over 20 cm to center the differential calorimeter on the maximum flux plane during the start-up and the cycle. This system is based on a previous design already used in the BR2, incorporating minimum modifications.

The objectives and the preliminary description of the device were presented to the SCK-CEN experiment study committee in the phase 1 (conceptual design) report in February 2023.
The detailed studies will be presented in the phase 2 (detailed design) report in November 2023. Following acceptance by the committee, it should be possible to manufacture the device in 2024.
Irradiation in the BR2 reactor is planned for the 2nd quarter of 2025 after completing phase 3 (manufacturing), whereafter the device for irradiation will be presented.

2.3. VERTICAL DISPLACEMENT SYSTEM

Considering that a single cell moving along a vertical axis provides better measurement consistency than many different sensors providing separates measurements at fixed elevations, it was decided that CARMEN would be equipped with a vertical displacement system.
This displacement system is designed to move the measurement cell over intervals of +/- 500 mm around the fuel mid-plane. This system will also be used to place the measuring cell in the withdrawal area outside the neutron flux to prevent drift or decalibration of its sensors.

2.3.1. Global design of the vertical displacement system

The kinematics of CARMEN's vertical displacement system revolve around a screw-nut connection whose rotational movement is provided by the motor located in the head of the device. The sensor cables are wound together and spiraled around the ball screw working in extension/compression, thus making it possible to vary the length of the cables according to the movement of the measuring cell.

The technology used for the CARMEN screw-nut connection is a recirculating ball screw. This solution has a better base yield than a classic screw-nut connection and has already proven itself on the CALMOS device in OSIRIS.

Magnetic coupling has been retained to transmit the rotational movement of the gear motor, installed in the head of the sealed device (in air), to the ball screw, inside the body of the device (in water).

A limit switch sensor is integrated into the system; it confirms that the measuring cell is in good condition in the withdrawal area and is used to reset the encoders in the event of loss of origin after an electronic failure.

The cables inside the device are wound together and spiraled, thus allowing the up and down movements of the measuring cell (see Figure 9). These cables made of mineral insulation (generally alumina or magnesia) are designed to resist radiation and are protected in a leaktight stainless steel sheath, making them highly rigid. Their mobility, in particular those with a diameter of 2.2 mm (used for fission and ionization chambers), is an issue that has been taken into account in the development of CARMEN. The winding diameter and the number of turns have been optimized with regard to the flexibility of the cables and the excess length necessary to perform the entire vertical displacement, generating the least possible strain.

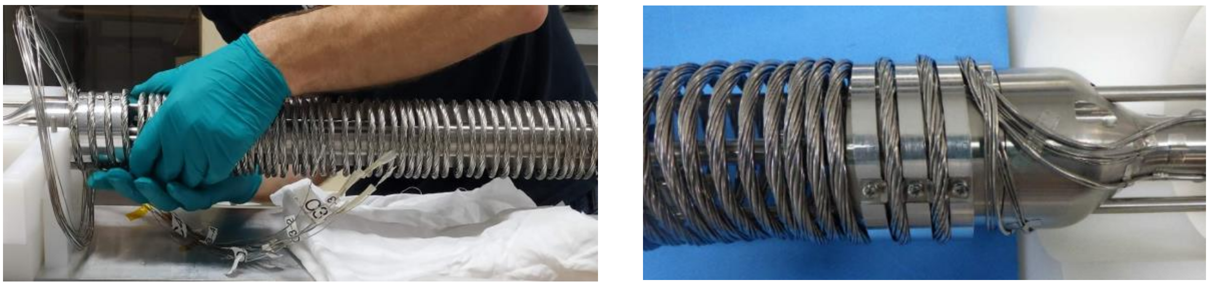


Figure 9: Cable spirals

These cables are radiation-resistant up to extremely high fluency levels, whether in neutron or gamma environment, but are relatively inflexible, fragile and very sensitive to humidity. Their implementation should therefore only be entrusted to an experienced contractor.

2.3.2. Full-scale endurance testing

A full-scale mock-up was produced to validate the design, the manufacturing process and the endurance of CARMEN's vertical displacement system.

The CARMEN mock-up was positioned vertically and immersed in an upward flow of demineralized water to represent the flow rates that will exist in the irradiation locations.
An endurance test comprising 2000 return trips of the dummy measuring cell was carried out over distance of 1650 mm at a speed close to 10 mm/s. This test represents a continuous operating time of approximately 200 hours, which is about the duration of use of the CARMEN device in the JHR.

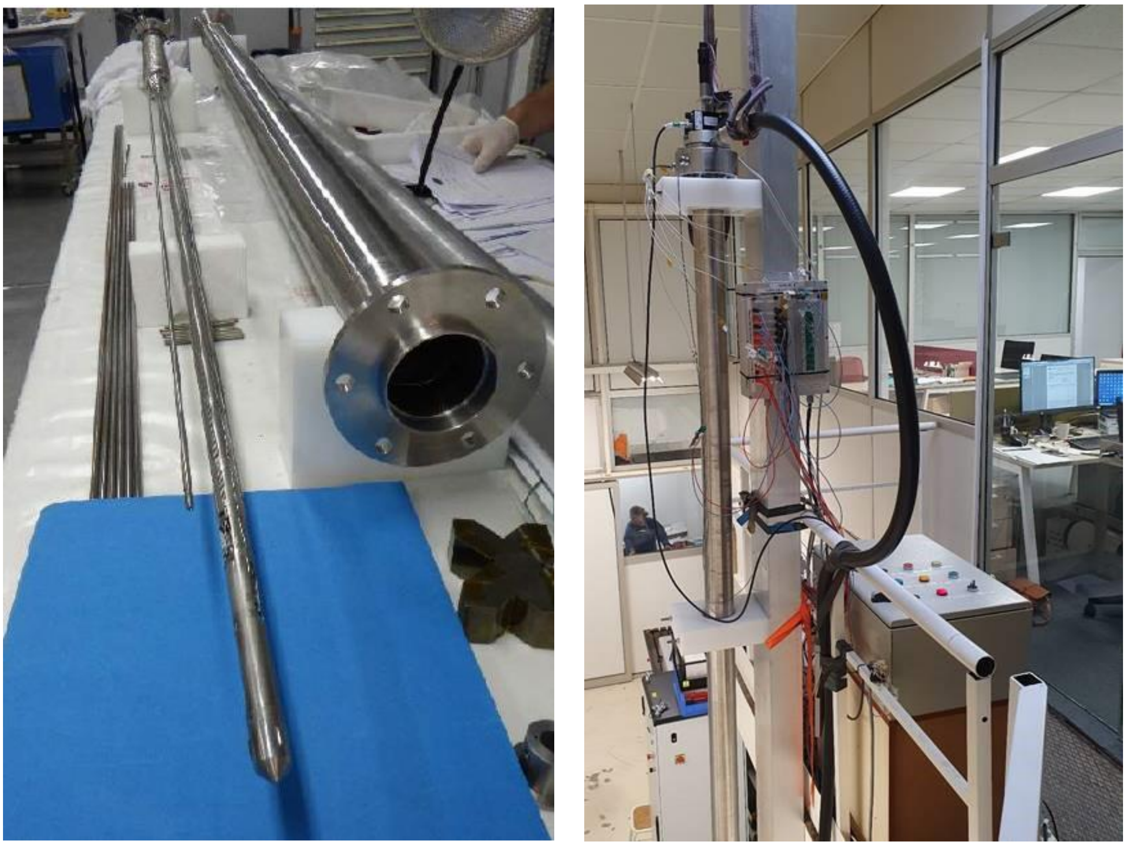


Figure 10: Full-scale mock-up of CARMEN (before assembly on the right, on its test bench on the left)

A lot of information was recorded during the test, in particular the continuity of each pair of cables.

At the end of the endurance test, the mock-up was completely disassembled to check for any traces of wear or corrosion.

The visual inspection of the cables made it possible to identify sheath wear on several of them. Wear on the cables was detected due to friction on the top part of the mock-up. This included the perforation of 4 cables, which explained the loss of insulation of these cables during the test.

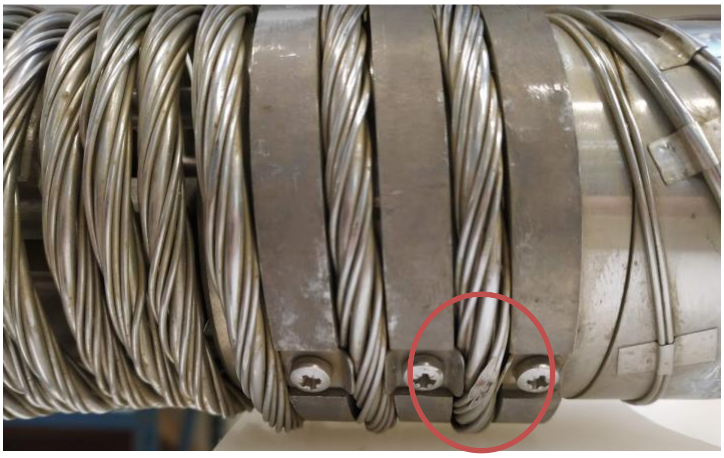


Figure 11: Indication of wear on the wiring

A design optimization is underway to resolve this issue.

Very local traces of corrosion were observed on 3 of-the-shelf parts, as well as on the threaded rod of the ballscrew. Precautions will be implemented to prevent this problem.

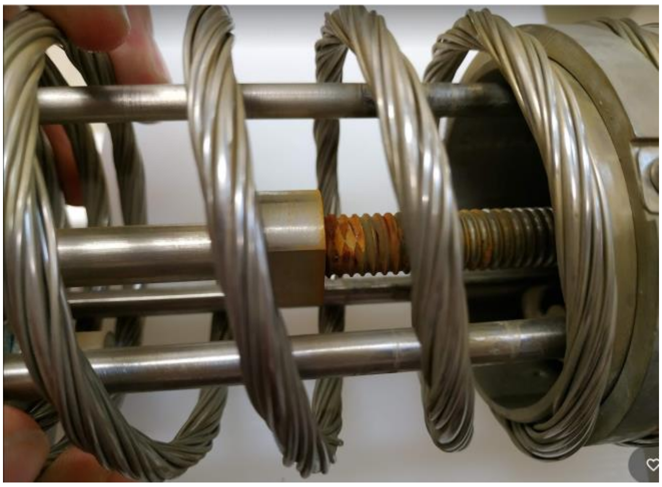


Figure 12: Traces of corrosion on the threading of the ball screw

Test results made it possible to validate the sizing of the motorization and the design of the kinematic chain. The spiral is resistant to cycling fatigue (continuity, insulation, wear). The entire mechanism resists corrosion. Overall, any major issues with design and process choices have been ruled out.
Cable sheath perforation and local corrosion can be handled without much difficulty.

2.4. HEAD OF THE DEVICE AND CONNECTOR BOX

A mock-up will be manufactured to conduct tests in order to validate the head part of the device.

2.4.1. Mock-up of the head and leak testing

The purpose of this mock-up will be to check the feasibility of manufacturing this part of the device, test its leaktightness and the feasibility of connector handling operations under conditions representative of those in the JHR.

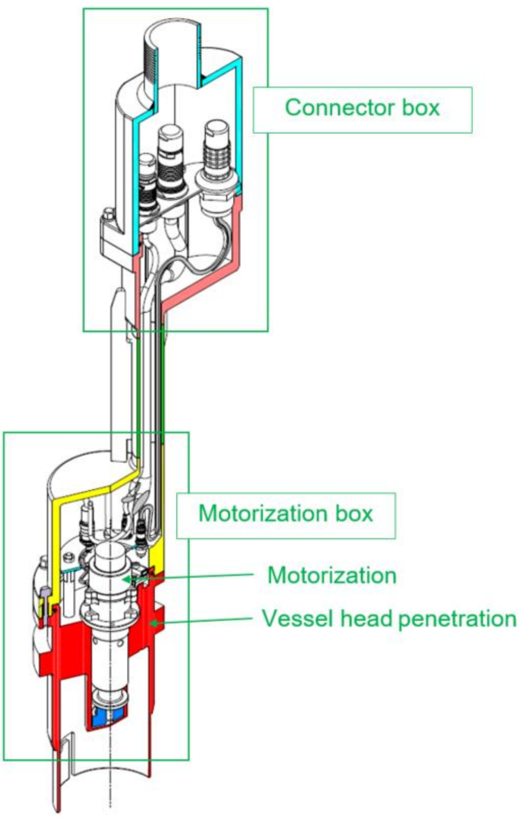


Figure 13: Mock-up of the CARMEN's head

On the lower part, the motorization box includes the motor which powers the vertical displacement of the measuring cell by means of magnetic coupling.

The motor has been the subject of a specific study given the restricted space allocated (15 cm long and 3 cm in diameter) and the specific environmental conditions to which it will be subjected (irradiation of 250 kGy for 2000 hours of operation).

The motorization box also includes the internal connectors, which make it easier to assemble/disassemble the device head. The top part of the head can be completely disconnected from the device by disconnecting the internal connectors.
An O-ring is used between the motorization box and the vessel head penetration to protect the components in the vessel head against water ingress once the device is immersed.

The connectors on the top part of the connector box are used to connect/ disconnect the underwater lines. These lines connect the in-pile part to the out-of-pile part of the device. The out-of-pile part of the device

includes the measurement acquisition system and the instrumentation and control (I&C) for the displacement system; these systems are housed in the same I&C cabinet.
To ensure leaktighness in the motorization box, the cables are fed through small holes in the vessel head penetration and the seal is made leakproof by brazing. A weld leak test will be carried out during assembly operations.
The vessel head penetration is shaped to interface with its environment and with the lower part of the CARMEN device.

The leaktightness of the CARMEN head mock-up will first be tested in pressurized air before being immersed in water.

The motor and all the connectors must be replaceable in the event of failure. Part of the tests carried out on the head's mock-up will make it possible to check the maintainability of these components under conditions representative of those in the JHR. A pressurized leak test and a cable continuity test will be carried out after the maintenance tests.

The TOTEM facility (see Figure 14) at the Cadarache center has a pool with a depth equivalent to that of the JHR. This facility is regularly used to test mock-ups of experimental devices in order to validate design options.

The TOTEM facility will therefore be used to test cable connection/disconnection operations and to perform maintainability tests on the head's mock-up under conditions representative of those in the JHR. These tests are planned for the first half of 2024.

Figure 14: The TOTEM facility

3. CONCLUSION

Design optimization of the CARMEN device and the related validation tests performed on numerous mock-ups will make it possible to provide a device design ready for manufacturing by the end of 2025. A fleet of 3 CARMEN devices will be manufactured and available for the JHR start-up tests. The availability of measurements will thus be guaranteed even if one of the CARMEN devices fails.

The device's on-board displacement system will allow fast and very precise measurements.

CARMEN's unprecedented measurement capabilities are expected to improve our knowledge of the JHR core, thus providing an optimized thermal design of the irradiation devices and better analysis of the experimental results.

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