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On Line Neutron Flux Mapping in Fuel Coolant Channels of a Research Reactor

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George Braoudakis, David Wassink, Bradley Sinclair, John C. Osborn, Huayou Wu,
Christophe Blandin, Mathieu Thévenin, Gwénolé Corre and Stéphane Normand

Abstract—This work deals with the on-line neutron flux mapping of the OPAL research reactor. A specific irradiation device has been set up to investigate fuel coolant channels using subminiature fission chambers to get thermal neutron flux profiles. Experimental results are compared to first neutronic calculations and show good agreement (C/E ~0.97).

Index Terms—On-line Neutron Flux Mapping, Fission Chamber, Campbell Mode, Research Reactor.

I. INTRODUCTION

Within the framework of a scientific and technological cooperation agreement between the French Alternative Energies and Atomic Energy Commission (CEA) and the Australian Nuclear Science and Technology Organisation (ANSTO), an on-line neutron flux profile in fuel coolant channels measurement campaign took place in the Australian OPAL research reactor in December 2012.

The campaign main objective was the on-line relative thermal neutron flux mapping of OPAL fuel assemblies, using three Ø1.5 mm sub-miniature fission chambers manufactured by the PHOTONIS France Company under CEA patent. A dedicated experimental rig was designed jointly by CEA and ANSTO specifically for this measurement campaign to fit within the nominally 2.45 mm wide fuel coolant channels. A brand new acquisition system was also specifically developed by CEA to perform simultaneous signal acquisition from a maximum of four separate fission chambers, over a wide range of neutron flux by operating jointly the Pulse and Campbell modes.

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Neutron flux profile measurements within coolant channels were performed in December 2012 leading to a thorough investigation of 5 of the 16 fuel assemblies: one complete quadrant of the two axis symmetrical core and one fresh fuel assembly in another quadrant. Data show good agreement with ANSTO expected neutron flux shapes.

The measurement campaign demonstrated that the whole measurement method and system specifically developed for this campaign is definitely appropriate to perform on-line neutron flux profile measurements in such small nuclear reactor locations as fuel coolant channels and under such high neutron flux environment.

II. EXPERIMENTAL SETUP

A. OPAL Reactor and Measurement Constraints

The Open Pool Australian Light-water reactor (OPAL), which first achieved criticality in 2006, is a 20 MW thermal power research reactor using low enriched uranium fuel plates. The core contains 16 fuel elements and is located at the bottom of a 13 metre deep light water pool. Reactivity control is provided by five hafnium control rods.

OPAL reactor activities are focused on neutron beams research thanks to the D₂O reflector surrounding the core, medical radioisotope production, silicon doping and neutron activation analysis.

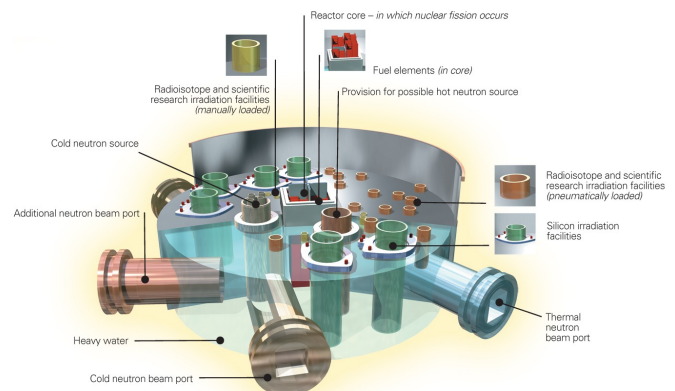


Fig. 1: 3D view of OPAL Reactor experimental irradiation locations

Thermal neutron flux mapping of OPAL fuel assemblies means a measurement system designed to fit in nominally 2.45

mm wide fuel coolant channels while preventing any scratch or damage to fuel clad. OPAL safety based operating conditions require the reactor to be in natural convection cooling state when an experimental rig is inserted within coolant channels. In this low power state neutron flux measurements can only be performed at a stabilized power of 100 kW leading to an expected maximum total neutron flux between fuel plates of around 4.10^{12} n.cm⁻².s⁻¹.

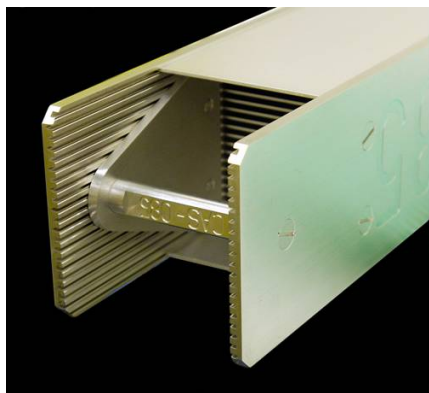


Fig. 2: OPAL Reactor fuel assembly

Main imposed experimental constraints and measurement requests were:

- 2.45 mm wide coolant channels, requiring small neutron detector as well as small irradiation rig,
- 13 metre deep light water pool, requiring long manoeuvring system and long signal cables for neutron detectors,
- Axial and horizontal neutron flux profiles,
- On-line neutron flux measurement, eliminating for example activation dosimetry,
- Relatively high neutron flux level, requiring dedicated electronic acquisition system.

B. Neutron Detector

Considering requirements, CEA proposed to use Ø1.5 mm sub-miniature fission chambers, manufactured by the PHOTONIS France Company under CEA patent [1]. Ø1.5 mm sub-miniature fission chambers are part of gas ionizing detectors type, using 10 µg ²³⁵U enriched uranium fissile deposit for incident neutrons to charged particles (fission products) conversion. Due to the ²³⁵U enrichment, these sub-miniature fission chambers are mainly sensitive to the thermal part of the neutron spectrum.

CEA fission chambers with integrated cable commonly stand with an Ø2.2 mm integrated highly effective EM/RF shielded mineral cable to withstand harsh conditions in the reactor. A specific Ø1.3 mm shrink to the sheath has been added for the first metre of the cable in order to fit on the irradiation rig.

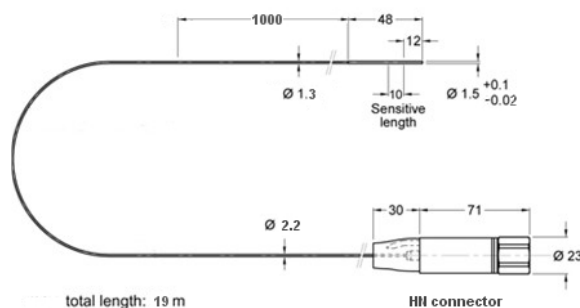


Fig. 3: CFUZ/CE2 fission chamber detector from PHOTONIS France.

Horizontal neutron profile measurements are achieved thanks to three identical Ø1.5 mm fission chambers placed on the irradiation rig at the same height.

C. Irradiation Rig

A dedicated experimental rig was designed jointly by CEA and ANSTO specifically for this measurement campaign to fit within the nominally 2.45 mm wide fuel coolant channels. It fulfils the important functions of hosting the three fission chambers and ensuring correct and repeatable positioning along the fuel height in the various coolant channels.

The rig design is based on a 2 mm thick aluminium plate precisely machined to host the three FC and their integrated mineral cable. Aluminium strips keep sensitive parts of fission chambers and cable in position. Extreme care has been applied to smooth every potentially sharp edge to protect the fuel clad.

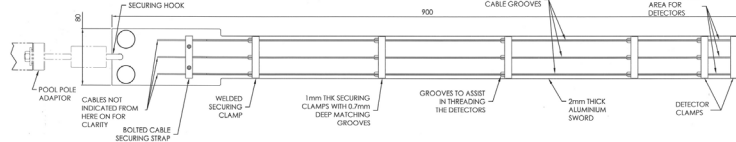


Fig. 4: Dedicated experimental rig overall sketch

The aluminium plate is attached to a 16 metre long pole made of carbon fibre for precise manoeuvring within the core. This is accomplished with the assistance of an underwater video camera. Axial profiles measurements are achieved manually over the core height using a measuring tape attached to the pole.

D. Signal Acquisition System

The Ø1.5 mm sub-miniature fission chambers operated at 100 kW reactor power corresponding to a total neutron flux of $\sim 4.10^{12}$ n.cm⁻².s⁻¹, have the Pulse mode saturated. Therefore, the three sub-miniature fission chambers need to be operated in Campbell (or Fluctuation) mode [2].

A brand new acquisition system was specifically developed by CEA Cadarache and Saclay sites to perform real time synchronous and simultaneous signal acquisition from a maximum of four separate fission chambers, over a wide range of neutron flux by operating jointly the Pulse and Campbell modes.

The new system is called MONACO, for ‘Multichannel Online Neutron Acquisition in Campbell mOde’ [3] and is described in Figure 5.

1) Hardware

The MONACO system is based on four current preamplifiers, developed by CEA to be immune to electromagnetic and radiofrequency perturbations. Their current integration design allows them to deal with up to several hundred meters (tested with 300 m) of wire to fission chambers.

Signals from preamplifiers are then injected into system boards developed by CEA in other research projects [4]. They integrate four 8 bit, 200 Msamples/s Analog Digital Converters (ADC) directly controlled by a Field Programmable Gate Array (FPGA). All the embedded algorithms are implemented on the FPGA for real time measurement and estimation of both count rate and variance. Values are updated every 250 ms.

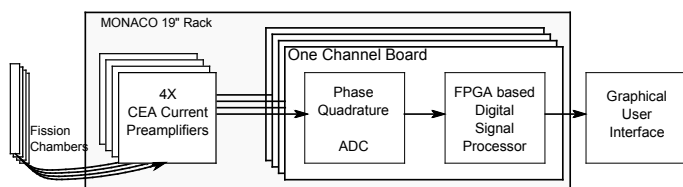


Fig. 5: Schematic diagram of the MONACO acquisition system.

2) Software

MONACO boards are controlled and monitored via a Graphical User Interface (GUI) thanks to a front panel Universal Serial Bus (USB). The end-user GUI is based on the National Instrument LabView 9.0.1 interface.

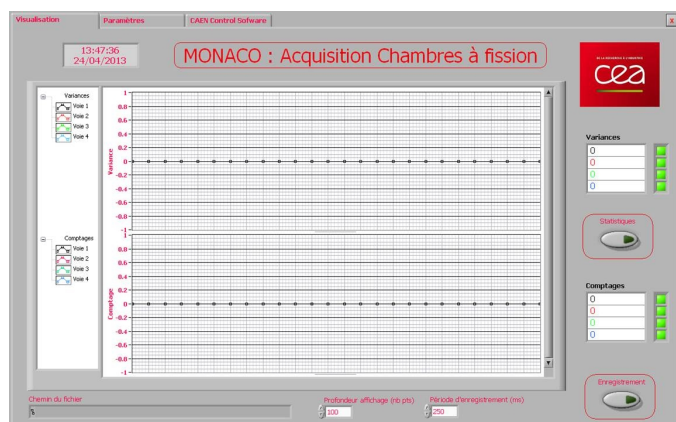


Fig. 6: Screen copy of the control and display interface during the measurement campaign.

GUI allows the operator to set all acquisition parameters such as frequency, sampling, offset or filters of acquired data to match requested values for Pulse and Campbell modes. All measurement data are recorded in a ‘.txt’ file.

E. Signals Processing

The reactor conditions are monitored throughout all measurement time using the reactor ex-core instrumentation to post-process every coolant channel measurement to the exact reactor power of 100 kW.

Sub-miniature fission chambers absolute fissile deposit mass have been evaluated by the PHOTONIS France Company using an alpha particle counter. These absolute masses are used afterwards to normalize every fission chamber to a 10 μg ^{235}U enriched uranium deposit.

III. MEASUREMENTS

Neutron flux profile measurements within coolant channels were performed in December 2012. All equipments met their requirements and allowed operators to fulfil the objectives: the irradiation rig design was perfectly adequate even if manoeuvring in the core is challenging, $\text{\O}1.5$ mm sub-miniature fission chambers were used for the first time in Campbell mode but operated normally and the new MONACO acquisition system was fully operational.

The measurement campaign lead to a thorough investigation of 5 of the 16 fuel assemblies: one complete quadrant of the two axis symmetrical core and one fresh fuel assembly in another quadrant.

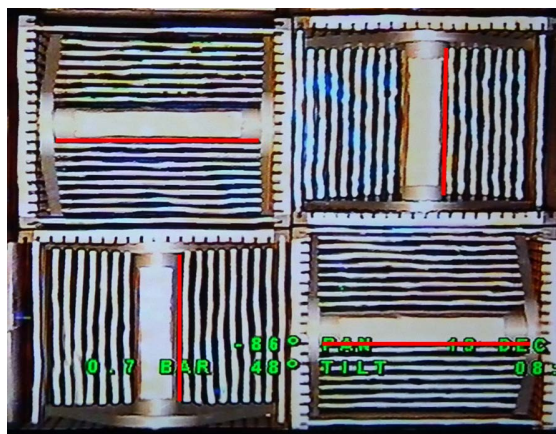


Fig. 7: Under water picture of OPAL reactor fuel assemblies during measurements with investigated fuel coolant channels (red line).

IV. RESULTS

A. Linearity versus Reactor Power

The MONACO acquisition system as well as $\text{\O}1.5$ mm sub-miniature fission chambers in Campbell mode were employed for the first time. Although theory and previous reactor experiments demonstrated the Campbell mode is the best flux estimate (gamma contribution rejection) [5][6], operators found opportunity to check the whole measurement system (fission chamber + acquisition system) linearity with the reactor power.

A dedicated reactor operation was performed with five stabilized reactor power steps from start to 150 kW (maximum reactor power achievable in the experimental conditions).

Reactor power is established accurately using reactor ex-core instrumentation, recalibrated afterwards using the reactor thermal balance at nominal power. MONACO measurements are recorded every second.

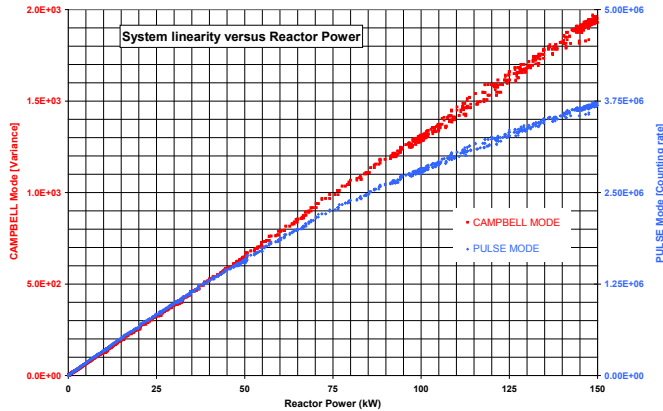


Fig. 8: Linearity of the MONACO acquisition system for the irradiation rig central fission chamber with reactor power (Channel 8 – B3 fuel assembly).

Figure 8 confirms the need to operate fission chambers in Campbell mode. Campbell mode is linear with reactor power from the startup of the reactor to the stabilized power of 150 kW. Measurement point discrepancies between 100 kW and 150 kW are explained by un-stabilized reactor conditions during reactor power increase.

Fission chamber Pulse mode can be considered as linear with reactor power (ie. incident neutron flux) until ~ 50 kW ($\sim 2 \cdot 10^{12}$ n.cm⁻².s⁻¹). This is consistent with other high standard acquisition systems in Pulse mode.

Results are only presented for the irradiation rig central fission chamber but linearity results are similar for the three neutron detectors.

B. Neutron Flux Profiles

Neutron flux profile measurements within coolant channels of 5 of the 16 fuel assemblies were performed with a total of 400 measurement points. The manual irradiation rig moving system was used for axial neutron flux profiles with measurement every 30 mm. All measurement locations are represented in Figure 9.

Results for sub-miniature fission chambers placed in the middle of the irradiation rig are presented on Figure 10:

- Fuel assemblies A3–Channel 8 and B3–Channel 8 show a similar neutron flux profile: the influence of the left (on graph) hafnium control rod (35% withdrawn) is dominant and the maximum neutron flux is forced to the bottom of the core.
- Fuel assemblies A4–Channel 8 and D1–Channel 7 have a similar shape. These assemblies are both away from control rods and symmetrical with respect to the reactor core centre.

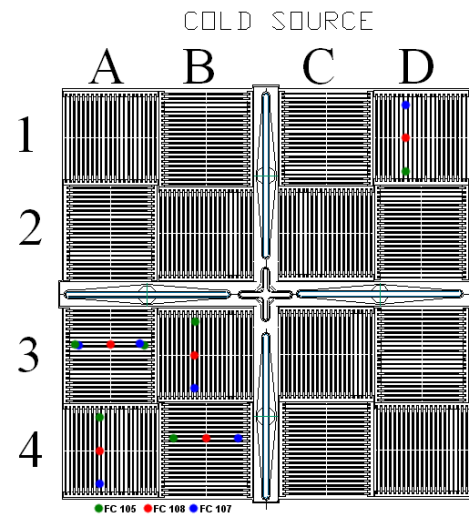


Fig. 9: Investigated fuel coolant channels in the OPAL reactor core.

- Fuel assembly B4–Channel 8 exhibits the highest measured neutron flux among all the central fission chamber positions. The neutron flux profile is minimally perturbed as the bottom (on graph) control rod is 85% withdrawn.
- All neutron profiles have a steep increase above the height of +300 mm due to thermalization of all neutrons when leaving the fuel zone.

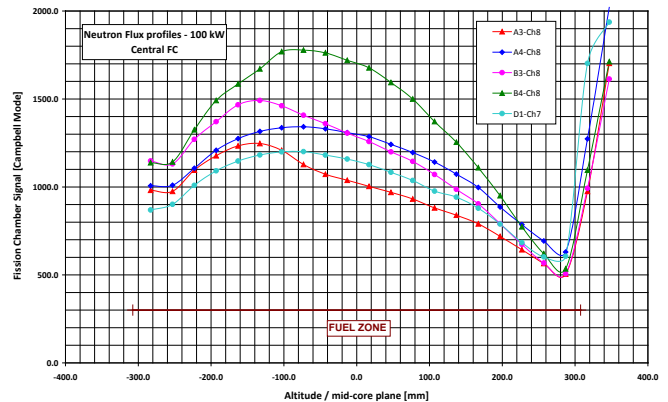


Fig. 10: Neutron flux profiles in investigated coolant channels (irradiation rig central fission chamber, outlined by red dots on Figure 9)

C. Measurement to Calculation Comparison

1) Calculation Model

Monte Carlo simulations of the flux and predictions of the fission rate have been conducted using the MCNP5 program, version 1.60 [7]. The model includes the reactor core and nearby structures, the heavy water reflector, some of the surrounding light water, and the following facilities located in the reflector: the cold neutron source, all of the irradiation facilities and neutron beam tubes. The fuel composition used in the Monte Carlo simulations is derived from calculations with a separate model based on diffusion theory, used in fuel management. Diffusion theory calculations made use of the

CITVAP program, developed by INVAP [8], which is an enhanced version of the CITATION program. The fuel composition allows for burn-up of the fuel and of the burnable poison (cadmium wires in the fuel assemblies) and includes fission products. The diffusion theory calculations have been carried out for an earlier operating cycle than the cycle in which this experiment was carried out, but the cycle which has been chosen was one for which the refueling history is similar to recent refueling sequences leading up to the cycle in which the flux measurements were performed, so the burn-up distribution across the core is expected to be similar.

2) Comparison

Both fission rates in detectors and unperturbed neutron fluxes at fission chambers locations are calculated with the MCNP5 model. Total fission rates in detectors (taking into account the isotopic composition of the fissile deposit) are chosen for comparison to measurements as fission rate is independent from calculated neutron spectra.

The MONACO system has been designed for relative neutron flux measurements. Thus measurement and calculated values need to be normalized to be compared. Authors chose to normalise to the maximum of the cosine zone (fuel zone).

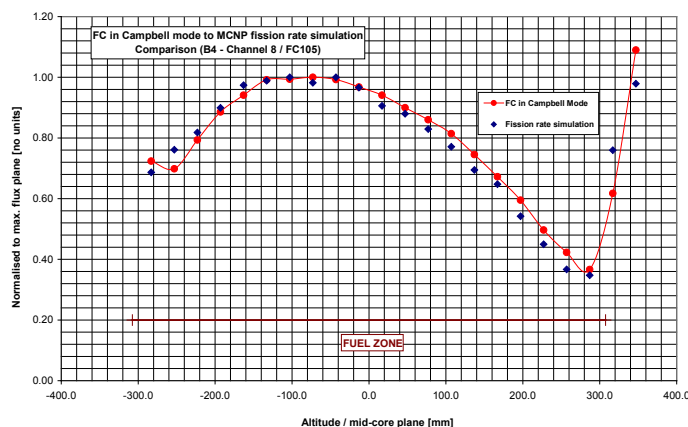


Fig. 11: Measurement to calculation comparison in the B4-Ch.8 coolant channel.

Figure 11 shows first measurements to MCNP5 simulations comparison results for the B4-Channel 8 fuel assembly (see FC105 in Figure 9). These first results are in good agreement with an average (over the fuel zone) calculation to measurement ratio (C/E) of 0.97 (dispersion of ~ 5%).

Exhaustive comparison, including side water effects, burnable poison and other local effects will be reported in a near future publication.

V. DISCUSSION-CONCLUSION

This measurement campaign first validated the use of Ø1.5 mm sub-miniature fission chambers operated in Campbell mode for neutron flux profile in very small irradiation locations such as fuel plates' coolant channel. This also confirmed the suitability of MONACO, a new electronic

acquisition system for in-core wide range neutron flux measurements in both Pulse and Campbell modes. The application and capabilities of this system for reactors are very important. The system will be fully qualified and calibrated in the near future.

Five of the 16 fuel assemblies have been thoroughly investigated. Precise thermal neutron flux profiles in fuel coolant channels are now available for comparison to calculations and possible future adjustments of the reactor neutronic model. First calculation to measurement comparison show very good results for global neutrons flux profiles. Final calculations to measurement ratios are close to 1 within the uncertainty of ~5%. Exhaustive comparison, including local neutron spectrum effects, will be reported later.

ACKNOWLEDGMENT

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