THE EOLE CRITICAL FACILITY IN SUPPORT TO EXPERIMENTAL REACTOR CORE PHYSICS VALIDATION: THE EXAMPLE OF AMMON EXPERIMENTAL PROGRAM FOR JHR START-UP VALIDATION

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Abstract

The CEA (Atomic and Alternative Energies Commission) is strongly involved in R&D research programs concerning the use of nuclear energy as a clean and reliable source of energy and consequently is working on the 3 generations of reactors (II, III and IV) on various topics such as ageing plant management, optimization of the plutonium stockpile, waste management and innovative systems exploration. Core physics studies are an essential part of this comprehensive R&D effort. In particular, the Zero Power Reactors (ZPR) play an important role in the validation of neutron physics calculation tools (codes and nuclear data). The proposed paper describes the main characteristics and strategy to design and conduct experimental programs in ZPRs and in particular the EOLE Critical Facility. The role of EOLE as a research reactor for the improvement of neutron physics computer codes for future industrial applications leads to its identification as a key structure for CEA R&D programs. Those programs are designed to complement the ongoing validation work of the lattice and core physics tool for LWR applications and in particular for the new MTR and GEN-III+LWR generations. All these programs focus on nuclear data improvement, and on In-Core Instrumentation and gamma heating. We will here focus on the AMMON experimental program in support to the validation of HORUS 3D neutron and photon deterministic transport calculation for the future Jules Horowitz MTR in Cadarache. The experimental phase ended, after 3 years of intense activity, by the end of March 2013. The main design options of the program, as the main performed measurements on the 7 core configurations and their uncertainties are detailed in the final paper. They concern:

- *critical size determination on the JHR-like pattern in various configurations,*
- *axial and azimuthal fission rate measurements by gamma peak check analysis in the curved fuel elements of the JHR-like assemblies*
- *TLD based gamma heating measurement in the structures and absorbers, using a novel approach.*
- *JHR-assembly Spectrum characterisation using combination of new prototypes of miniature fission chambers and selective dosimetry.*

I. INTRODUCTION

Experimental programs in critical facilities – or Zero Power Reactors – such as EOLE, MINERVE and MASURCA [1] play a key role in the validation of neutron lattice and core codes as they enable the access to information neither reachable in power reactor nor existing for new concepts. With time, both numerical methods and precision on calculated parameters have improved dramatically. This improvement, coupled with the emergence of HPC (High performance computing) requires new approaches to the design of experimental programs compared to past design studies. One of them is the use of representativity concept to optimize the information transfer from the mock-up to the actual reactor design. This has been the case for previous programs in EOLE, such as BASALA for the analysis of full MOX Advanced BWR mock-ups [2]. Representativity approach enables to transpose the C/E (or C-E) result from the ZPR to the target core. It requires both representativity close to 1, and experimental uncertainties as low as possible. As today codes and nuclear data becomes very precise, a major improvement on the measurements accuracy must then been made to ensure a pertinent use of experimental results.

In this context, the present paper details the complete study made to design and to conduct a new experimental program in EOLE, called AMMON [3], in support to the validation of the HORUS 3D code package for JHR MTR reactor currently being built on Cadarache.

II. APPLICATION TO THE AMMON EXPERIMENTAL PROGRAMME IN EOLE

The particular geometry of the JHR core requires the development and the full validation of new calculation capabilities. In this context, the HORUS3D neutron and photon tool, based on APOLLO2 and CRONOS2 deterministic transport codes and their updated JEFF3.1.1 nuclear data library, has been developed. The HORUS3D is currently undergoing an important V&V (Verification & Validation) process, to end up with a complete neutron and gamma calculation scheme used for the design studies of the Jules Horowitz Reactor (JHR). The verification step has been performed on the basis of comparisons between calculations using the deterministic scheme and reference Monte Carlo calculations on realistic benchmarks. The experimental validation step is made to compare the computational results of the “code / calculation scheme / nuclear data library” package to measurement data in representative configurations [4].

For this purpose, the AMMON experimental program has been designed from 2006 and launched in 2009 in the EOLE critical facility. Its objective was to provide experimental data for the HORUS3D scheme on the main safety and design parameters such as criticality, power map, absorber reactivity worth, kinetics parameters and gamma heating. Several configurations have been foreseen for the 3-years experimental phase. The experimental planning takes into account the most important information to be validated, and leads to different configurations, representative of normal, incidental or accidental situations.

The experiment aims to better validate - and potentially to improve - the basic design uncertainties and biases to be applied to local and global core neutron and photon parameters.

Different design features of the JHR have been studied, depending on different configurations: standard assemblies in a reference configuration (AMMON/REF), full (or half) Hafnium control rod (AMMON/Hf), Beryllium reflector (AMMON/Be), as incidental situations such as loading error (water hole, AMMON/WH) or rod follower ejection (AMMON/ rod ejection). Figure 1 reproduces a top view of the AMMON/REF configuration in the EOLE cavity.

II.A Core design

The AMMON programme is based on a coupled core approach: it consists in an experimental zone dedicated to the physics of the JHR fuel elements enclosed in a hexagonal aluminium cask of 30 cm side length surrounded by a driver zone loaded with UO_2 standard PWR fuel pins. Each AMMON fuel assembly, exact replica of an actual JHR fuel assembly, is composed of 3 x 8 curved fuel plates, maintained by 3 aluminium alloy stiffeners. The external diameter of the assembly is about 10 cm for a 60-cm active length. The fuel plates are composed of U_3Si_2-Al fuel (with 27% ^{235}U enrichment) and Al-Fe-Ni cladding. A 3 cm height Al-B insert is positioned 1 cm above the active height.

- The central cavity of the assembly hosts an aluminium absorber rod follower. Additionally, 6 fillers are also inserted in the rack between fuel assemblies. The followers and fillers can be instrumented with neutron and gamma detectors.

- The driver zone is composed of standard PWR UO_2 fuel pins, with Zircaloy-4 cladding and stainless steel overcladding inserted in a triangular lattice whose pitch was optimized to reproduce as well as possible the central zone neutron spectrum.

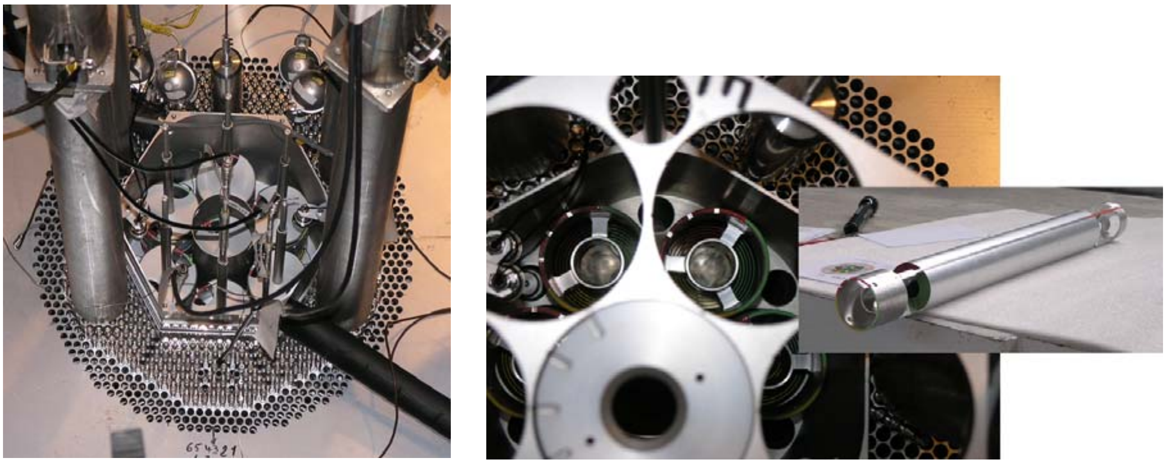

Figure 1. *Cross section of the AMMON reference core. Left;: bird eye-view; Right :zoom on the central part and of one JHR fuel element*

II.B. Improvement of experimental techniques

As explained, a precise management of both accuracy and uncertainty is required today for modern program interpretation. One of the challenging tasks for experimental teams is then to improve the experimental techniques used for reaching integral quantities of interest:

- Doubling time measurements for the reactivity excess measurement of each core configuration (within 10 pcm)
- Radial and axial fission rate distributions on the fuel plates by using integral and peak γ-ray spectrometry techniques (1% uncertainty)
- miniature fission chambers and activation dosimeters inserted in the centre of the fuel assembly or in the water gap, for flux distributions (between 1 and 3% uncertainty),
- gamma heating measurements performed by using thermo-luminescent detectors and OSL techniques, with an uncertainty of about 3-4% (1SD).
- Temperature coefficient measurements

The full validation of some data required the design and the fabrication of special components, as the modification of existing experimental devices, such as:

7 dedicated JHR-like AMMON assemblies made by AREVA/CERCA for the purpose of the program. One of these elements is fully dismountable, in order to measure local (axial and azimuthal) fission rate distributions on each curved plate.

A special gamma-scanning device to enable the gamma activity measurement with a high positioning precision (figure 2), coupled with an azimuthal coder for the particular γ-spectrometry measurements on the fuel plates

A second thermoregulation station was installed in the facility, to completely separate the experimental zone from the buffer zone. The aim is double:

- The buffer zone can contain boron is some configurations, as the experimental one will not,
- Temperatures must be controlled separately, in order to uncouple the reactivity effects of the 2 zones, and produce valuable isothermal temperature coefficient results.

Hafnium control rod components (complete and half rod),

A beryllium block (10cm diameter cylinder, 60 cm tall) used for studying the reflector effect,

New experimental detectors for the gamma-heating measurements, using Optically Stimulated Luminescent Detectors (OSLDs).

The experimental measurements performed on the 7 configurations were devoted to the internal experimental zone characterization, with the following measurements:

- Axial and azimuthal power distribution on several RJH fuel plates [5]
- Neutron flux distribution by using small activation detectors between the plates and in the central part of the RJH assemblies,

- Breeding ratio using peak-check gamma spectrometry method,
- Gamma dose using thermo luminescent detectors [6]
- Additional γ-scanning measurements in the buffer zone, for interface characterization.

Each technique or measurement has been improved either by increasing the number of measurements, or by modernising the experimental devices. We give hereafter some examples of improvement of measurements and accuracies in the experimental results.

II.C. Gamma scanning

Gross (integral) gamma-scanning and particular peak check are used to access the quantity of interest. Each new program is a challenging opportunity to improve the measurement techniques and their treatment. Improvements can be made either on the electronics *(*new and more sensitive Germanium detectors, fast acquisition – low dead time electronics, calibration) or on the experimental conditions (irradiation time, fresh fuels), even nuclear data (yields, intensities, decay constants, etc..). The γ-scanning bench has undergone an extensive validation benchmarking in order to optimize the counting phase: window collimation, angular stepping, etc... The complete work is described in a devoted publication [5].

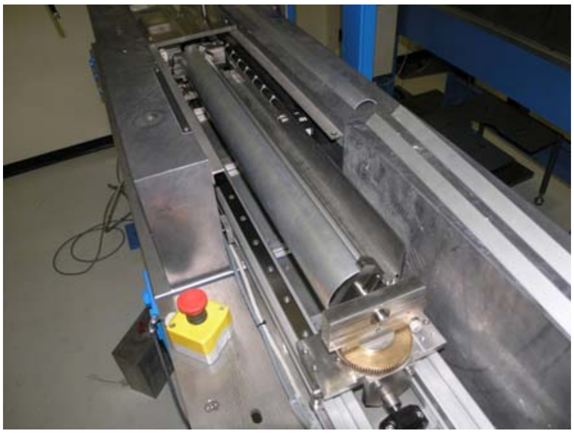

Figure 2. *Top view of the γ-scanning bench for curved plate axial and azimuthal measurements*

a. Plate power

Average plate powers are measured on the bench using peak check technique on several FPs. Each plate of the dismountable assembly is placed on the bench and counted for several minutes. The example in Table 1 gives the last results obtained on the ejected rod follower configuration. Experimental uncertainties are within 0.5% (1 SD). All averaged plate values are within 1 standard deviation.

Table 1. *Normalized average plate fission rate in the central assembly (AMMON/rod ejection configuration)*

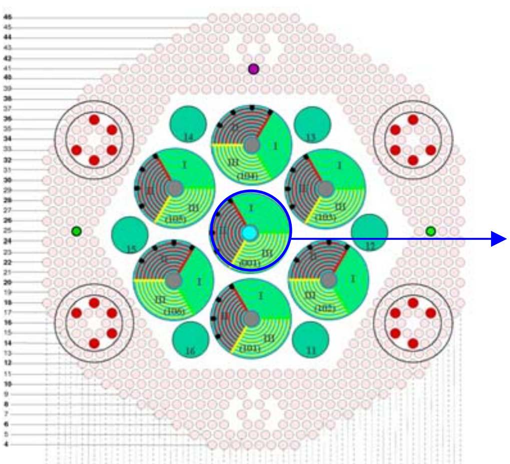

Plate n°	SI	SII	SIII
P1(inner)	1,510	1,498	1,498
P2	1,237	1,234	1,235
P3	1,080	1,080	1,073
P4	0,975	0,976	0,974
P5	0,911	0,918	0,912
P6	0,882	0,882	0,885
P7	0,877	0,876	0,880
P8(outer)	0,898	0,900	0,904

b. Axial measurements of fission rate with Hf inserted

The axial perturbed fission rate, due to the half-inserted hafnium rod (“1/2 hafnium” configuration), was measured and compared to the unperturbed one. The fission rate is measured axially along several plates of the central assembly using γ-peak of ^{135}Xe at 250keV. Collimation width has bee optimized to ensure a sufficient count rate for each plate slice. The distortion due to the inserted hafnium rod is precisely described (Figure 3).

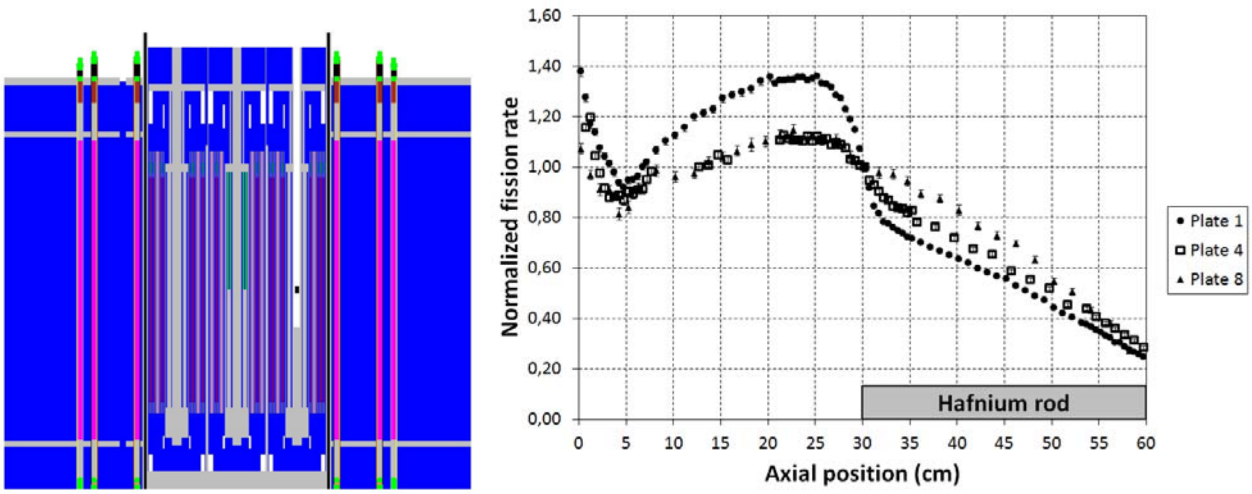

Figure 3 *Axial fission profile on plates 1 (inner), 4 (mid) and 8 (outer)of the central assembly, in the “1/2 hafnium” configuration.* In this particular configuration, an hafnium rod is inserted in the central assembly.

c. Azimuthal measurements in the “Be periphery” configuration

The azimuthal power profile was measured on plates in the “Reference” and “Beryllium periphery” configuration. In the latter, a beryllium block replaces one of the periphery assemblies. Fission profiles of the plates in front of this block are perturbed, especially for the outer one (Figure 4).

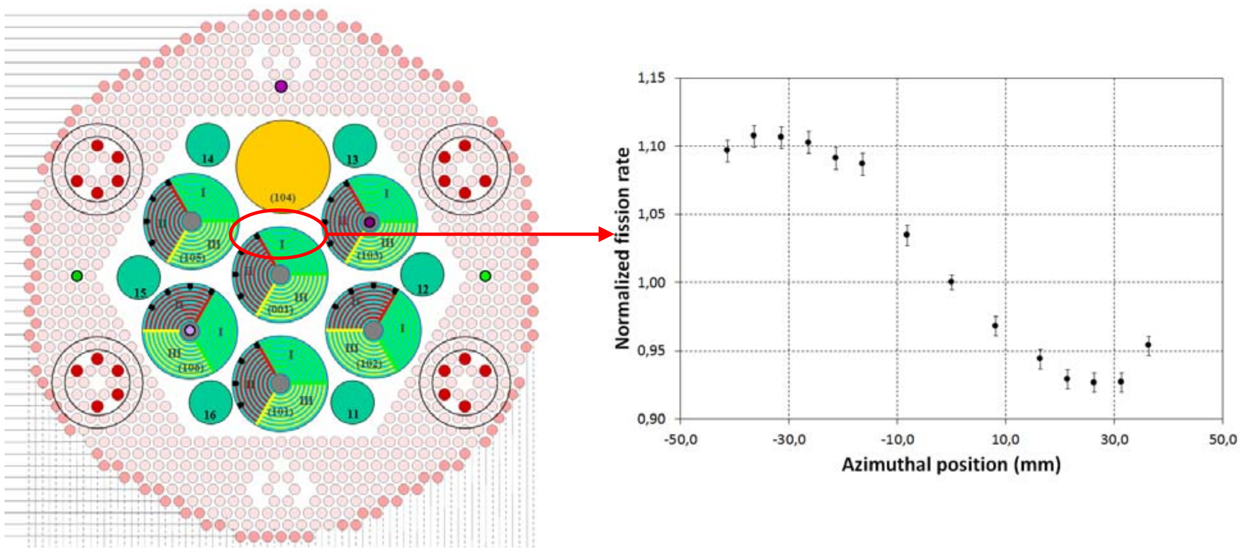

Figure 4*. Azimuthal fission profile on external plate of the central assembly, in the “Beryllium periphery” configuration. Left : configuration – Right : fission rate profile*

Very good repeatability is achieved, for both azimuthal and axial measurements, and overall uncertainties are between 0.7% and 1.5% on each measurement point. Some reproducibility studies were also performed, which consist in measuring the same plate after two separate irradiations, and show good agreement between measurements (discrepancies are within measurement uncertainties).

II.D. Nuclear heating measurements

A very important work has been accomplished on the nuclear heating technique using thermoluminescent detectors. Both calibration and experimental phases have undergone an in-depth re-analysis and improvement. The complete is described in a devoted paper [6]. It enabled to improve by almost a factor 2 the experimental uncertainties versus the previous measurement phase in EOLE and MINERVE during the ADAPh program [7].

A first feedback on the γ-heating in the AMMON/REF shows an underestimation by about -8% $\pm$ 6% (2SD) [8], to be compared with the previous calculation/experiment from the ADAPh program C/E ≈ -25% ± 15% (2σ) [9].

II.E. Management of the technological uncertainties

The management of technological uncertainties represents a very specific feature of the experimental precision. They can be used by model computer codes to assess their impact and transposition to the actual MTR core design and characteristics. A first technological uncertainty calculation has been made on the assembly characteristics [10], and leads to Figure 5 shows some excerpts from the particular metrology phase on the AMMON structures.

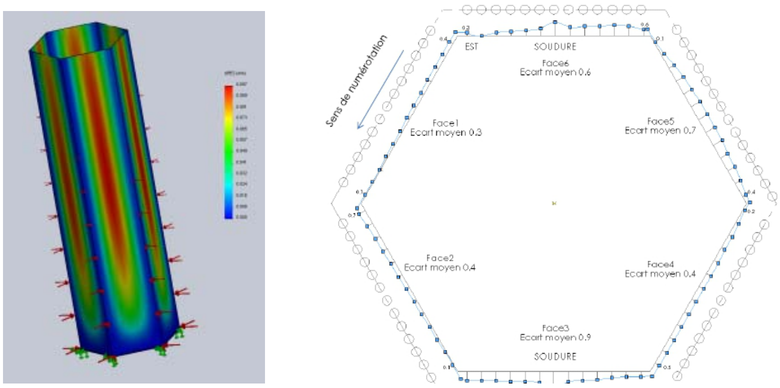

Figure 5. Central chimney deformation due to water pressure (left) - Average shape vs theoretical shape (0.3 to 0.7mm discrepancy) on the central cask (right)

These data can then be injected directly into the TRIPOLI Monte Carlo 3D input geometry in order to perform direct sensitivity and compare it to the theoretical values.

A first feedback of C-E (or C/E) using reference calculation tools (TRIPOLI4 Monte Carlo code) has been performed [11]. The available analysis is resumed in Table 2.

Table 2. First Feedback on JHR core design parameters and uncertainties via AMMON C/E transposition

Integral parameter	Nuclear Data uncertainties (2σ)		
	guaranteed	*best estimate*	**AMMON/REF Feedback**
Reactivity (3D)	±2000 pcm	*±1200 pcm*	**+246 ± 318 pcm**
Temperature Coefficient	-	± 1 pcm/°C	
Integral/differential absorber efficiency	±10%	*±8%*	
Assembly fission rate	±10%	4%	
Plate axial fission rate	±10%	*4%*	
Plate azimuthal fission rate	±10%	*4%*	
In-core ϕ_{fast}/ϕ_{th} ratio	±20%	2.	
Experimental Device reactivity Worth	±10%	4%	
Beta effective		±8%	
Prompt neutron lifetime		±10%	
γ Heating in core and Materials	±30%	*+25 ±15%* (1)	
γ Heating in Hf control rods	±30%	*+25 ±15%* (1)	

The gain in precision on k_{eff} represents several days of full power cycle days.

The completion should be finished by the end of 2014.

III. CONCLUSIONS

The role of EOLE as a research reactor for the improvement of neutron physics computer codes for future industrial applications leads to its identification as a key structure for CEA R&D programs. Those programs are designed and conducted so that the experimental information can be almost directly transposed to the target design.

To ensure an optimized transposition, representativity studies are performed to design the configurations before the experiment. Moreover, experimental techniques and management of the technological characteristics (geometry, material balance…) are consequently improved to reduce the experimental uncertainties.

To illustrate the purpose of experimental core physics programs design for code V&V, the present paper focuses on the AMMON experimental program in support to the validation of HORUS 3D neutron and photon deterministic transport calculation for the future Jules Horowitz MTR in Cadarache. Improvement of almost all experimental techniques and adequate devices – such as γ-scanning benches or exact replicas of JHR fuel assemblies - has enabled to reach incomparable accuracies on the experimental results.

The AMMON experimental phase ended up, after 3 years of intense activity, by the end of March 2013, with the rod follower ejection configuration. This configuration completed this unique experimental database for the HORUS3D validation. The first feedback on the 2010-2012 experimental phase has already enabled to strongly improve the uncertainties on key-parameters. The first analysis of critical states and absorbers worth by ASM technique leads to very good results in terms of precision and reproducibility of the measurements. Critical states are determined within 400pcm that is the order of magnitude of a traditional PWR UO_2 lattice, as the absorber worths are calculated within less than 1%. All power distributions (local or global) are generally calculated within 2 experimental standard deviations (2 to 4%).

Those programs are designed to complement the ongoing validation work of the lattice and core physics tool for LWR applications and in particular for the new MTR and GEN-III+LWR generations. In particular, a new program, called EGERIE (*E*xperimental program on *G*amma h*E*ating and *R*esponse of in-core *I*nstrumentation in *E*ole) is undergoing intense design phase, based on representativity studies. This program, foreseen for 2017 in EOLE, focuses on nuclear data improvement, and on In-Core Instrumentation and gamma heating in fuel and in structures for GEN-III reactors.

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