AMMON: an experimental program in the EOLE critical facility for the validation of the Jules Horowitz Reactor neutron and photon HORUS3D calculation scheme

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Abstract

The HORUS3D is the neutron and gamma calculation scheme used for the design studies of the Jules Horowitz Reactor (JHR), a new irradiation reactor foreseen to be the centerpiece of the European fission research platform in Cadarache, France. The AMMON experimental program, started in 2009 in the EOLE critical facility, is carried out to validate the design parameters such as critical parameters of the core and reactivity effects to give support to the JHR safety report. The experimental zone contains 7 JHR assemblies (U_3Si_2 fuel) enclosed in a hexagonal cask of 30 cm side length surrounded by UO_2 standard PWR fuel pins. All design features of the JHR are studied as different configurations: standards assemblies, Hafnium control rod, voided assembly, Aluminum rod ejection, Beryllium reflector and experimental devices.

The experimental measurements and techniques cover:

- The reactivity changes between the core configurations: the Modified Source Multiplication technique, based on fission chamber counting, is used in addition to the critical size characterization.
- The fine radial and axial power distribution in the fuel plates constituting the fuel assemblies (and the modified conversion ratio) by γ-spectrometry using the peak check technique with a very narrow collimation and by activation foils
- The modified conversion ratio by γ-spectrometry
- The spectral indices using miniature fission chambers and activation foils
- The γ heating in specific materials (Be, Hf) using Thermo-Luminescent Detectors

KEYWORDS: JHR, EOLE, AMMON, Integral experiments.

1. Introduction

The Jules Horowitz Reactor design objectives, based on flexibility and versatility by requiring high in-core fast neutron fluxes and large number of high-flux reflector irradiation positions, are obtained with an unconventional geometry of the core and the utilization of specific materials. The core design of the development phase is based on 34 cylindrical fuel assemblies, composed of 3x8 curved fuel plates held by stiffeners, within an Aluminum matrix. The fuel assemblies are arranged in an irregular pattern and irradiation devices can be loaded in the center of the fuel assemblies or take, in a cluster of three, the place of an assembly in the Al-matrix. As well control rods are inserted in the center of fuel assemblies, the center of “standard” fuel assemblies is loaded with an aluminum rod. A cylindrical pressure vessel and a Beryllium reflector, with more irradiation positions, surround the core.

This irregular geometry requires the development and the validation of a new core calculation scheme [1], based on recent enhancements of the CRONOS2 code's [2] iso-parametric finite elements method.

This scheme takes advantage of a macro-symmetry of the core, by partitioning it in a hexagonal mesh. Each mesh cell, which contains 5 or 7 fuel assemblies in the core region, holds a specific "super finite element" (SFE). These SFEs are composed of a conform mesh of arbitrary triangles, which form the basic finite elements. The fuel assemblies are therewith modeled in form of dodecagons, preserving their rotational symmetry. The use of particular SFEs in the reflector region allows for an accurate modeling of the core's azimuthal heterogeneities and a reduction in the number of mesh cells in the outer, less perturbed regions of the core.

This neutron and gamma calculation scheme, named HORUS3D and used for the design studies of the JHR core, is being developed within the framework of a rigorous verification-validation methodology. HORUS3D is validated against the continuous energy Monte-Carlo code TRIPOLI-4 (reference route), but must be compared with experimental values. In fact, the existing extensive validation database, mainly focused on UOX and MOX fuels, lacks from representativeness with regard to JHR fuel characteristics:

- an ^{235}U enrichment of 27%, compared to 3–5% in standard LWR applications,
- a particularly high moderator / fuel volume ratio (JHR: 4.2, PWR ≈ 1.4),
- very high neutron and gamma fluxes across the fuel plates.

The AMMON experimental program in the EOLE critical facility will provide a global neutronics validation of the HORUS3D calculation scheme. It consists in six different configurations that will constitute a complete database for the validation of the design parameters such as the critical parameters of the core and the reactivity effects for the control rods, as a full validation of the neutron and gamma fluxes (Fig.1) within the assemblies and the experimental devices.

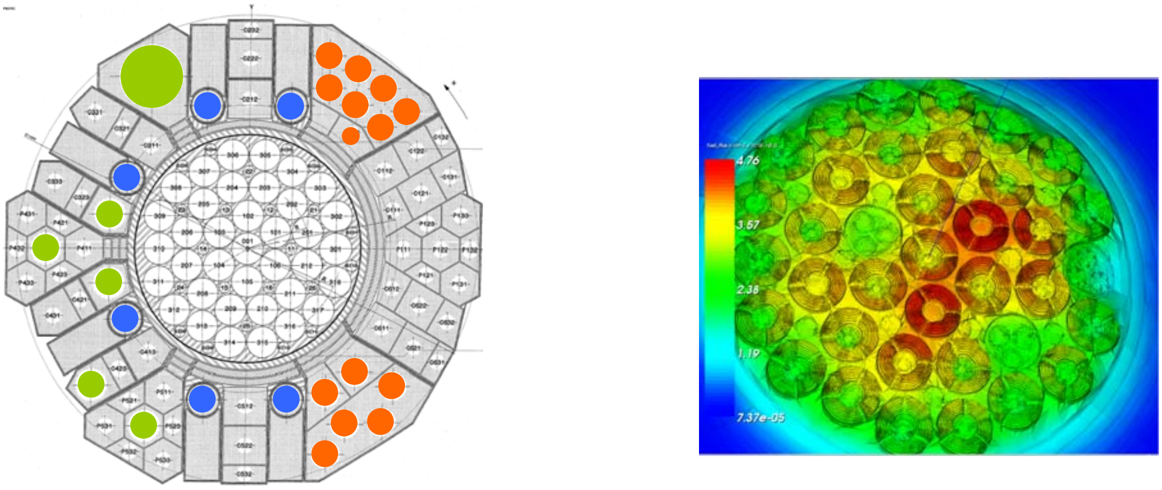

Figure 1: JHR schematic view and thermal flux distribution calculated with HORUS3D

2. The EOLE critical facility

The EOLE reactor is a critical facility operating to a maximum power of 100W dedicated to the neutronic studies of water moderated lattices (PWRs and BWRs). EOLE is an easily flexible facility composed of a concrete structure offering biological shielding for flux levels up to 10^9 $n.cm^{-2}.s^{-1}$ [3].

The facility is being operating since 1965, through major experimental programs in support to the French and Foreign Industrial needs, as well as innovative phases for knowledge improvement of core physics. As examples, one can note:

- the MISTRAL program (1996-2000), which has been undertaken in order to measure the main neutronics parameters of Advanced Light Water Reactors with high moderation 100% MOX fuel cores as a collaboration between NUPEC (Nuclear Power Engineering Corporation - Japan), CEA and their associated industrial partners.
- to complete the MISTRAL program, the BASALA experimental program (2000-2002), performed to measure the main design neutronics parameters of high moderated 100% MOX 9X9 ABWR (Advanced Boiling Water Reactor) cores and to provide accurate experimental results,
- the ADAPh experimental program (2003), being a first step for the validation of the JHR HORUS3D calculation scheme, dedicated to the gamma heating calculations,
- BASALA was extended by the FUBILA experimental program, (2005-2006), a very important step for the licensing of the 100% MOX BWR OHMA Japan core,
- the FLUOLE program (acronym of FLUence in eOLE – 2006-2007) performed in support to the validation of the computer codes used in the neutron analysis of the PWR’s vessel fluence estimation,
- the PERLE experimental Program (French acronym of Experimental Study of Heavy Reflector in EOLE – 2007-2009), following FLUOLE, designed to provide experimental data needed to validate the computer codes used in the neutron analysis of the Gen3 PWR’s core-reflector boundary and heavy reflector estimation.

The important flexibility of the EOLE facility is a key feature of the AMMON program. The innovative characteristics of this program have needed several important modifications of the facility, which are described in this paper. The first modification concerns the new type of fuel used for this program (JHR assemblies with U_3Si_2 fuel curved plates).

During the operation of the Jules Horowitz Reactor, it is planned to use EOLE as the critical facility of this reactor, for example in support to the qualification of new core configurations.

3. Basis of the design – The AMMON experimental configurations

The design of the experimental program is based on an experimental central zone containing 7 JHR assemblies (U_3Si_2 fuel) enclosed in a hexagonal Aluminum cask of 30 cm side length, surrounded by an outer driver zone made of standard UO_2 (^{235}U 3.7%) fuel pins (Fig.2). The lattice pitch of UO_2 pins is calculated to reproduce the same neutron spectrum as the experimental central zone and contains the pilot and safety rods used for operating the reactor.

Each zone has an independent, temperature regulated water circuit, in order to measure independently the temperature coefficient of each experimental zone. The driver zone can contain boron to adjust criticality but the experimental central zone is filled only with pure water as in JHR. The modification of the EOLE reactor to receive a second independent temperature regulated water circuit for the experimental zone is an important new feature of the facility.

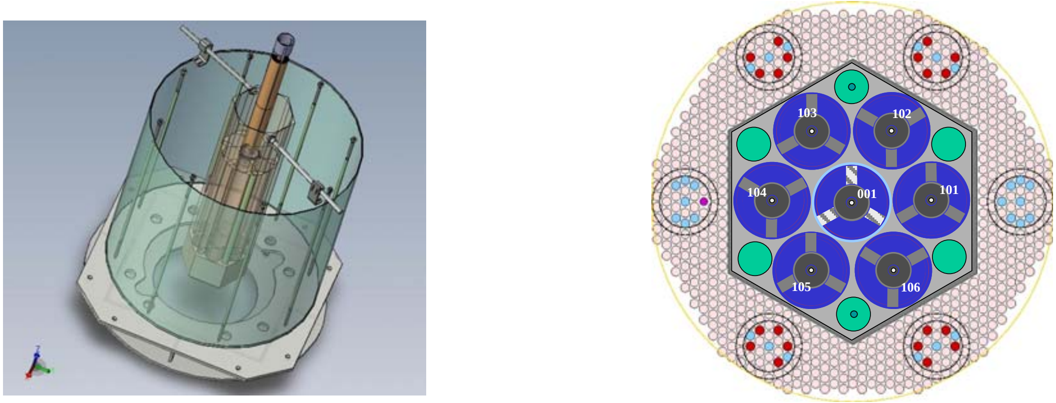

Figure 2: Schematic views of the AMMON experimental core

The criticality is ensured by adjusting the driver zone content: boron concentration adjustment and/or UO_2 pins addition/withdrawal, according to the following experimental configurations:

- AMMON-Ref: reference configuration, containing 7 JHR assemblies in the central zone, for the validation of all the basic design parameters,
- AMMON-Hf: “control rod configuration”, containing a full length (or half length) Hafnium control rod in the inner part of one JHR assembly,
- AMMON-Rod: configuration with the central aluminium rod ejected (safety case),
- AMMON-Void: configuration with the voiding of the central JHR assembly water,
- AMMON-WH: configuration with a water hole in place of the central JHR assembly (withdrawal of a fuel element),
- AMMON-Be: configuration with a beryllium block inserted in place of a JHR assembly, to study the neutronics impacts of the beryllium reflector on the fuel assemblies,
- AMMON-GC: configuration with a group of experimental devices in place of a fuel assembly.

4. The experimental measurements and techniques

The experimental measurements concern integral and local parameters to fully characterize the different configurations. These measurements and techniques used during the AMMON experimental program cover:

4.1. The reactivity change between the core configurations

The Modified Source Multiplication (MSM) method (improvement of the Amplified Source Multiplication (ASM) method) have been widely used in the CEA’s EOLE and MASURCA critical facilities over the past decades for the determination of reactivity worths by using miniature fission chambers and larger detectors in subcritical configurations [4]. These methods are based on the assumption that, in any fissioning system, detector count rates are linked to subcritical levels, and, consequently, count rate variations are linked to the reactivity variation between two configurations. They have been successfully applied to single or clusters absorber worth measurement in both thermal and fast spectra, or for sodium or water void reactivity worths. These techniques give *relative* reactivity variations since they are based on the use of a calibration reactivity sample, which is a pilot rod worth, measured in critical condition by the rod drop technique.

In addition to the critical parameters characterization of the configurations, the MSM method will be used during the AMMON program for measuring the subcritical levels of the Hf control rod insertion, for example. The important subcritical level (~4$) will require the use of fission chambers with significant fissile contents and irradiation times of several hours for obtaining sufficient counting rates. Miniature fission chambers with ^{235}U masses larger than 1 mg will be put in the core for these measurements.

4.2. The fine radial and axial power distribution in the fuel plates and the modified conversion ratio

The measurement of the power distribution in the fuel plates of the JHR assemblies is a key safety parameter for the validation of the HORUS3D calculation of the peak power.

The fine radial and axial power distribution in the fuel plates will be measured by using γ-spectrometry with the peak check technique [5]. Particular photopeak measurements (called here peak check) on selected fission products are used routinely in the EOLE facility, in particular as a "scaler" to renormalize fission map distributions measured by using the so-called integral gamma scanning technique.

During the AMMON program, this technique will be used in particular for comparing the measurements performed on the JHR assemblies and on the UO_2 pins of the driver zone, or to normalize the fission map over the different fuel plates of a JHR assembly (one of the 7 assemblies can be entirely taken apart to perform individual plate measurements). The experimental counting room of the EOLE facility was largely modified and very narrow collimations of the γ-spectrometry devices were adapted to the geometries of the JHR plates.

Irradiation of thin activation detectors (Au1%-Al) located between the plates of the dismountable JHR assembly will support the γ-spectrometry measurements. After the irradiation, these foils will be measured on the experimental devices of the MADERE dosimetry plateform of the CEA Cadarache Experimental Physics Section [6 and this conference].

The power distribution in the fuel plates will be measured in the nominal case, but also with different perturbations:

- the rotation of a neighboring JHR assembly (impact of the position of the stiffeners),
- the insertion of the Hafnium control rod in the center of the measured assembly,
- the insertion of the Beryllium block closed to the measured assembly,
- the voiding of the measured JHR assembly,
- the insertion of a water hole closed to the measured assembly.

4.3. The modified conversion ratio

The measurement of the modified conversion ratio, defined as the ratio of the number of ^{238}U captures on the total number of fissions, is based on the same peak check technique. This technique has been developed and improved, based on past studies related to this modified conversion ratio. The measurement consists of γ-ray spectrometry applied directly on the irradiated fuel plates, in order to determine the capture and fission rates with their specific activities. The feasibility of the experiment depends on the radioactive periods, γ-ray emission probabilities and fission yields of the reaction products [7].

4.4. The spectral indices

The spectral indices are important parameters to validate the energetic distribution of the neutrons in the core. They are measured by using miniature fission chambers (4 mm diameter) with various fissile contents (^{235}U, ^{238}U, ^{237}Np, ^{239}Pu) which have different threshold energies.

For the AMMON program, these fission chambers will be placed successively or simultaneously:

- in the center of the JHR assemblies (hollowed aluminum rod),
- in place of UO_2 fuel pins in the driver zone (in particular close to the interface with the experimental zone),
- and in specific devices (center of the Hafnium control rod and the Beryllium block).

As for the power distributions, these measurements will be performed in addition to the irradiation of activation detectors.

4.5. The γ heating measurements

The gamma heating in a reactor core mainly comes from fissions, captures and inelastic scatterings. In the AMMON program, the evaluation of the heating of different components, in particular the Hafnium control rod and the Beryllium block, is an important feature. So, a set of experimental heating measurements using Thermoluminescent Detectors (TLD) will be carried out during this program.

TLD providing relative measurements, a calibration stage is required to determine the absolute dose. Based on the ADAPh experimental program, performed in the EOLE facility in 2003, an important effort was already undertaken to quantify the various sources of uncertainties and will be pursued during the AMMON program [8] [9]: the representativeness of the calibration conditions, the cavity and photon spectrum corrections, the background noise generated by thermal, epithermal and fast neutrons, the weight of the TLDs, the choice of the heating ramp-up speed, the control over TLD positions, the control over the irradiation power, the TLD material chosen, and the concentration of the TLD doping agent, etc.

As an example, for the representativeness aspects, specific pill boxes in Hafnium and Beryllium/Aluminum alloy were designed for the TLD irradiations in the Hafnium control rod and the Beryllium block.

4.6. The temperature coefficient measurements

The measurement of the temperature coefficient of the experimental central zone, i.e. the reactivity change due to a variation of the water temperature in the JHR experimental zone, is another important aspect for the validation of the safety calculation scheme.

Two complementary approaches are typically used to determine this temperature coefficient [10]:

- Doubling time measurement: the reactivity is deduced from doubling time measurement when the pilot rod is on top position. When the reactivity decrease cannot be balanced by the pilot rod withdrawal, the boron concentration or the critical size is adjusted to recover reactivity margin,
- the subcritical approach, by using the so-called MSM methodology, where one follows the count rate behavior of fission chambers versus temperature increase.

The water temperature is maintained constant in the core during each step by using the thermoregulation station of the EOLE facility. It heats or cools the moderator on demand, with precision of less than 0.1°C. Moreover, several temperature probes are inserted in various axial and radial places in the core to ensure the temperature homogeneity all over the tank. For the AMMON program, the measurements will be performed for the experimental central zone, by using the second temperature regulation water circuit specifically built in the EOLE facility.

All these experiments must, at least confirm, at last improve, the basic design biases on local and global core characteristics, whose values are reproduced in Table 1.

	Neutron data	**Uncertainty target (2 σ)**
Performance of experimental devices	Reactivity worth	±10%
	Nuclear heating	±15%
	Fast flux	±10%
Control	Reactivity	< ±0.025 $
	Fast flux in core	±10%
	Thermal flux in core	±10%
	Power peak	±5%
	Isothermal temperature coefficient	±5%
Safety	Control rod worth	±5%
	Nuclear heating in hafnium	±15%

Table 1: Target measurements uncertainties for the AMMON program

5. Conclusions

The AMMON experimental program is carried out in the EOLE critical facility to provide experimental results for the validation of the Jules Horowitz Reactor HORUS3D neutronics and photonics calculation scheme. The design of the program is based on a core composed of an experimental central zone with 7 JHR assemblies and an outer driven zone made of standard UO_2 PWR pins.

Several configurations representative of the JHR core in normal operation or accidental situations will be characterized: successive insertion of a Hafnium control rod, a Beryllium block, an experimental device, a water hole and finally the voiding of a JHR assembly.

The flexibility of the EOLE critical facility has allowed the design of this very innovative experimental program: use of new type of fuel (JHR assemblies with U_3Si_2 fuel curved plates), modifications of the experimental counting room for measuring curved plates by γ

spectrometry, modification of the facility to receive a second independent temperature regulation water circuit.
A large number of measurements, using different experimental techniques, will be carried out in order to characterize global and local physical parameters: reactivity worths, fine power distributions, spectral indices, gamma heating and temperature coefficient.

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