CARMEN: an experimental configuration in the MINERVE critical facility for the qualification of neutron cross sections in epithermal spectrum

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Abstract

The OSMOSE and OCEAN experimental programs, currently on-going in the MINERVE facility, aim at improving the knowledge on nuclear basic data for both major and minor actinides as well as for different neutron absorbers. Measurements are performed by using the oscillation technique, which consists in measuring the reactivity effect due to the periodic insertion and extraction of samples containing the nuclide of interest in a well characterized neutron spectrum.
The different neutronic spectra cover a range from over-moderated thermal spectrum, PWR UOx standard spectrum, PWR 100% MOX spectrum, corresponding respectively to the R2-UO2-2, R1-UO2 and R1-MOX experimental lattices. In order to extend the energy range to under-moderated spectrum and to improve the energy domain decomposition of the C/E values, a new experimental configuration has been designed in view of its set-up at the MINERVE core: the CARMEN (Core with An epitheRMal nEutron moderatioN) lattice. This paper provides the main characteristics of this future configuration and details the associated experimental measurements.

Introduction

By the past, extensive studies were made by CEA to gain experimental data relevant to under-moderated reactors. A set of three complementary experiments were carried out in order to:

- ✓ Qualify neutronic parameters of an under-moderated core at the beginning of cycle (k_{eff}, conversion ratio, absorbers efficiency…) with the ERASME program performed in the EOLE facility. Three different lattices with moderation ratio V_m/V_u = 0.5, 0.9, 2.1 (hot conditions) were investigated [1], [2].
- ✓ Determine the capture rates of separated isotopes of some heavy nuclides and fission products, with ICARE irradiations in the MELUSINE facility [3], [4]
- ✓ Measure the global capture of fission products with reactivity oscillation of spent fuels in the MINERVE facility: the MORGANE program [5].

In order to cover the whole integral data involved in the under-moderated concepts, complementary results were foreseen for separated isotopes of some heavy nuclides and new neutron absorbers on the end of the nineties, in the framework of the ambitious OSMOSE and OCEAN programs. Unfortunately, the MORGANE configuration was not so far available because of safety considerations. Indeed, a new configuration has been designed in the center of the MINERVE core: the CARMEN (Core with An epitheRMal nEutron moderatioN) lattice.

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1. The MINERVE facility

MINERVE is mainly devoted to neutronics studies, in view to improve the knowledge of integral absorption cross sections by using the reactivity-Oscillator Method [6].
MINERVE is a pool type reactor operating at a maximum power of 100 watts. The core consists of a rectangular stainless steel tank containing about 100 m^3 of water. The cooling is performed by natural convection. The core includes a driver zone, composed by standard Materials Testing Reactor (MTR) fuel elements, coupled with different experiments located in a central square cavity with a size of about 70 cm by 70 cm [7].
About 40 fuel elements form the driver zone which is surrounded by a graphite reflector. Hafnium absorber plates are used for the reactivity control.
Picture of the reactor is shown in Fig. 1.

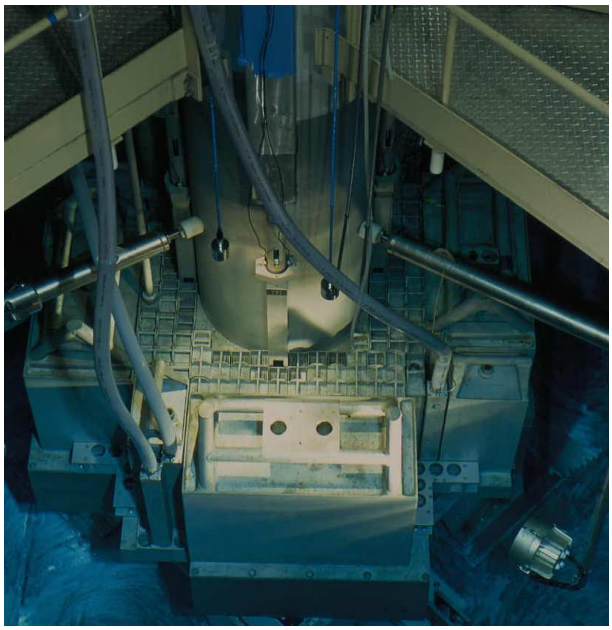

Fig. 1: Top view of the MINERVE reactor

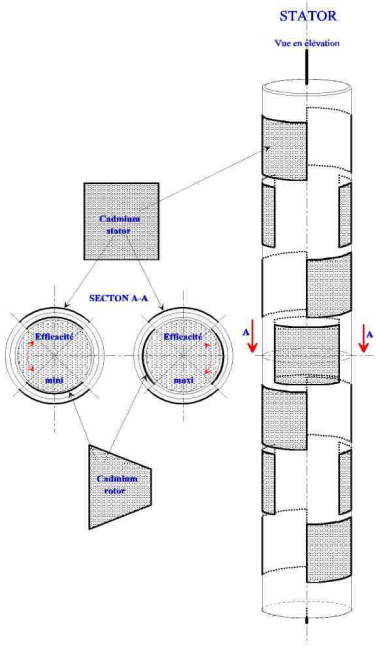

Fig. 2: Scheme of the automatic pilot rod

The coupled lattices in the central cavity are built so that they can reproduce the neutronics spectra of various reactors, from over-moderated thermal spectrum, PWR UOx standard spectrum, PWR 100% MOX spectrum. The oscillating of sample in these different lattices allows contributing to a better decomposition by energy domains for the qualification of the nuclear data involved in the calculations of reactors.

2. The oscillation technique [8]

The technique consists in moving periodically samples, that contain the isotope to be characterized, in the centre of the experimental lattice, in order to measure their reactivity worth with an accuracy around 1% (at 1σ). In a practical way, each sample is located into an oscillation cane between aluminum spacers. This device is then vertically shifted in a repetitive manner between two extreme positions located inside and outside the experimental core zone.

Each sample is introduced into an oscillation cane between aluminum spacers. Each measurement typically corresponds to 5 cycles of 120 s. Each sample is measured at least 5 times in order to improve the reproducibility of the experiment and to decrease significantly statistical errors on sample loading.

The reactivity changes due to the oscillation of the samples (in the range ± 15 pcm) are compensated by a rotary automatic pilot rod. This servo-control system rotates cadmium sections in overlapping patterns, to cause a change in the neutron absorption of the pilot rod as a function of the angle of the rotor (Fig. 2). The recorded experimental signal is the angle of rotation of the pilot rod rotor, that is, in a certain way, proportional to the reactivity worth of the studied sample.
The signal of the pilot rod can be calibrated using two series of reference samples. The first one contains elements made of a UO2 matrix with different uranium enrichments (0.25%, 0.5%, 0.72%, 1%, 2%, 3%, 4% and 4.95% in U-235). The second one is made of boron samples that will be replaced by a new set currently under manufacturing. This new set will include high purity (99.95 %) golden stalks at various diameters in air matrix. All these isotopes have very well characterized cross sections in thermal and epithermal domain of energy. They should allow an important reduction of the uncertainties in the calibration process.

3. The OSMOSE and OCEAN programs

The OSMOSE [9] and OCEAN [10] programs are being performed in the MINERVE facility, in the framework of the European JEFF3 project, with the contribution of AREVA and EDF industrials.

The need for improved nuclear data for actinides (OSMOSE program: OScillation in Minerve of isOtopes in “Eupraxic” Spectra) has been stressed by different organizations throughout the world – especially for the studies linked to plutonium management, waste incineration, transmutation of waste, and Pu burning in future nuclear concepts. Several international programs have indicated a strong desire to obtain accurate integral reaction rate values for improving the major and minor actinides cross sections. Data on U-235, U-236, U-238, Pu-239, Pu-240, Pu-241, Pu-242 and Am-241 are reasonably well-known and available in the Evaluated Nuclear Data Files (JEFF, JENDL, and ENDF-B) but still need to be improved. On the other hand, information on the minor actinides (i.e. Th-232, U-233, Np-237, Pu-238, Am-243, Cm-244 and Cm-245) are less well-known and considered to be relatively poor in some cases, having to rely on model and extrapolation of few data points.

OCEAN (Oscillation in Core of SamplEs of Neutron Absorbers) is an ambitious experimental program. It aims at improving the knowledge on nuclear basic data for the following neutron absorbers: Gd-155, Gd-157, Gd-Nat, Hf-177, Hf-178, Hf-179, Hf-180, Er-166, Er-167, Er-168, Er-170, Dy-160, Dy-161, Dy-162, Dy-163, Dy-164, Eu-151, Eu-nat, and Eu-153. It deals at the same time with the improvement of the calculation tools and with the feasibility studies on new options for fuel cycle. It particularly concerns, for the LWR reactors, the research on the increase of the fuel cycle length in nuclear power plants, the plutonium management issue, and the performances of calculation tools with new neutron absorbers.
In the OSMOSE and OCEAN programs, the reactivity worth of samples containing separated actinides and separated absorbers are measured in different neutron spectra using an oscillation technique with an overall expected accuracy better than 3%.

Since 2006, the OSMOSE and OCEAN programs were already carried out in the R1-UO2 and R1-MOX configurations, representative respectively of PWR UOx standard spectrum and PWR 100% MOX spectrum. In 2011, experiments will be performed in the R2-UO2-2 lattice, which consists in a thermalized configuration (Fig. 3). The following experiments will provide results in an epithermal HCLWR[4] type spectrum, thanks to the CARMEN lattice. This paper will detail the design studies of this new configuration, expected to take place after the R2-UO2-2 experiments.

[4] High Conversion Light Water Reactor

4. Estimation of experimental signals

The experimental signals of identical samples generally observed in the R1-MOX configuration are lower than in the R1-UO_2 configuration. It leads to a slight increase of the experimental relative uncertainties. In order to optimize these uncertainties for the CARMEN lattice, the experimental signals should be as high as possible. Hence, it is of great interest to estimate these signals, by using all the information already available from the R1-UO2 configuration. This estimation can be obtained with the methodology detailed below.

As presented in the previous paragraph, the experimental signal obtained with the reactivity oscillator is proportional to the reactivity effect of the oscillated sample. The reactivity effect of the sample can be expressed as the opposite of the reactivity effect introduced by the displacement of the cadmium control rod:

$$\Delta\rho = -\frac{\int_E \int_{V_{Cd}} \Delta N_{Cd}\sigma_{Cd}(E)\Phi(E,\vec{r})\Phi^*(E,\vec{r})dEd\vec{r}}{I_f} \qquad \text{Eq. 1}$$

Given the cadmium is a thermal absorber, the former equation can be rewritten:

$$\Delta\rho = -\frac{\Delta N_{Cd}\sigma_{Cd}^{th}\Phi_{th}\Phi_{th}^*}{I_f} \qquad \text{Eq. 2}$$

The experimental signal is directly linked to the overlapping of the control rod cadmium sectors:

$$\Delta N_{Cd} = c\Delta S \qquad \text{Eq. 3}$$

This proportionality is conserved for each configuration of the reactor because it depends only of the servocontrol system. Comparing the signal expected in the CARMEN configuration to those, well known, in the R1-UO_2 lattice with these 3 equations leads to the following one:

$$\frac{\Delta S_{CARMEN}}{\Delta S_{R1-UO2}} = \frac{\Delta\rho_{CARMEN}}{\Delta\rho_{R1-UO2}} \frac{\left(\Phi_{th}\Phi_{th}^*\right)_{R1-UO2}}{\left(\Phi_{th}\Phi_{th}^*\right)_{CARMEN}} \qquad \text{Eq. 4}$$

The product of the flux by the adjoint flux corresponds to the differential efficiency of the pilot rod. Assuming that the variation of this product from one configuration to another is only spatial, Eq. 4 can be approximated:

$$\frac{\Delta S_{CARMEN}}{\Delta S_{R1-UO2}} \cong \frac{\Delta\rho_{CARMEN}}{\Delta\rho_{R1-UO2}} \frac{\left(\Phi_{th}^2\right)_{R1-UO2}}{\left(\Phi_{th}^2\right)_{CARMEN}} \qquad \text{Eq. 5}$$

Reactivity effect and thermal neutron flux on the pilot rod are assessed with Monte Carlo calculations. In order to achieve reasonable statistical uncertainties, the reactivity effect of a boron pin compared to the void is determined, leading to an uncertainty of less than 8%. The thermal flux on the pilot rod is obtained with accuracy lower than 0.3 %. Since the reactivity effects of OSMOSE and OCEAN samples are very small (sometimes lower than 1 pcm), their straightforward calculation with Monte Carlo code is not achievable. For this reason a boron pin is used as a surrogate method. The reactivity effect of the same boron pin is assessed with a deterministic code, based on APOLLO2.8 [11], involved for the interpretation of MINERVE experiments. Experimental signals are related to the reactivity effect estimated with the deterministic route though the calibration process:

$$\Delta S = \alpha^{calib}\Delta\rho^{APOLLO2} \qquad \text{Eq. 6}$$

where α^{calib} is obtained with the set of calibration samples containing well-know isotopes.

Assuming proportional reactivity effects of the boron pin for both the Monte Carlo and the deterministic calculation, Eq. 5 is rewritten:

$$\alpha_{CARMEN}^{calib} = \frac{\Delta\rho_{CARMEN}}{\Delta\rho_{R1-UO2}} \frac{\left(\Phi_{th}^{2}\right)_{R1-UO2}}{\left(\Phi_{th}^{2}\right)_{CARMEN}} \frac{\Delta\rho_{R1-UO2}^{APOLLO2}}{\Delta\rho_{CARMEN}^{APOLLO2}} \alpha_{R1-UO2}^{calib} \qquad \text{Eq. 7}$$

From Eq. 6 and 7, the experimental signals expected for CARMEN are directly linked to those obtained in the R1-UO_2 configuration. The estimated signal in the CARMEN configuration corresponds to the oscillation of two UO_2 calibration samples, with respective enrichment of 0.25 % and 4.95 % in U-235, already oscillated in the R1-UO_2 lattice.
This method has been applied to determine the signal for the R1-MOX lattice, which was already known by previous measurements. We observed a good agreement between the estimated value and the measured value.

5. Main characteristics of the CARMEN configuration

The main purpose of the CARMEN lattice is to offer an epithermal spectrum with a moderation ratio V_m/V_u = 0.9. One of the first design constraints is to keep approximately the same number of fuel pins as for the R1-UO_2 and the R1-MOX lattices, considering:

- ✓ A high content in plutonium is required to be representative of under-moderated concepts,
- ✓ 7% Plutonium pins are available in the facility,
- ✓ The fission importance in the experimental zone does not exceed 50 % compared to the driver zone (safety criteria).

Besides, oscillation of samples will be performed in a dry environment, to decrease as much as possible the sensitivity of the amount of water inside the oscillation cane. Hence, a specific device has been developed around the oscillation cane. This device may reduce significantly the uncertainties of the measurements, which are mainly linked to the reproducibility of the location of the samples inside the oscillation device.
Getting free space enough for this “dryer” device and conserving an adequate moderation ratio leads straightforward to an hexagonal pitch (Fig. 4). Each fuel pin will be included in an adapted overclad. This overclad allows to fit to every pins a plug adapted to the under water prehension. Radius of the overclad and length of the pitch are constraint on the one hand by the space required by the “dryer” device and on the other hand by the size of the MINERVE experimental zone. A lattice of 12.8 mm, associated with an overclad of external diameter of 11 mm is chosen, while an external diameter of the “dryer” device was fixed to 14 mm.

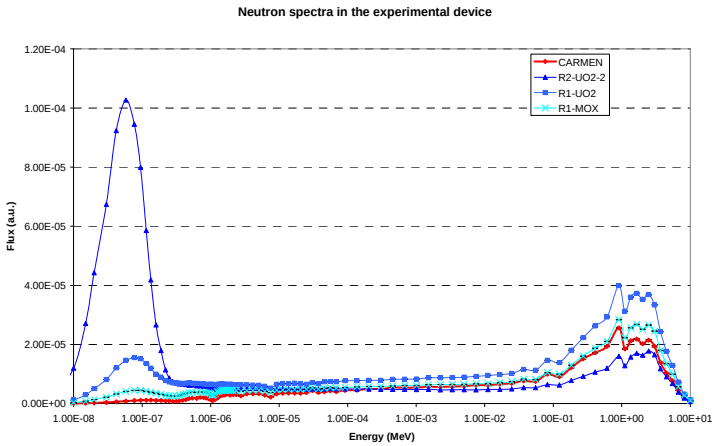

Fig. 3: Neutron distribution calculated with the different lattices in the centre of the experimental zone

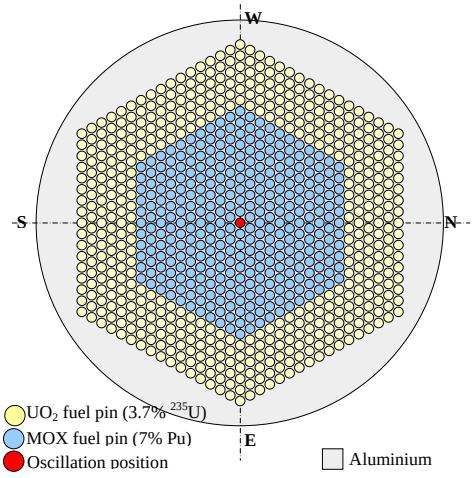

Fig. 4: Schematic view of the CARMEN experimental zone

From the Eq. 5, we can see that an increasing of the experimental signal magnitude can be obtained by increasing the reactivity effect of the sample in the core and decreasing the thermal neutron flux on the pilot rod. In other words, it corresponds to amplify the neutron importance of the experimental zone, compared to the driver zone. Hence, neutronic studies have been carried out for three different kinds of experimental lattices:

- ✓ The first one is composed of an homogeneous lattice of 816 MOX 7% fuel pins
- ✓ The second one includes an heterogeneous lattice of 330 MOX 7% fuel pins, surrounded by a buffer zone of 486 UO_2 fuel pins with an 3.7 % enrichment in U-235 (Figure 4).
- ✓ The third one is almost similar to the second one, except than the UO_2 fuel pins overcladding are reduced until 10.2 mm, and drilled to let water going inside.

The substitution of the MOX fuel pins (lattice 1 to lattice 2) and the increase of the moderation ratio of the UO_2 fuel pins (lattice 2 to lattice 3) lead to a greater core reactivity, which has to be compensated by decreasing the number of the driver zone fuel plates. The following table presents the variation of the expected signal with the different configurations of the experimental zone (the uncertainties are given for 1σ).

Lattice number	Reactivity effect $\Delta\rho_{CARMEN}$	Ratio of the square of the thermal flux: $\frac{\left(\Phi_{th}^2\right)_{R1-UO2}}{\left(\Phi_{th}^2\right)_{CARMEN}}$	Calibration factor α_{CARMEN}^{calib}	ΔS_{CARMEN} (pilot unit)
1	- 133 ± 10	1.766 ± 0.01	835 ± 89	114 178 ± 12 170
2	- 168 ± 10	1.779 ± 0.01	1063 ± 90	145 355 ± 12 307
3	- 203 ± 10	2.043 ± 0.01	1475 ± 103	201 692 ± 14 084

For the homogeneous lattice, the experimental signal obtained is roughly equal to those of R1-MOX which were equal to 119 572 pilot unit. Two factors are involved:

- ✓ The reactivity effect increase of the fuel sample
- ✓ The decrease of the thermal neutron flux on the pilot rod, due to the diminution of the number of the fuel plates of the driver zone

An increase of more than 70 % of the signal may be achieved in the third lattice. However, it should be insure that the neutron spectrum in the centre of the core is not affected by the UO_2 buffer zone. The comparison of the 3 conversion factors (Uranium-238 capture divided by total fission of the MOX fuel pin) in the centre of the zone with the different lattices is presented in the figures 5 and 6.

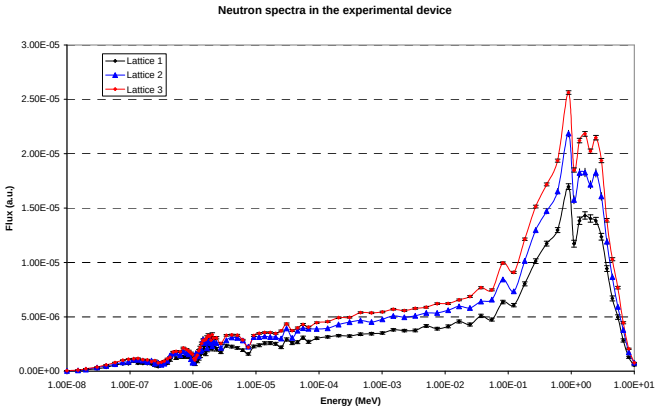

Fig. 5: Neutron distribution calculated with the different lattices in the centre of the experimental zone

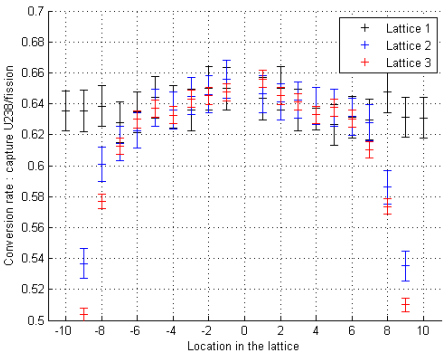

Fig.6: Conversion rate for the three lattices

We can observe only slightly differences between the three lattices on these two parameters. For the neutron spectra, a small increase of the flux level is obtained with the substitution of the MOX fuel pins and the over-moderating of the buffer zone, due to the increase of the fission importance of the experimental zone, compared to the driver zone. However, the shapes of the three spectra are still conserved. The conversion ratio around the oscillation device remains the same on the first six fuel pins.

Indeed, the third lattice will provide better results in terms of experimental signal, with the expected conditions for an epithermal neutron spectrum.

As complementary studies, an optimization could concern the research of the best positions as possible inside the driver zone for the ionization chamber connected to the automatic pilot rod, which is one of the major components of the acquisition system.

6. Mechanical design

The versatility of the CARMEN lattice is obtained by the use of dedicated grids located in an aluminium cask (Fig. 7). The fuel pins can be introduced in the core, under a water thickness of 2 meters, thanks to a first thick grid, which will drive the pins into the inferior grid. A dedicated device has been designed for extracting the samples out of the oscillation cane, from the top of the pool, until 10 times a day.
A suitable biological protection will be designed on the top of the lattice, in order to compensate the decrease of the water level inside the chimney (Fig. 8).

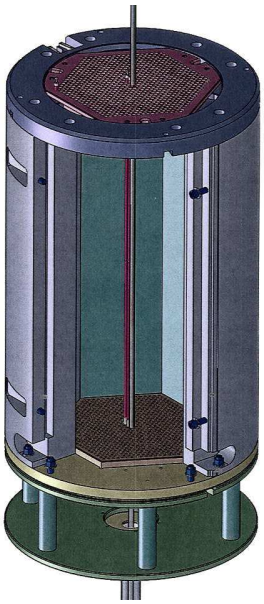

Fig. 7: Zoom on the lattice of fuel pins

Fig.8: Mechanical design of the CARMEN configuration

7. Experimental techniques

7.1 Measures currently used

The main experimental technique concerns the reactivity oscillator method used to determine the reactivity effects of the samples, thanks to a calibrated rotary automatic pilot using cadmium sectors. Besides, different kinds of measurements and techniques will be applied for the neutronic characterization of the lattice:

- ✓ The fine radial and axial power distribution of the core in the pins by γ-spectrometry
- ✓ The spectral indices using U-235, Pu-241, Pu-239 and Np-237 miniature fissions chambers, located in the central oscillation channel at the fuel mid-plane. The measured spectral indices are:

$$\frac{\text{Pu}-239}{\text{U}-235}, \frac{\text{Pu}-241}{\text{Pu}-239}, \frac{\text{Np}-237}{\text{Pu}-239}$$

  As the fission of Np-237 is a threshold reaction (~1 MeV), the last spectral index is an indicator of the "hardness" of the neutron spectrum.
- ✓ The modified conversion ratio, based on the measurement of particular peak activities by γ-spectrometry. The modified conversion ratio, noted C8/Ftot, is the ratio of neutron capture in U-238 compared to the total fission rate. It thus gives information on the neutron spectrum. The principle of the γ-ray spectroscopy measurements is to determine the reaction rate of a nuclide by measuring the activity of its capture product. The determination of the total fission rate is based on the measurement of the integral photopeak of a high-yield fission product relative to the total fission rate inside the fuel pin. The specific fission product gamma ray line is the 293.27 keV line from Ce-143. The 277.60 keV gamma ray line from Np-239 is used to measure the U-238 capture rate because it is related to the number of U-238 captures through subsequent beta decays:

$$^{238}U + n \longrightarrow {}^{239}U \xrightarrow{\beta^-\ 23.5\ \text{min}} {}^{239}Np \xrightarrow{\beta^-\ 2.355\ \textit{days}} {}^{239}Pu$$

  This technique has been generalized to spectral indices CX(n,γ)/Ftot, defined as the ratio of the (n,γ) capture rate on “X” to the total fission rate. The measurement consists of γ-ray spectrometry applied directly on irradiated fuel samples, in order to determine the capture and fission rates with their specific activities. The adapted isotopes for this technique are: Th-232, Np-237, Pu-242, Dy-164, Er-170, Hf-180, Eu-151 and Eu-153. More details about the experimental technique can be found in references [12], [13].

7.2 Perspectives

Moreover, very successful techniques for the measurements of integral cross sections (2200 m/s cross sections and effective resonance integrals) of a wide range of absorbing materials have been developed by the past. The most widely used approach has been the two-spectrum method in which reactivity measurements on the studied sample are performed both in a well-thermalized spectrum, and in a spectrum containing an appreciable epithermal component. From the first measurement, the thermal cross section is obtained directly; if the epithermal component of the second spectrum is known, the resonance integral can be deduced from the difference between the two results [6].
Since the next configuration of MINERVE will be a well-thermalized one (R2-UO2-2 configuration), the combination of experimental results on the two lattices may be of great interest for the determination of effective resonance integrals of some of OSMOSE and OCEAN samples.

Besides, this new CARMEN lattice should be easily adapted for measurements under cadmium shield, with a high level of epithermal flux (Fig. 9). The versatility can be achieved by replacing the MOX fuel pins by graphite or beryllium cylinders, inside the UO_2 fuel pins buffer zone (Fig. 10). The center of these former cylinders can be drilled, to add a cadmium filter of 1 mm thickness on the specific device designed to performed oscillation in a dry environment. With the use of beryllium cylinder, the 1/E variation of the epithermal flux can be observed on the whole range 1 eV– 100 keV. Such a configuration might allow a more detailed decomposition by energy domain of the C/E values.

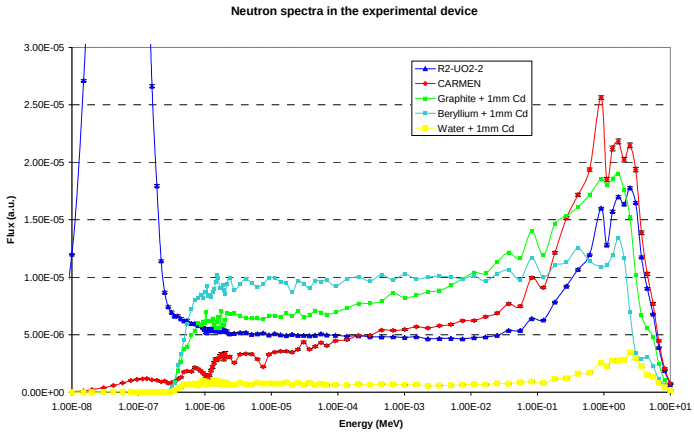

Fig. 9: Neutron distribution calculated with the different lattices in the centre of the experimental zone

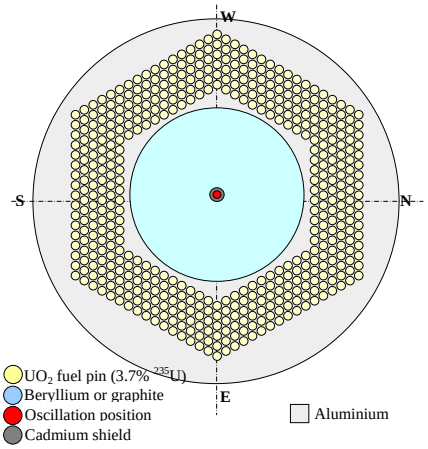

Fig.10: Cross section of a cadmium shielded experimental zone

Conclusion and perspectives

The neutronic conception of the CARMEN lattice has been achieved and the mechanical building is in progress. This new configuration for the MINERVE facility will bring appropriate results for the qualification of the nuclear data involved in the calculations of under-moderated reactors. The OSMOSE and OCEAN programs in this new lattice are foreseen to be performed in 2011-2012. The various improvements of the nuclear data will be used as feedback for the JEFF3 library.
Moreover, the design of the CARMEN lattice is versatile enough to consider future evolutions, like for example a neutron spectrum without thermal component thanks to a cadmium shield.

Acknowledgments

The authors of this paper thank all the participants to the experimental programs as well as the industrial partners.

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