

## **OSMOSE: An Experimental Program for the Qualification of Integral Cross Sections of Actinides**

Jean-Pascal HUDELLOT<sup>1</sup>, Raymond KLANN<sup>2</sup>, Philippe FOUGERAS<sup>1</sup>, Frederic JORION<sup>3</sup>, Nicolas DRIN<sup>3</sup>, Louis DONNET<sup>3</sup>

<sup>1</sup> CEA Cadarache, DEN/DER, 13108 Saint Paul lez Durance, France

<sup>2</sup> Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439, USA

<sup>3</sup> CEA VALRHÔ, DEN/DRCP, BP171, 30207 Bagnols-sur-Cèze Cedex, France

The design of nuclear systems has shifted over the years from a “test and build” approach to a much more analytical methodology based on the many advances in computational techniques and nuclear data. To a large extent current reactors can be calculated almost as well as they can be measured. This is due in particular to the high quality nuclear data available for the few major isotopes which dominate the neutronics of these systems. Nevertheless, most future nuclear systems concepts and advanced fuels development programs use significant quantities of minor actinides to address modern day issues such as proliferation resistance and low cost. For example, high burnup fuels contain large quantities of americium and curium. Systems designed for plutonium and minor actinide burning are very sensitive to uncertainties in americium and curium data. There are also several other programs where the minor actinide data are essential. These include the Accelerator Transmutation of Waste concepts and Burnup Credit programs.

The need for better nuclear data on minor actinides have been stressed by various organizations throughout the world, and results of studies have been published which demonstrate that current data are inadequate for designing the projects under consideration [1, 2]. The first step in obtaining better nuclear data consists of measuring accurate integral data and comparing it to integrated energy dependent data: this comparison provides a direct assessment of the effect of deficiencies in the differential data.

An ambitious program between the Commissariat à l’Energie Atomique (CEA) and the U.S. Department of Energy (DOE) has been launched with the aim of measuring the integral absorption rate parameters in the MINERVE experimental facility located at the CEA Cadarache Research Center. The OSMOSE Program (Oscillation in Minerve of isotopes in “Eupraxis” Spectra) includes a complete analytical program associated with the experimental measurement program and aims at understanding and resolving potential discrepancies between calculated and measured values.

The OSMOSE program began in 2001 and will continue until 2013. The reactivity worth of samples containing separated actinides from <sup>232</sup>Th to <sup>245</sup>Cm will be measured by an oscillation technique with an expected accuracy better than 3%. The measurements will cover a wide range of neutron spectra, from over-moderated thermal spectra to fast spectra.

**KEYWORDS:** *actinides, oscillation, reactivity worth, MINERVE facility, cross section*

## 1. Introduction

The objective of the OSMOSE program is to measure very accurate integral reaction rates in representative spectra for the actinides important to future nuclear system designs and to provide the experimental data for improving the basic nuclear data files. These data will support advanced reactors designed for transmutation of waste or plutonium burning, sub-critical systems such as found in advanced accelerator applications, and waste disposal and treatment programs in the area of criticality safety. This program is very generic, in the sense that it will measure these reaction rates over a broad range of isotopes and spectra and will be used to provide guidance to all nuclear data programs in the world. These data will provide information valuable to a large number of projects as noted above.

The design of nuclear systems has shifted over the years from a "test and build" approach to a much more analytical methodology based on the many advances in computational techniques and nuclear data. To a large extent current reactors can be calculated almost as well as they can be measured. This is due in particular to the high quality nuclear data available for the few major isotopes which dominate the neutronics of these systems. Nevertheless, most of the future nuclear systems concepts and advanced fuels development programs currently underway use significant quantities of minor actinides to address modern day issues such as proliferation resistance and low cost. For example, high burnup fuels contain large quantities of americium and curium. Systems designed for plutonium and minor actinide burning are very sensitive to uncertainties in americium and curium data. There are also several other programs where the minor actinide data are essential. These include the Accelerator Transmutation of Waste concepts and Burnup Credit programs.

The need for better nuclear data have been stressed by various organizations throughout the world, and results of studies have been published which demonstrate that current data are inadequate for designing the projects under consideration [1, 2]. In particular, a Working Party of the OECD has been concerned with identifying these needs [3] and has produced a detailed High Priority Request List for Nuclear Data. The first step in obtaining better nuclear data consists of measuring accurate integral data and comparing it to integrated energy dependent data: this comparison provides a direct assessment of the effect of deficiencies in the differential data. Several US and international programs have indicated a strong desire to obtain accurate integral reaction rate data for improving the major and minor actinide cross sections. Specifically, these include:  $^{232}\text{Th}$ ,  $^{233}\text{U}$ ,  $^{234}\text{U}$ ,  $^{235}\text{U}$ ,  $^{236}\text{U}$ ,  $^{238}\text{U}$ ,  $^{237}\text{Np}$ ,  $^{238}\text{Pu}$ ,  $^{239}\text{Pu}$ ,  $^{240}\text{Pu}$ ,  $^{241}\text{Pu}$ ,  $^{242}\text{Pu}$ ,  $^{241}\text{Am}$ ,  $^{242}\text{Am}$ ,  $^{243}\text{Am}$ ,  $^{242}\text{Cm}$ ,  $^{243}\text{Cm}$ ,  $^{244}\text{Cm}$ ,  $^{245}\text{Cm}$ ,  $^{246}\text{Cm}$ , and  $^{247}\text{Cm}$ . Data on the major actinides (i.e.  $^{235}\text{U}$ ,  $^{236}\text{U}$ ,  $^{238}\text{U}$ ,  $^{239}\text{Pu}$ ,  $^{240}\text{Pu}$ ,  $^{241}\text{Pu}$ ,  $^{242}\text{Pu}$ , and  $^{241}\text{Am}$ ) are reasonably well-known and available in the Evaluated Nuclear Data Files - (JEF, JENDL, ENDF-B). However, information on the minor actinides (i.e.  $^{232}\text{Th}$ ,  $^{233}\text{U}$ ,  $^{237}\text{Np}$ ,  $^{238}\text{Pu}$ ,  $^{242}\text{Am}$ ,  $^{243}\text{Am}$ ,  $^{242}\text{Cm}$ ,  $^{243}\text{Cm}$ ,  $^{244}\text{Cm}$ ,  $^{245}\text{Cm}$ ,  $^{246}\text{Cm}$ , and  $^{247}\text{Cm}$ ) is less well-known and considered to be relatively poor in some cases, having to rely on models and extrapolation of few data points. This is mainly due to the difficulty of obtaining relatively pure samples of sufficient quantity (up to about one gram) to perform reliable reaction rate measurements.

The OSMOSE program [4] aims at providing precise experimental data (integral absorption cross-sections) about heavy nuclides -  $^{232}\text{Th}$ ,  $^{233}\text{U}$ ,  $^{234}\text{U}$ ,  $^{235}\text{U}$ ,  $^{236}\text{U}$ ,  $^{238}\text{U}$ ,  $^{237}\text{Np}$ ,  $^{238}\text{Pu}$ ,  $^{239}\text{Pu}$ ,  $^{240}\text{Pu}$ ,  $^{241}\text{Pu}$ ,  $^{242}\text{Pu}$ ,  $^{241}\text{Am}$ ,  $^{243}\text{Am}$ ,  $^{244}\text{Cm}$ , and  $^{245}\text{Cm}$ . The study of these nuclides is performed on a large range of

neutron spectra corresponding to specific experimental lattices (thermal, epithermal, moderated/fast, and fast spectra).

The measurement program is utilizing the MINERVE reactor at CEA-Cadarache, which is a low-power uranium fueled pool reactor. The normal accuracy for small-worth samples in this reactor is on the order of 1% for relative reactivity-worth measurements and 2% for absolute reactivity-worth measurements. The total uncertainty in the OSMOSE samples is estimated to be about 3% including the uncertainty in the isotopic composition. Reactivity effects of less than 10 pcm (0.0001 or approximately 1.5 cents) will be measured and compared with calibrations to determine the differential reactivity-worth of the sample. Accuracies in small reactivity effects this low are only achieved through oscillation techniques.

Seven different neutron spectra will be created in the MINERVE facility: over-moderated  $\text{UO}_2$  (representative of a fuel processing plant or flooded storage cask),  $\text{UO}_2$  matrix in water (representative of LWRs), mixed oxide fuel matrix (representative of cores containing MOX fuels), two thermal/epithermal spectra (representative of under-moderated reactors), moderated fast spectrum (representative of fast reactors which have some slowing down due to moderators such as lead-bismuth or sodium), and a very hard spectrum (representative of fast reactors with little moderation from reactor coolant). The different spectra are achieved by changing the lattice within the MINERVE reactor.

The OSMOSE program began in 2001 with the preparation of samples. Reactor modifications were completed in 2003. The measurement program at MINERVE began in 2003 with the qualification of the MINERVE reactor and will continue through 2013.

## **2. Program Goals and Objectives**

The OSMOSE experimental program will produce very accurate sample worth measurements for a series of actinides in various spectra, from over-moderated thermal spectra to fast spectra. The objective of the analytical program is to make use of this experimental data to establish deficiencies in the basic nuclear data libraries, identify their origins, and propose paths towards correcting them, in coordination with international nuclear data programs.

The OSMOSE program aims at studying a majority of the separated heavy nuclides appearing during the reactor and the fuel cycle physics, i.e.  $^{232}\text{Th}$ ,  $^{233}\text{U}$ ,  $^{234}\text{U}$ ,  $^{235}\text{U}$ ,  $^{236}\text{U}$ ,  $^{238}\text{U}$ ,  $^{237}\text{Np}$ ,  $^{238}\text{Pu}$ ,  $^{239}\text{Pu}$ ,  $^{240}\text{Pu}$ ,  $^{241}\text{Pu}$ ,  $^{242}\text{Pu}$ ,  $^{241}\text{Am}$ ,  $^{243}\text{Am}$ ,  $^{244}\text{Cm}$  and  $^{245}\text{Cm}$ . Table 1 shows the isotopes of interest in the OSMOSE program and highlights which isotopes are critical for the various programs. Table 2 shows the target improvements [5] in the quality of the nuclear data for the listed actinide isotopes.

	JEFF3 validation	Criticality Burn-up credit	Pu recycling	Transmutation and incineration	Decay Heat power	Subsurface long-term Storage	Reactivity loss per cycle	Thorium cycle
<sup>232</sup> Th	⊗							⊗
<sup>233</sup> U	⊗							⊗
<sup>234</sup> U	⊗	⊗					⊗	
<sup>235</sup> U	⊗	⊗				⊗	⊗	
<sup>236</sup> U	⊗	⊗					⊗	
<sup>238</sup> U	⊗	⊗					⊗	
<sup>237</sup> Np	⊗	⊗		⊗		⊗	⊗	
<sup>238</sup> Pu	⊗	⊗	⊗	⊗	⊗	⊗	⊗	
<sup>239</sup> Pu	⊗	⊗	⊗	⊗	⊗	⊗	⊗	
<sup>240</sup> Pu	⊗	⊗	⊗	⊗	⊗	⊗	⊗	
<sup>241</sup> Pu	⊗	⊗	⊗	⊗	⊗	⊗	⊗	
<sup>242</sup> Pu	⊗	⊗	⊗	⊗	⊗	⊗	⊗	
<sup>241</sup> Am	⊗	⊗	⊗	⊗	⊗	⊗	⊗	
<sup>243</sup> Am	⊗	⊗	⊗	⊗	⊗	⊗	⊗	
<sup>244</sup> Cm	⊗	⊗	⊗	⊗	⊗	⊗	⊗	
<sup>245</sup> Cm	⊗	⊗		⊗	⊗	⊗	⊗	

Actinide	Parameter	Current Uncertainty (at 1σ)	Target Uncertainty (at 1σ)
U233	$\eta_{\text{therm}}$	± 2500 pcm	± 1500 pcm
	$\eta_{\text{epitherm}}$	± 4000 pcm	± 2500 pcm
U234	$I_r$	± 10 %	± 3 %
	$S_c^{\text{th}}$	± 2 %	± 1.5 %
U236	$I_r$	± 5 %	± 3 %
Np237	$I_r$	± 7 %	± 2 %
	$S_c^{\text{th}}$	± 3 %	± 1.5 %
Pu238	$I_r$	± 9 %	± 4 %
	$S_c^{\text{th}}$	± 2 %	± 1.5 %
Pu239	$\eta_{\text{therm}}$	± 3000 pcm	± 2000 pcm
	$\eta_{\text{epitherm}}$	± 4000 pcm	± 2000 pcm
Pu240	$I_r$	± 3 %	± 1.5 %
Pu242	$I_r$	± 4 %	± 2 %
Am241	$I_r$	± 7 %	± 2 %
	$S_c^{\text{th}}$	± 3 %	± 1.5 %
Am243	$I_r$	± 5 %	± 3 %
Cm244	$I_r$	± 5 %	± 3 %
Cm245	$\eta_{\text{therm}}$	± 4000 pcm	± 1500 pcm
Th232	$I_r$	± 4 %	± 2 %

$I_r$  = resonance integral,  $S_c^{\text{th}}$  = microscopic capture cross section,  $\eta$  = reproduction factor

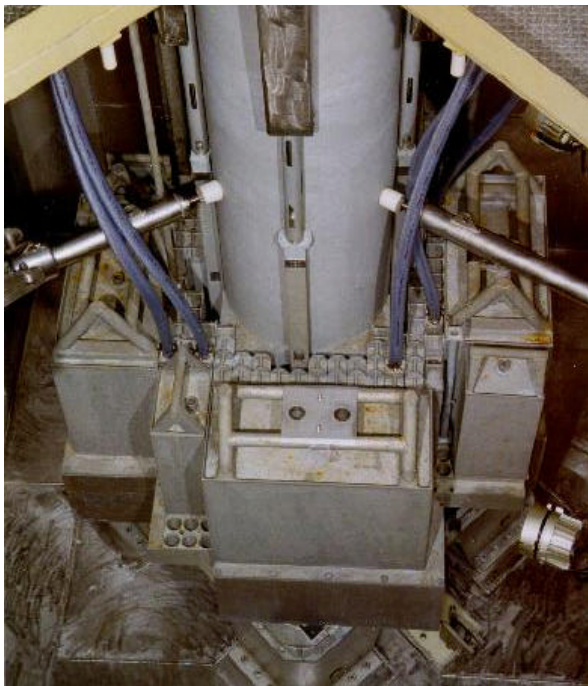
### 3. Experimental Conditions

#### 3.1. The MINERVE facility

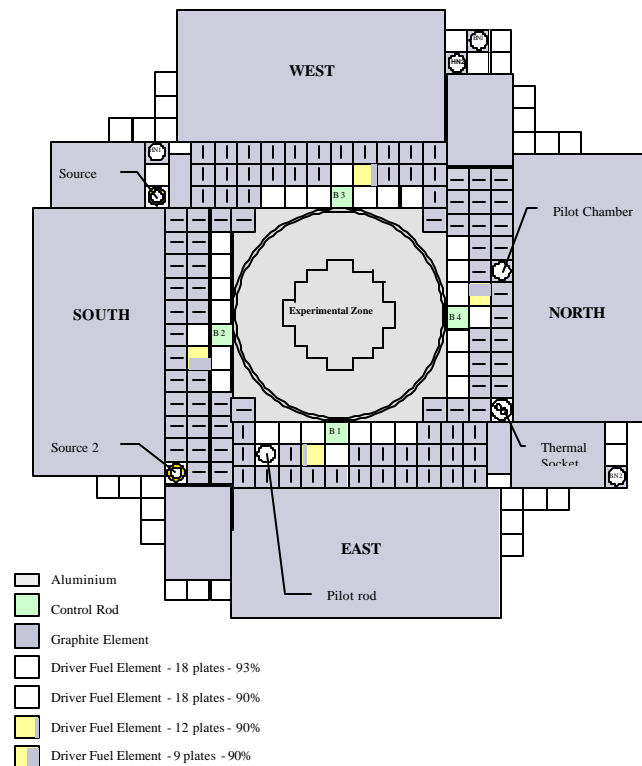
The experimental reactor MINERVE is devoted to neutronic studies of lattices of different reactor types. MINERVE achieved its first criticality in 1959 at the center of Fontenay-aux-Roses (near Paris). The reactor was transferred to CEA-Cadarache in 1977.

MINERVE is a pool type reactor operating at a maximum power of 100 watts. The core is submerged under 3 meters of water and is used as a driver zone for the different experiments located in a central square cavity with a size of about 70 cm by 70 cm. The coupled lattices in this cavity are built such that they can reproduce the neutronic spectra of various reactors. These lattices are discussed further in Sections III.2 and III.3.

The core is contained in a rectangular stainless steel tank containing about 100 m<sup>3</sup> of water. The moderator is distilled water and the cooling is performed by natural convection. The driver zone consists of enriched metallic uranium/aluminum plates clad with aluminum and gathered in elements of 9, 12, and 18 plates. These are standard Materials Testing Reactor (MTR) fuel elements. About 30 elements comprise the driver zone which is surrounded by a graphite reflector. A photograph of the reactor is shown in Figure 1. Figure 2 shows the core loading for a typical configuration (R1-UO<sub>2</sub>).



**Figure 1:** Photograph of the MINERVE Reactor



**Figure 2:** Core Loading for the R1-UO<sub>2</sub> Configuration

### 3.2. The experimental lattices

Several lattices corresponding to different neutron spectra can be built in the central region of the MINERVE Reactor.

For the OSMOSE program all of the lattices will be utilized, including an over-moderated  $\text{UO}_2$  spectrum (R2- $\text{UO}_2$ ), PWR spectrum (R1- $\text{UO}_2$ ), PWR MOX spectrum (R1-MOX), two epithermal spectra (MORGANE-R, MORGANE-S), moderated fast spectrum (ERMINE), and fast spectrum (ERMINE/COSMO). Figures 3-8 show the experimental lattices in the MINERVE reactor.

### 3.3. Neutron Spectra

The neutron spectra in the experimental zone vary based on the configuration of the lattice. Table 3 includes information on the moderation ratio ( $V_m/V_f$ ) and on the slowing-down density  $q$  (energy cut-off at 2.77 eV) for the different lattices. Figure 9 shows the calculated spectra in the sample location for the R1- $\text{UO}_2$  and R1-MOX configurations.

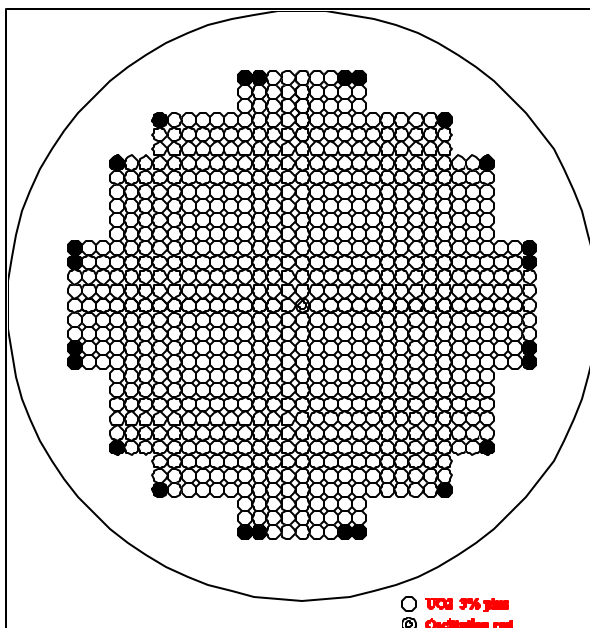


Figure 3: PWR  $\text{UO}_x$  lattice in MINERVE (R1- $\text{UO}_2$ )

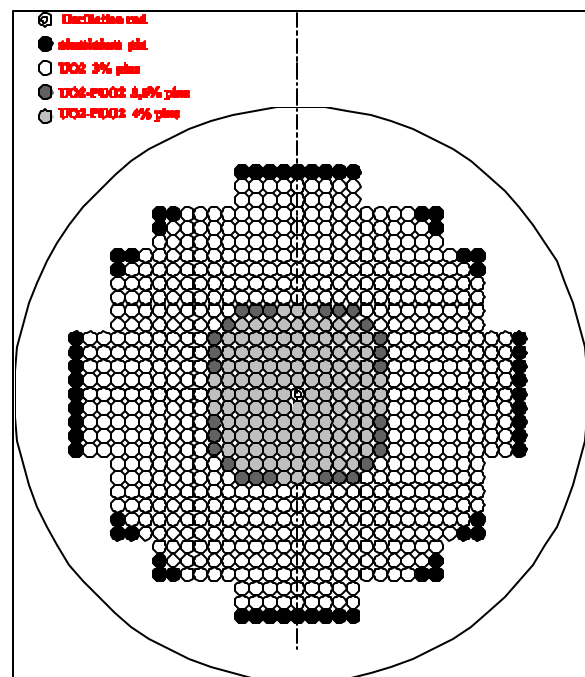
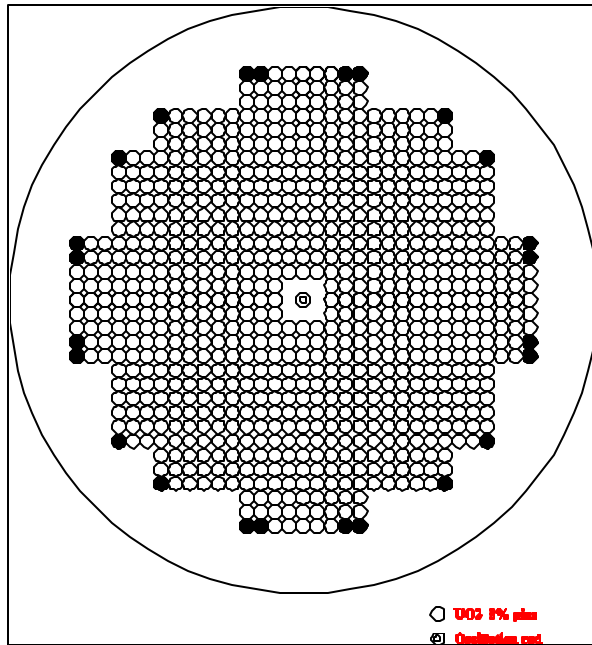
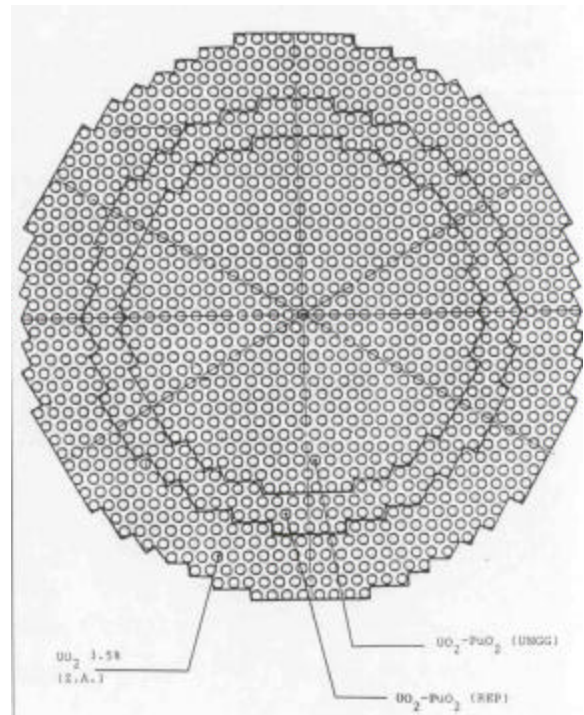


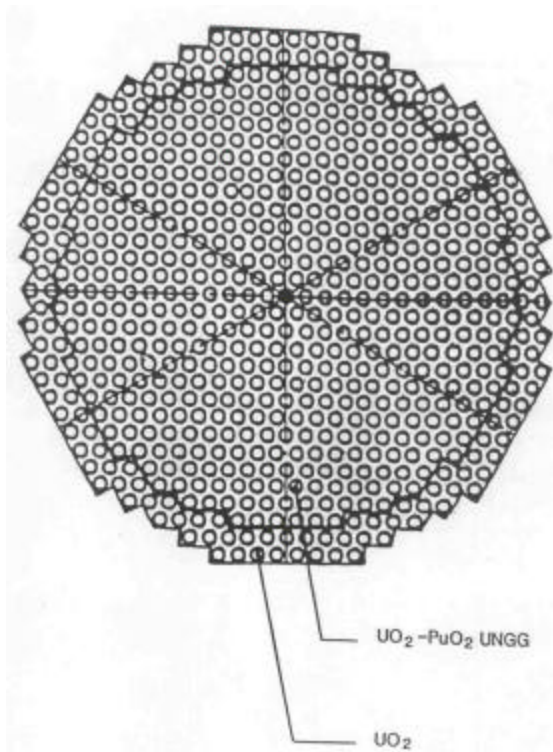
Figure 4: PWR MOX lattice in MINERVE (R1-MOX)



**Figure 5:** Over-moderated  $\text{UO}_2$  lattice in MINERVE (R2-UO2)



**Figure 7:** Epithermal spectrum lattice in MINERVE (MORGANE-S)

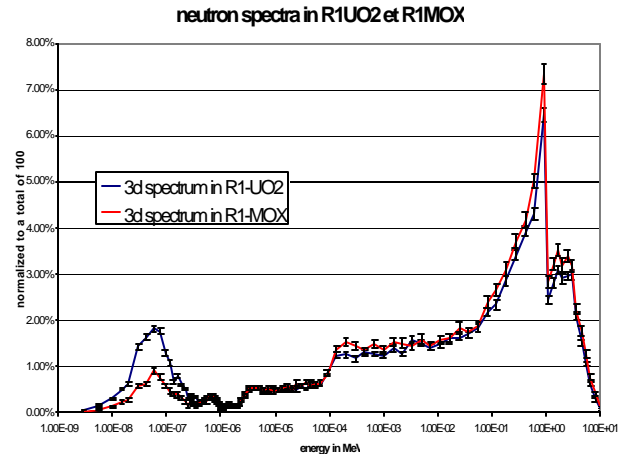


**Figure 6:** Epithermal spectrum lattice in MINERVE (MORGANE-R)



**Figure 8:** Fast spectrum lattice in MINERVE (ERMINE)

Table 3 Spectral Information for the experimental lattices in MINERVE		
Experimental Lattice	$V_m/V_f$	$q$
R1-UO2	1.4	0.60
R2-UO2	1.4	0.80
R1-MOX	1.4	0.55
MORGANE R	0.9	0.35
MORGANE S	0.5	0.32



**Figure 9:** Neutron spectra in R1-UO2 and in R1-MOX

## 4. Experimental Technique

### 4.1. The oscillation technique of measurement

The technique consists in oscillating samples that contain the studied actinide in the center of the experimental lattice in order to measure the associated reactivity variation with an accuracy better than 1% (at  $1\sigma$ ). Each sample is placed in an oscillation rod and moved periodically and vertically between two positions located in and out of the experimental zone as shown in figure 10.

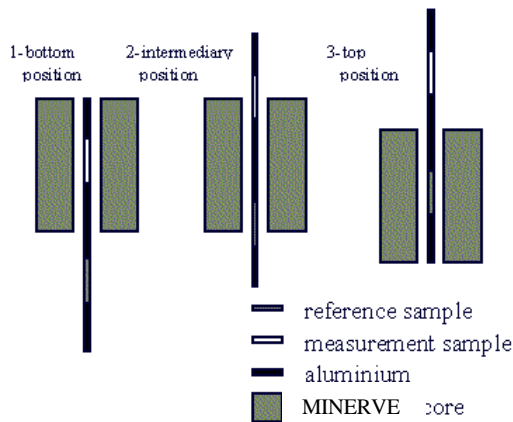
The studied sample is compared to a reference sample that differs just by the lack of actinide and that is placed in the bottom of the oscillation rod. Each sample is measured at least 4 times in order to significantly decrease systematic errors. A measurement corresponds to 20 oscillations of 60 seconds each.

The variations of flux induced by the oscillation are detected by a fission chamber placed in the driver zone, called the pilot chamber, that is servo-driven to a rotary automatic pilot rod. The pilot rod uses cadmium sectors, as shown in figure 11, to compensate for the reactivity variations. The pilot rod is calibrated using  $^{235}\text{U}$  and  $^{10}\text{B}$  samples, whose reactivity worth is known with uncertainties better than 1% through deterministic calculations.

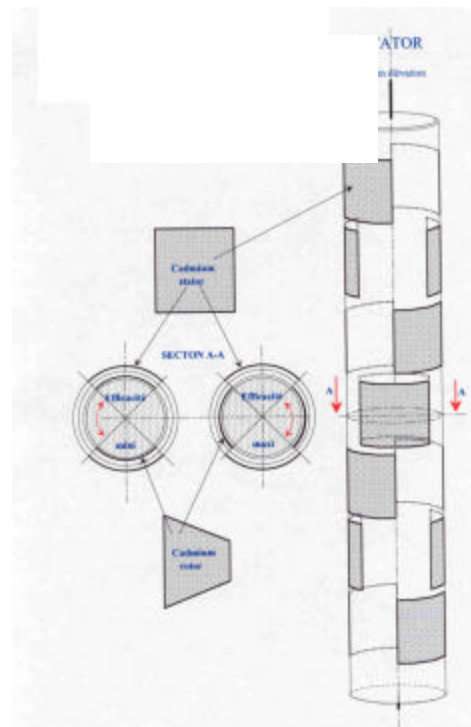
Taking into account the uncertainties on the measurement ( $\sim 1\%$ ), the samples ( $\sim 2\%$ ), and the calibration of the pilot rod ( $\sim 2\%$ ), the final experimental accuracy on the reactivity worth is about 3% (at  $1\sigma$ ).

Additional measurements are performed to precisely characterize the neutron spectra. These measurements include spectral indices, the conversion ratio of  $^{238}\text{U}$ , and axial and radial reaction rate distributions. Combined with the spectral characterization, the analysis of the experimental results using perturbation theory[6] provides accurate information on the integral absorption cross sections of the studied actinides.





**Figure 10:** Movement of the oscillation sample inside the MINERVE facility



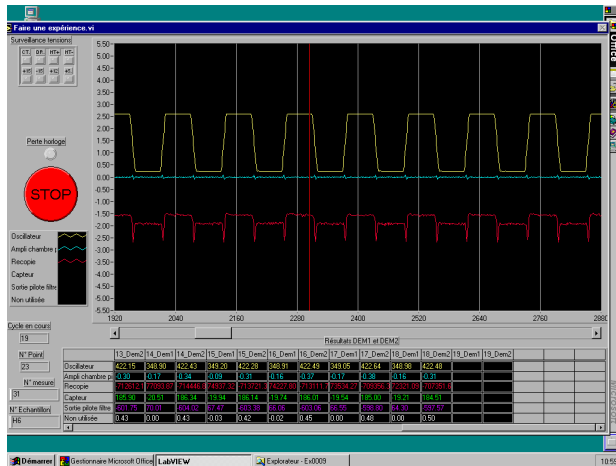
**Figure 11:** Scheme of the MINERVE automatic pilot rod

#### 4.2. Reactor Signal

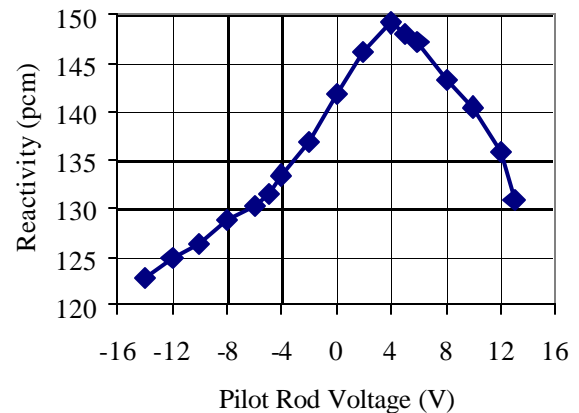
For each sample, five measurements are taken. Each measurement consists of a series of 20 cycles of oscillation of the sample. Figure 12 shows an example of the signal during one measurement. The signal of the automatic pilot rod (in red), the position of the oscillator rod (in yellow), and the pilot chamber signal (in blue) are recorded.

The mean amplitude of the automatic pilot rod signal is determined for each cycle of oscillation. The comparison of the amplitude for each cycle within one measurement provides information on the repeatability of the oscillations. The amplitudes of the 20 cycles are averaged to obtain the mean amplitude for a given measurement. The comparison of the mean amplitude for 5 measurements of the same sample provides information on the reproducibility of the measurement. The mean amplitudes are then averaged over all of the measurements to determine the mean amplitude for a given sample. The mean amplitude for a sample is then compared with the values from the calibration samples to determine the relative reactivity effect of the sample.

The reactivity effect of the calibration samples are then related to absolute reactivity-worths via reactor physics calculations. This then allows the determination of the reactivity-worth of unknown samples or samples containing isotopes with uncertain cross-sections.



**Figure 12:** Signals recorded during an oscillation measurement



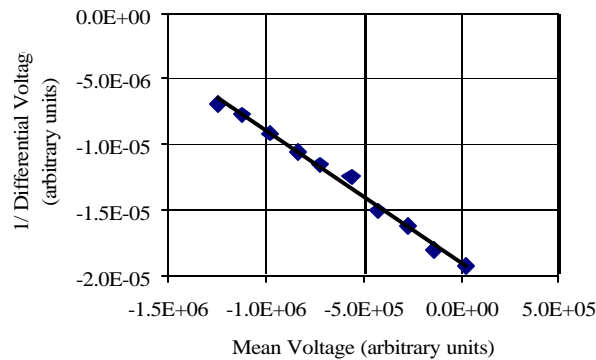
**Figure 13:** Example of reactivity curve of the pilot rod

### 4.3. Calibration of the Pilot Rod

The ability of the oscillation technique to accurately determine the reactivity-worth of unknown samples relies on the accurate calibration and understanding of the reactivity effects from the operation of the pilot rod. The pilot rod is a servo-driven system that 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. Because of the overlapping cadmium regions and the rotation of the cadmium sections, the effect on reactivity is not proportional to the rotor position for all angles of rotation. The calibration of the pilot rod is necessary to determine the range of angles of rotation of the rotor that are proportional to reactivity, and to accurately determine the differential change in reactivity. The technique does not determine the absolute value of reactivity for a given rotor position, but instead is based on the relative reactivity effect, which is significantly more accurate for determining small changes in reactivity.

To calibrate the pilot rod for oscillation measurements, two stages of calibration are performed. The first stage deals with verifying that the reactivity range of the pilot rod matches the range of the sample reactivity, i.e.  $\pm 0.0001$  (10 pcm). This is accomplished by positioning the pilot rod at different angles (i.e. different values of voltage on the rotor) and measuring the reactivity excess of the core. By doing this over the entire range of angles, a calibration curve of the pilot rod is created, as shown in Figure 13. This is a crude calibration that is adequate for initial positioning of the pilot rod but not sufficient for detailed measurements of small reactivity changes.

In the second stage of the calibration, the differential reactivity effect is determined for small changes in the voltage applied to the pilot rod. The position of the pilot rod is controlled by the bias voltage applied to the rotor. As observed in Figure 13, the change in reactivity effect is not directly proportional to the voltage. This means that the differential effects of applying a constant voltage to the rotor will also not be a constant effect, i.e. it will depend on the initial positioning of the rotor (or voltage applied to the rotor).



**Figure 14:** Example of differential efficiency curve of the pilot rod

This initial voltage is equivalent to the mean amplitude during the oscillations of the samples. So a calibration curve is created which relates the variation of the angle of the pilot rod (i.e. the amplitude of the signal) to its mean angle (mean value of the signal). This relation is linear over a small range and allows the normalization of all measurements to a specified reference angle. Figure 14 shows a calibration curve. In this region of linearity, the response from all samples can be directly compared based on the same reference angle  $\theta_0$  using the following relationship:

$$f(q) = f(q_0) \times (1 + K \times (q - q_0))$$

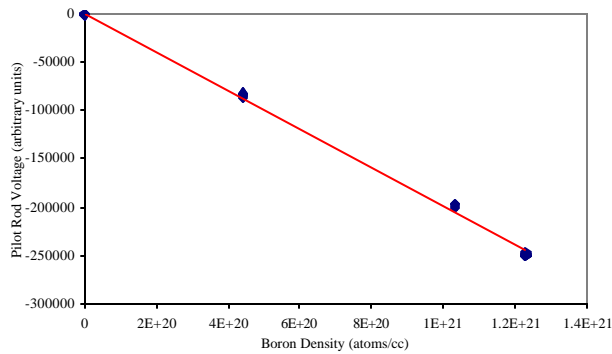
with  $f(\theta)$  is the measured amplitude,  $\theta$  is the mean position of the pilot rod during the measurement,  $\theta_0$  is the reference mean position (chosen in the middle of the linear part of the differential efficiency curve),  $f(\theta_0)$  is the amplitude of the signal if the measurement had been performed with a mean position of the pilot rod equal to  $\theta_0$ , and  $K$  is the constant dependant on  $\theta_0$  and on the linear equation of the differential efficiency curve.

The pilot rod calibration allows the reference angle  $\theta_0$  to be established and the normalization factor  $K$  to be determined. This calibration then allows all of the oscillation measurements to be normalized to the same reference angle.

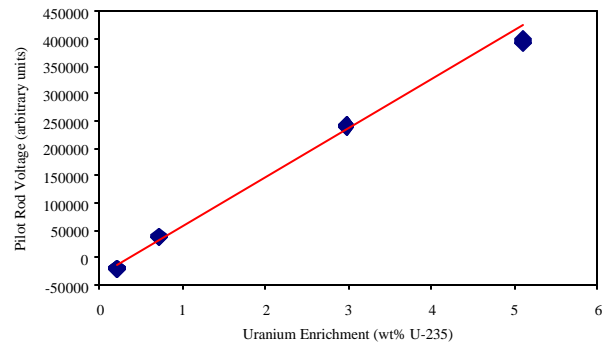
#### 4.4. Calibration Curves for Sample Measurements

Once the response of the pilot rod is calibrated, the signal can be calibrated using reference samples. There are two series of calibration samples, one contains a  $UO_2$  matrix with different uranium enrichments (natural, 0.25%, 0.5%, 0.72%, 1%, 2%, 3%, 4% and 4.95%  $U^{235}$ ) and the other contains a  $UO_2$  matrix with a range of boron concentrations (0, 60, 150, 333, 419, and 1062 ppm). Figures 15 and 16 show examples of the calibration curves.

The reactivity worth of the calibration samples is obtained by deterministic calculations with an accuracy of approximately 1%. Thus, the reactivity worth of every sample that is oscillated in MINERVE can be determined by comparing the response to the response from the calibration samples. Samples with a positive reactivity effect are compared to  $^{235}U$  calibration samples, and samples with negative reactivity effects are compared to boron calibration samples. The total uncertainty on the calibration



**Figure 15:** Calibration curve for boron loaded samples



**Figure 16:** Calibration curve for  $^{235}\text{U}$  calibration samples

measurements, involving material balance of the samples, reproducibility of the measurement and uncertainty on the reactivity worth calculation, is about 2%.

## 5. OSMOSE Samples

### 5.1. Samples

The samples are made of a  $\text{UO}_2$  matrix of natural uranium containing separated actinides. Each sample is made of assembled fuel pellets with standard PWR dimensions that contain the studied actinide. Each sample is double clad in Zircaloy with an external diameter of 1.06 cm and a length of 10.35 cm.

Table 4 presents the actinide samples that will be fabricated for the OSMOSE program. The actinide masses for each sample were determined based on initial calculations in order to provide an appropriate signal for the experimental conditions. For some specific actinides, two samples are fabricated in order to obtain information about neutron self-shielding effects.

High accuracy chemical and isotopic analysis will be performed for each sample before and during every step of the fabrication process. Furthermore three control fuel pellets are fabricated in parallel to each sample, in order to allow future analysis if necessary. Finally, each part of each sample is measured and weighed in order to avoid systematic errors induced by fabrication.

### 5.2. Fabrication Status

All the actinides have been obtained and are being purified in order to meet purity requirements. Demonstration tests have shown that the manufacturing process is contamination-free and samples are within the specified tolerances. Special equipment (including a dedicated oven, pressing and mixing tools) was fabricated and qualified in 2003. Pellets for the first 5 samples were manufactured in 2003, and fabrication is on schedule to provide all 20 samples by 2005. Figure 17 shows results of the first pellets that were sintered in 2003.

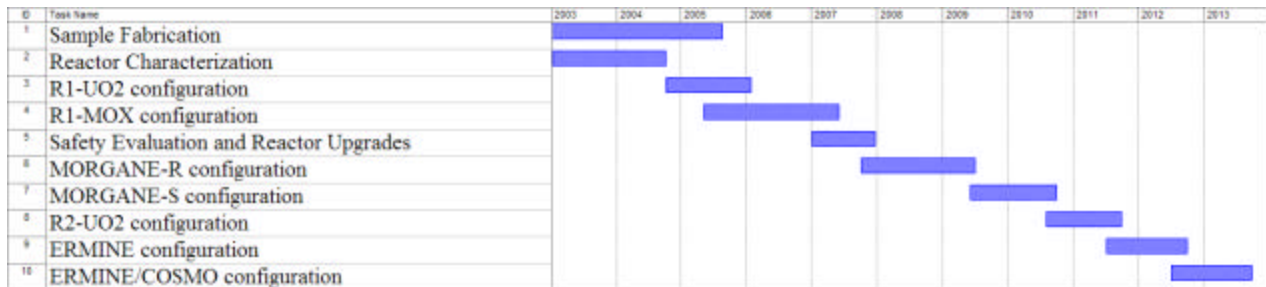
Table 4 Actinide Samples for the OSMOSE Program		
Actinide	Actinide Mass (grams)	Mass Concentration ( $M_A/(M_A+M_U)$ )
Th-232	48	1.0000
Th-232	2	0.0417
U-233	0.5	0.0104
U-234	0.3	0.0063
URE <sup>[1]</sup>	48	1.0000
Natural U	48	1.0000
Np-237	0.1	0.0021
Np-237	0.6	0.0125
Pu-238	0.4	0.0083
Pu-239	0.6	0.0125
Pu-240	0.15	0.0031
Pu-241	0.1	0.0021
Pu-241	0.5	0.0104
Pu-242	0.5	0.0104
Am-241	0.06	0.0013
Am-241	0.2	0.0042
Am-243	0.1	0.0021
Am-243	0.5	0.0104
Cm-244 <sup>[2]</sup>	2	0.0417
Cm-244+Cm-245 <sup>[2]</sup>	1	0.0208

Notes :

1. The signal from U-236 will be determined using a reprocessed uranium sample that contains 1.2% of U-236.
2. The signal from Cm-244 and Cm-245 will be determined from the signals of two curium samples containing different isotopic compositions. The first sample contains 90.47% Cm-244 and 3.45% Cm-245. The second sample contains 82.16% Cm-244 and 8.05% Cm-245.



**Figure 17:** Initial fuel pellets of  $UO_2$  and  $(UO_2 + 4\% ThO_2)$



**Figure 18:** Schedule of Measurements for the OSMOSE Program

## 6. Conclusions

This paper has described the OSMOSE experimental program that has begun and will continue until 2013 in the MINERVE facility of CEA-Cadarache. The schedule of the program is shown in Figure 18.

The OSMOSE program covers the majority of actinides that are important for reactor physics and the nuclear fuel cycle, from  $^{232}\text{Th}$  up to  $^{245}\text{Cm}$  and is therefore highly valuable for every domain of neutron physics study, especially for advanced reactor concepts and fuels that utilize larger quantities of the minor actinides.

The OSMOSE program will allow the determination of the reactivity of samples containing the separated actinides with an accuracy better than 3% that takes into account the uncertainties on the experiments, on the calculations and on the isotopic analysis.

As a consequence, the OSMOSE program will involve an improvement in the nuclear data (integral resonance, capture cross section, reproduction factor) of the studied actinides, and on a wide range of neutron spectra (thermal, epithermal and fast). A single and accurate experimental database for heavy nuclides will thus be obtained and will enrich nuclear data programs (JEFF3 and ENDFB-VII). It will also contribute to the database on burnup credit studies[5] that only currently address the fission products created during the nuclear fuel cycle.

## Acknowledgements

The authors of this paper thank all the participants to the experimental program and their industrial partners for their financial support and in particular Electricité de France (EdF) and the United States Department of Energy.

The submitted manuscript has been authored by a contractor of the U.S. Government under contract No. W-31-109-ENG-38. Accordingly, the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes.

## References

1. M. Salvatores, *Experimental Facilities, Training and Expertise in the Nuclear Data Field: Needs and Gaps for Reactor Physics Applications*,<sup>@</sup> Conference Proceedings, Vol. 59, Nuclear Data for Science and Technology, G. Reffo, A. Ventura and C. Grandi (eds.), SIF, Bologna, 1997.
  2. G. Palmiotti, et al., *Uncertainty Assessment for Accelerator Driven Systems*,<sup>@</sup> Proceedings of GLOBAL99, Jackson Hole, WY, September, 1999.
  3. P. Finck, et al., *Activities of the OECD NEANSC Working Party on International Evaluation Cooperation*,<sup>@</sup> Conference Proceedings, Vol. 59, Nuclear Data for Science and Technology, G. Reffo, A. Ventura and C. Grandi (eds.), SIF, Bologna, 1997.
  4. JP. Chauvin, et al., “The MINERVE facility and the OSMOSE program”, ANS-San Diego June 2000, USA.
  5. JP. Hudelot, et al., “An experimental programme to qualify the integral cross section of the most important fission products – burn up credit problematics”, ANS-San Diego June 2000, USA.
  6. N. Thiollay, et al., “Burnup Credit for Fission Products Nuclides in PWR (UOX) Spent Fuels”, International Conference on Nuclear Criticality Safety (ICNC'99), November 20-24, 1999, Versailles, France.
-