The OSMOSE Program for the Qualification of Integral Cross Sections of Actinides: Preliminary Results in a PWR-UOx Spectrum

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Abstract

The need for improved nuclear data for minor actinides has been stressed by various organizations throughout the world – especially for studies relating 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 data for improving the major and minor actinides cross sections. Data on major actinides (i.e. ^{235}U, ^{236}U, ^{238}U, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu and ^{241}Am) are reasonably well-known and available in the Evaluated Nuclear Data Files (JEFF, JENDL, ENDF-B). However information on the minor actinides (i.e. ^{232}Th, ^{233}U, ^{237}Np, ^{238}Pu, ^{242}Am, ^{243}Am, ^{242}Cm, ^{243}Cm, ^{244}Cm, ^{245}Cm, ^{246}Cm and ^{247}Cm) is less well-known and considered to be relatively poor in some cases, having to rely on model and extrapolation of few data points.

In this framework, the ambitious OSMOSE program between the Commissariat à l'Energie Atomique (CEA), Electricité de France (EDF) and the U.S. Department of Energy (DOE) has been undertaken with the aim of measuring the integral absorption rate parameters of actinides in the MINERVE experimental facility located at the CEA Cadarache Research Center. The OSMOSE Program (OScillation in Minerve of isOtopes in "Eupraxic" 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. In the OSMOSE program, the reactivity worth of samples containing separated actinides are measured in different neutron spectra using an oscillation technique with an overall expected accuracy better than 3%. Reactivity effects of less than 10 pcm (0.0001 or approximately 1.5 cents) are measured and compared with calibrations to determine the differential reactivity-worth of the individual samples.

The first experimental results were obtained with a very good reproducibility in 2005 and 2006 in the R1-UO2 core configuration representative of a PWR UOx standard spectrum. The preliminary results of measurements and comparison to calculational models are reported.

KEYWORDS: OSMOSE program, actinides, oscillation technique, cross section, MINERVE facility, calibration

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1. Introduction

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 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. 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.

The OSMOSE program aims at providing precise experimental data (integral absorption cross-sections) about heavy nuclides - ^{232}Th, ^{233}U, ^{234}U, ^{235}U, ^{236}U, ^{238}U, ^{237}Np, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, ^{241}Am, ^{243}Am, ^{244}Cm, and ^{245}Cm. The study of these nuclides is performed on a large range of neutron spectra corresponding to specific experimental lattices (over-moderated, thermal and epithermal spectra). Table 1 shows the target improvements in the quality of the nuclear data for the listed actinide isotopes that the OSMOSE program is hoping to achieve through the combination of more precise measurements and code assessment and validation efforts.

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 (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.

Currently, 6 different neutron spectra can be created in the MINERVE facility: over-moderated UO_2 (representative of a fuel processing plant or flooded storage cask), UO_2 matrix in water (representative of LWRs), mixed oxide fuel matrix (representative of cores containing MOX fuels), two epithermal spectra (representative of under-moderated reactors), and a very hard spectrum (representative of sodium fast reactors). 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. Calibration measurements followed in 2004-2005 using samples with different enrichments of uranium and boron concentrations. Measurements using the OSMOSE separated-actinide samples in different spectra began in 2005 and will continue through 2008.

Table 1 : Target Improvements in Nuclear Data from the OSMOSE Program

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

Ir = resonance integral, σ_c^{th} = microscopic capture cross section, η = reproduction factor

2. Framework of the CEA/DOE collaboration on the OSMOSE program

The need for improved nuclear data for minor actinides has been stressed by various organizations throughout the world – especially for studies relating 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 data for improving the major and minor actinides cross sections. Data on major actinides (i.e. ^{235}U, ^{236}U, ^{238}U, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu and ^{241}Am) are reasonably well-known and available in the Evaluated Nuclear Data Files (JEFF, JENDL, ENDF-B). However information on the minor actinides (i.e. ^{232}Th, ^{233}U, ^{237}Np, ^{238}Pu, ^{242}Am, ^{243}Am, ^{242}Cm, ^{243}Cm, ^{244}Cm, ^{245}Cm, ^{246}Cm and ^{247}Cm) is less well-known and considered to be relatively poor in some cases, having to rely on model and extrapolation of few data points.

Because it was recognized that qualification and improvement in the data for minor actinides is a global issue relevant for advanced reactor development programs (such as the Generation-IV Reactor Program and the Global Nuclear Energy Initiative), a collaboration between the Commissariat à l'Energie Atomique (CEA), Electricité de France (EDF) and the U.S. Department of Energy (DOE) was established to support and conduct the ambitious OSMOSE program. The goal of the collaboration is to measure the integral absorption rate parameters of actinides in a range of neutron spectra and generate a reactor physics benchmark that can be used for the validation and improvement of the cross-section data for the actinides of interest.

The collaboration was established in 2001 under the International Nuclear Energy Research Initiative (I-NERI) between CEA and DOE and continues today under the revised format for the I-NERI program. The collaboration has included the sharing of measurement data, calculational models and results, and comparison of calculations based on the different models and cross-section data sets. A concerted effort is made to perform comparisons and produce all reports together and with agreement between the parties. The collaboration has also included tangibles such as delivery of key isotopes from DOE to CEA for sample fabrication and delivery of fabricated sample pellets from CEA to DOE for chemical analysis. In addition to performing calculations, personnel from ANL have supported the measurement program at CEA. As such, the OSMOSE program continues to be an active international collaboration between DOE and CEA for the improvement of nuclear data.

This presentation of the initial results of measurements in a PWR UOx spectra is a demonstration of the extensive collaboration between CEA and DOE for the conduct of the OSMOSE program.

3. Status and characteristics of the samples fabrication

3.1 Fabrication of the fuel samples

The samples are made of a UO_2 matrix of natural uranium containing separated actinides. These fabrications need the development of dedicated equipment (including a dedicated sintering oven placed inside a hot cell, and pressing and mixing tools), and the utilization of very precise and complicated fabrication process [1].

Each sample is made of assembled sintered fuel pellets (~50 g) with standard PWR dimensions that contain the studied actinide. 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.

Each sample is made of fuel pellets inside a waterproof laser welded double clad in Zircaloy, with an external diameter of 1.06 cm and an overall length of 10.35 cm.

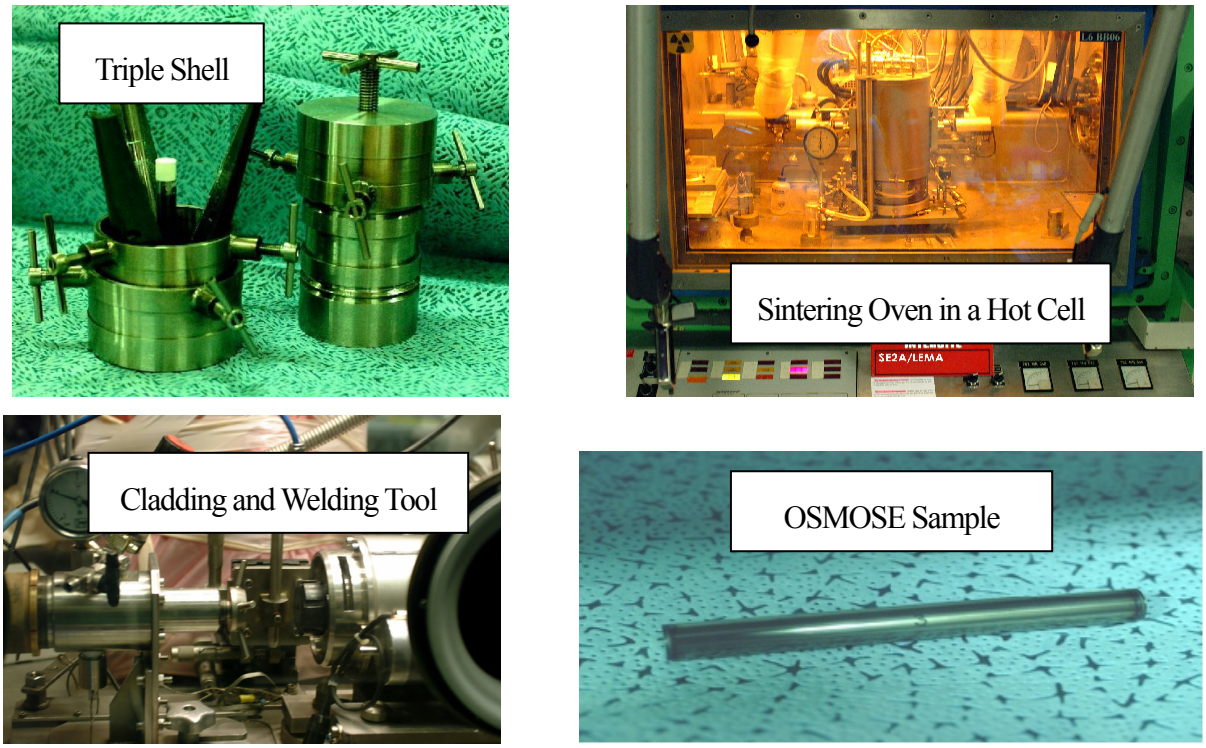
Very precise specifications were imposed on the diameter and the density of the fuel pellets, on the height of the column of fuel pellets, on the homogeneity of the distribution of the actinides inside the UO_2 matrix of natural uranium, and on the overall height of the samples, so that the geometry and masses of the samples are very accurately controlled.

Table 2 presents the status of the actinide samples fabrication. Figure 1 shows the 4 major steps of the sample fabrication.

Table 2: Status of Actinide Sample Fabrication

June 2005		February 2006		February 2007	
Sample	Target Mass	Sample	Target Mass	Sample	Target Mass
UO_2 nat	pure	Th-232	Pure	U-233	0.5
U-234	0.3	Pu-238	0.4	Am-243/1	0.1
URE (a)	pure	Pu-240	0.15	Am-243/2	0.5
Th232	2	Pu-241	0.3	Cm-244	2
Np-237/1	0.1	Am-241/1	0.06	Cm-244+245	1
Np-237/2	0.6	Am-241/2	0.2	Target mass in grams	
Pu-239	0.6	(a) Reprocessed and re-enriched uranium in order to study U-236. URE contains UO_2 with 1% of U-236 and 4% of U-235			
Pu-242	0.5				

Figure 1: The Four Major Steps in the Sample Fabrication Process



3.2 Chemical and isotopic analysis of the samples

All the actinides have been purified in order to meet purity requirements. Demonstration tests have shown that the manufacturing process is contamination-free. A high level of confidence can be assigned to the material balance known from the actinide and natural UO_2 weighing before the fabrication.

However, three additional control fuel pellets are fabricated in parallel to each sample, in order to allow future analysis if necessary. The analysis is performed in two different laboratories at ANL and CEA Marcoule, in order to reduce the statistical uncertainties on the results, and to check the consistency of the analysis.

Finally, each part of the sample is measured and weighed in order to avoid systematic errors induced by fabrication.

4. Experimental conditions

4.1. The MINERVE facility

MINERVE is a pool type reactor operating at a maximum power of 100 watts [2] [3]. 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 neutronics spectra of various reactors, from over-moderated spectrum to fast spectrum.

Figure 2: Photograph of the MINERVE Reactor

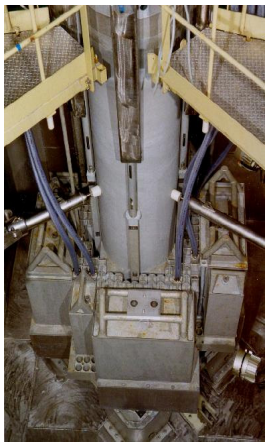
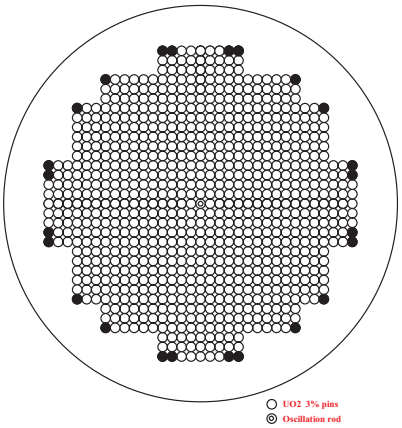


Figure 3: View of the R1-UO2 Lattice



The core is contained in a rectangular stainless steel tank containing about 100 m^3 of water. The cooling is performed by natural convection. The driver zone consists of enriched metallic uranium/aluminum plates clad with aluminum. These are standard Materials Testing Reactor (MTR) fuel elements. About 40 elements comprise the driver zone which is surrounded by a graphite reflector. A photograph of the reactor is shown in Figure 2. Figure 3 shows the core loading for a typical configuration (R1-UO2).

4.2 The studied experimental lattices – the associated neutron spectra

OSMOSE is planned to be performed, in parallel to the OCEAN program [4] in 4 different core configurations – R1-UO2 (in 2005-2006), R1-MOX (in 2006-2007), R2-UO2 (in 2007-2008) and MORGANE-R (in 2008), respectively representative of PWR-UOX, PWR-MOX, over-moderated and RSM epithermal spectra.

This paper will deal with the first results obtained in the R1-UO2 configuration (Figure 3). This last one is made of 776 UO_2 fuel pins enriched at 3% in U-235, and of 24 surrounding aluminum pins, in a square pitch of 1.26 cm.

5. The oscillation technique

5.1 Principle

The technique consists in oscillating samples that contain the studied actinide in the center of the experimental lattice in order to measure their reactivity worth with an accuracy of around 1% (at 1σ). Each sample is placed into an oscillation rod and moved periodically and vertically between two positions located inside and outside the experimental core zone by the mean of an oscillator as shown in Fig. 4 [3] [5].

Each sample is measured at least five times in order to improve the reproducibility of the measurement and to decrease significantly statistical errors on sample loading. A measurement corresponds to 10 oscillations of 120 s each, to improve the repeatability.

The reactivity variations, between ± 15 pcm, due to the oscillation are compensated by a rotary automatic pilot rod that 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

Figure 4: Movement of the oscillation sample inside the MINERVE facility

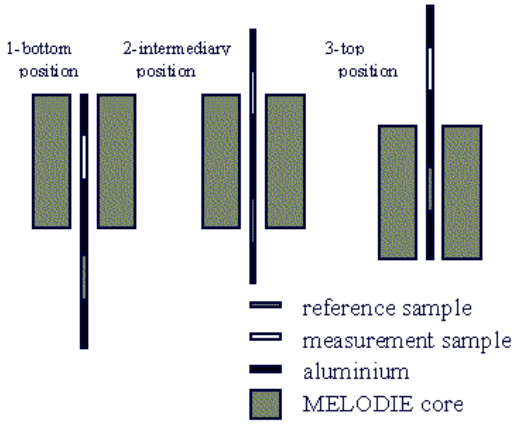
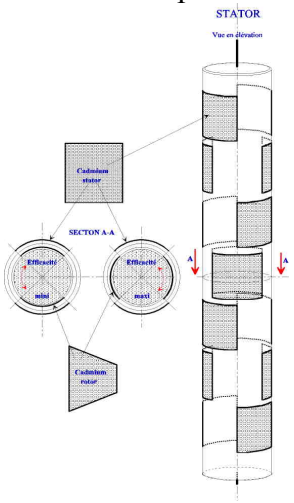


Figure 5: Scheme of the automatic pilot rod



of the angle of the rotor (Figure 5). The pilot rod is calibrated using U-235 and B-10 samples. The recorded experimental signal is the angle of rotation of the rotor of the pilot rod which is proportional to the reactivity worth of the studied sample over a specified range.

5.2 Calibration of the pilot rod

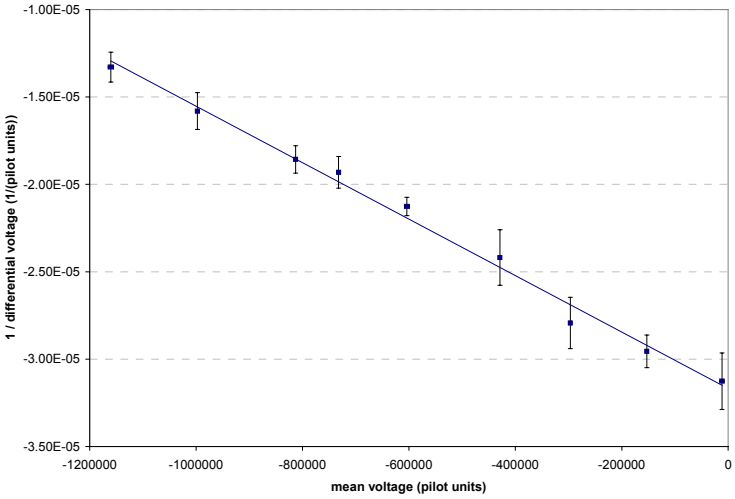
The ability of the oscillation technique to accurately determine the reactivity-worth of unknown samples relies on the accurate calibration of the reactivity effects from the operation of the pilot rod. Thus, the calibration of the pilot rod is necessary to determine the range of rotation of the rotor which is proportional to reactivity.

For this, the differential reactivity effect of the pilot rod is determined for small changes in the voltage applied to the pilot rod [3]. The position of the pilot rod is controlled by the bias voltage applied to the rotor. 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, given in arbitrary unit called “pilot unit” that is proportional to the applied voltage) 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 6 shows an example of calibration curve.

In this region of linearity, the response from all samples can be directly compared based on the same reference angle θ_0 using the relationship $f(\theta) = f(\theta_0) \times (1 + K \times (\theta - \theta_0))$, with $f(\theta)$ is the measured amplitude, θ is the mean position of the pilot rod during the measurement, θ_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 θ_0, and K is the constant dependant on θ_0 and on the linear equation of the differential efficiency curve.

The pilot rod calibration allows the reference angle θ_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.

Figure 6: Example of differential efficiency curve of the pilot rod



5.3 Calibration curve for sample measurements

The signal of the pilot rod can be calibrated using samples containing well-know isotopes. There are two series of calibration samples. One contains samples made of a UO_2 matrix with different uranium enrichments (0.25%, 0.5%, 0.72%, 1%, 2%, 3%, 4% and 4.95%) in U-235. The other contains samples made of a UO_2 matrix with a range of boron concentrations (0, 60, 100, 150, 200, 299, 333, 400, 419, 500 and 1062 ppm).

Fig. 9 in section 7.4 plots the measured reactivity effect (ordinate is the pilot rod angle given in arbitrary unit called "pilot unit") versus the calculated reactivity effect (abscissa in pcm) of ^{235}U calibration samples. The slope of the regression line allows a conversion from pilot units to calculation units (pcm).

5.4 Statistical treatment of the experimental data

The main difficulty of the experiment is to determine the uncertainty on the results obtained by the oscillation technique. This uncertainty can be logically split into a term δ_{eSij} corresponding to statistical fluctuations (dealing with the repeatability on the position of the oscillator and on the stability of the reactor and of the servo-driven system of the pilot rod) and another term δ_{cSi} related to the reproducibility of the measurement (dealing with the reproducibility on the position of the oscillations samples inside the oscillation rod between each oscillation measurement, and with the reproducibility on the position of the oscillator), so that the signal can be written as: $S_{ij} = S_0 + \delta_{cSi} + \delta_{eSij}$, where I is the number of measurements for each sample (i=1-5), j is the number of oscillation cycles for one measurement (j=1-10), S_{ij} is the signal of the sample during cycle j of measurement i, S_0 is the mean of S_{ij}.

The $\hat{\sigma}_c$ and $\hat{\sigma}_e$ standard deviations respectively related to δ_{cSi} and δ_{eSij}, are given by:

$$\hat{\sigma}_c^2 \approx \frac{1}{n} \times \sum_{k=1}^{n} \left(\overline{S}_i - S_0 \right)^2 \quad \text{and} \quad \hat{\sigma}_e^2 \approx \frac{1}{n} \times \sum_{k=1}^{n} \left(\frac{1}{10} \sum_{j=1}^{10} \left(S_{ij} - \overline{S}_i \right)^2 \right)$$

where n is the total number of oscillation measurement (over all the samples), $\overline{S_i}$ is the mean signal of a sample during measurement n°i.

Finally, a generic $\hat{\sigma}_S$ estimated standard deviation can be assigned to the experimental result of each sample, i.e. to the mean value of the 5 measurements for each sample:

$$\hat{\sigma}_S = \sqrt{\left(\hat{\sigma}_e^2 + \hat{\sigma}_c^2\right)/5}$$

In the end, this estimated generic variance $\hat{\sigma}_S^2$ is compared to the external variance $s = \sqrt{\sum_{i=1}^{5}\left(S_i - S_0\right)^2 \Big/ 4}$ on the 5 signals corresponding to the 5 measurements of each sample, using a KHI² statistical test, in order to check the consistency of the obtained generic variance (i.e. to check no other source of uncertainty has occurred during the measurements).

5.5 Experimental uncertainties

The detail of the different experimental uncertainties discussed above is given in Table 3.

Table 3: Detail of the Uncertainties on the Experimental Signal (in pilot units – pu)

Sources of uncertainty	Standard uncertainty
Repeatability of the measurements	< 2000 p.u. (a)
Reproducibility of the measurements	< 2000 p.u. (a)
Linear correction from the pilot rod	< 200 p.u. (a)
Mean overall uncertainty on experimental results	< 1200 p.u. (b)

(a) given in pilot units (p.u.) for a single oscillation measurement

(b) given in pilot units, and related to the mean value of 5 measurements, when the KHI² statistical test is accepted (see section 5.4)

6. Experimental results in R1-UO2

Table 4 gives the experimental results and the associated uncertainties obtained in the R1-UO2 core configuration for the first 6 OSMOSE samples oscillated in MINERVE between October 2005 and March 2006. An excellent accuracy, better than 1.3% in every case, is obtained on the experimental results, that is calculated as the difference of the signal given by the OSMOSE samples (containing the natural uranium matrix and the doping actinide X) and the signal of the Unat sample (only containing the natural uranium matrix).

Table 4: First Experimental Results in the R1-UO2 Core Configuration

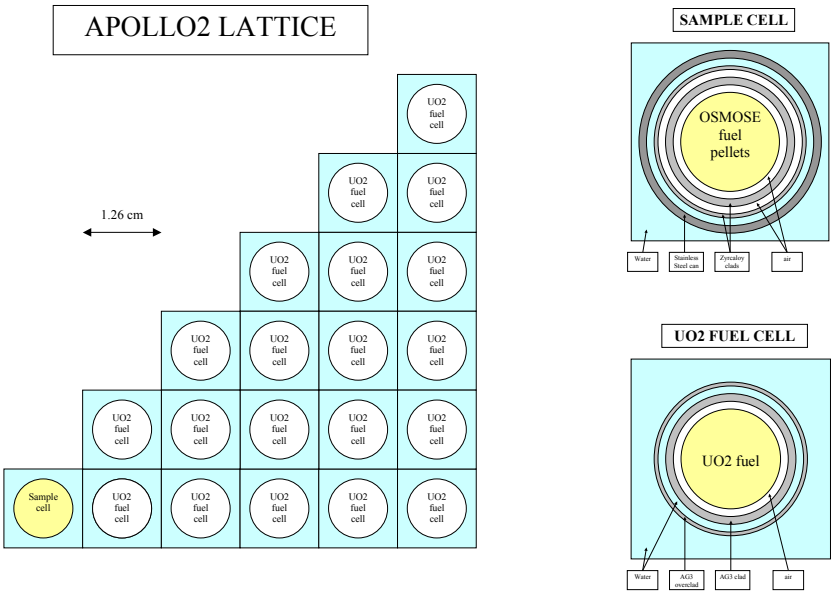
Sample	Experimental signal (p.u.)	Mean overall uncertainty (p.u.)	Relative uncertainty (%)
Unat	62 444	451	-
U-234	-5 343	507	1.0%
Pu-239	250 028	700	0.4%
Pu-242	-2 801	526	1.1%
Np-237/1	11 727	484	1.3%
Np-237/2	-211 132	731	0.3%

7. Reactor modeling – data analysis

7.1 CEA model for data analysis

The CEA model for data analysis is based on the APOLLO2 deterministic code with the JEF2.2 and the JEFF3.1 data libraries. It consists of a 2-dimensional (11x11) multi-cell calculation (see Figure 7), using the probabilities of collisions and 2D interface currents with imposed leakage. It is based on the current French PWR optimized calculation scheme, with 172 energy groups and space dependant self-shielding. More details about this model can be found in reference [6].

Figure 7: (11x11) multi-cell APOLLO2 calculation model



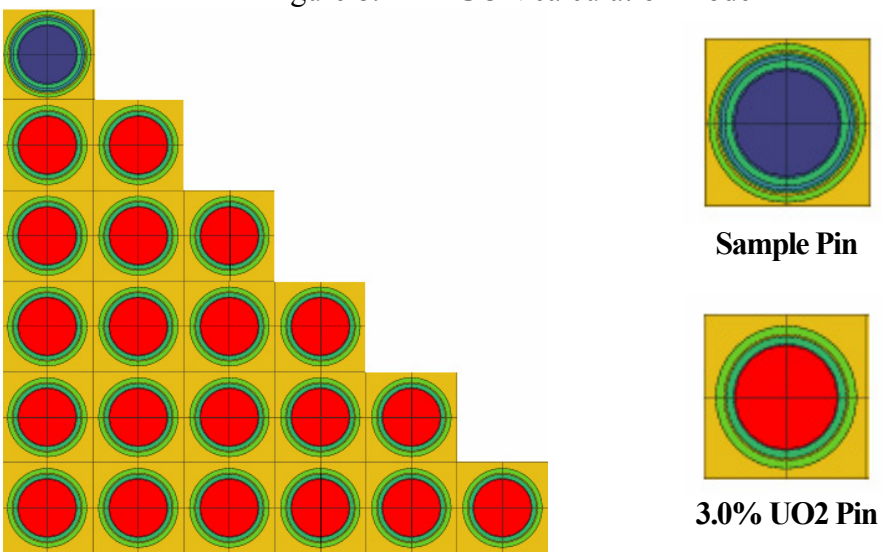
The APOLLO2 model was previously qualified on the basis of modified conversion ratio of U-238 measurements [7]. Due to small differences in the height of the columns of pellets inside samples and to the axial flux distribution at the sample position, a length correction is applied to every sample taking into account the axial buckling. These corrections are generally less than 5% of the experimental signal. They are controlled with an accuracy of better than 0.5% (1σ).

7.2 ANL model for data analysis

The ANL model for data analysis is based on the lattice physics code DRAGON using ENDFB/VI 172 group neutron library. It consists of a two-dimensional (11×11) multi-cell calculation (see Figure 8), using the two-dimensional surface net current coupled collision probability method.

In DRAGON calculation, the critical buckling search is superimposed upon the iteration so that the effective multiplication factor (k_{eff}) is forced to 1.0, and using the calculated flux, the infinite multiplication factor (k_{inf}) can be determined, this value is used as the calculated result for the analysis.

Figure 8: DRAGON calculation model



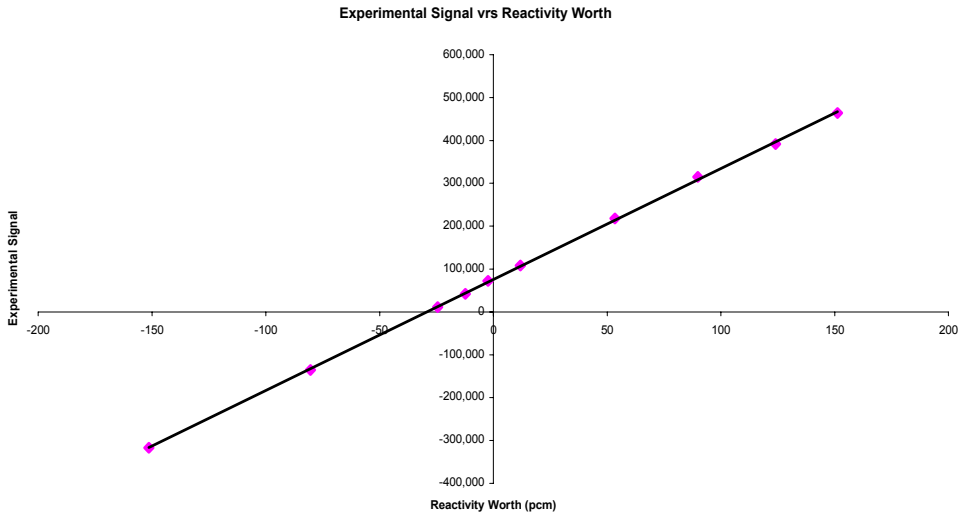
7.3 Basis for the preliminary data analysis

Both of ANL and CEA data analysis are based on the same geometry and material balance of the MINERVE facility and of the OSMOSE samples. The material balance of the samples comes from the masses of natural UO_2 and actinide inserted before fabrication inside samples. It needs to be confirmed by the post-fabrication chemical analysis, so the following calculation results are considered as preliminary.

7.4 Calibration curve

The calibration curve shows the relation between the experimental signal (in pilot unit) of the B-10 and U-235 calibration samples, and the calculated reactivity worth (in pcm given by the deterministic 2D model). The example of the calibration curve obtained with the ANL calculation model is shown in Fig. 9.

Figure 9: Calibration Curve Obtained with the ANL 2-D DRAGON Model



A linear relation is found. A linear fit is performed using a standard least square method. It takes into account the uncertainties on the material balance, on the experimental signal, on the nuclear data related to the calibration samples and on the length corrections on the experimental signal. In the end, a normalization factor (i.e. the slope of linear fit) is obtained (in (pilot unit / pcm)).

7.5 Uncertainties related to the data analysis

Table 5 summarizes the uncertainties on the data analysis. A standard overall uncertainty of 1.8% is obtained in each case. In the future, this uncertainty could be reduced taking into account the post-fabrication chemical analysis on control fuel pellets.

Table 5: Standard Relative Uncertainties Related to the Data Analysis

Material balance of the calibration samples (a) (b)	1%
Length corrections (a)	0.5%
Nuclear data about B-10 and U-235 (a)	<1 %
Slope of the calibration curve	1.5%
Material balance of the OSMOSE samples (b)	1%
Overall uncertainty on data analysis	1.8%

(a) taken into account in the uncertainty for the determination of the slope of the calibration curve
(b) uncertainty on the material balance known from weighing before fabrication

7.6 Comparison of experimental and calculation results

The (*C-E)/E* comparison of the preliminary calculation results (*C*) with experimental results (*E*) is given in Table 6 and Table 7, for the U-234, Pu-239, Pu-242 and Np-237 samples. An excellent overall uncertainty on (*C-E)/E* of around 2% is obtained when combining quadratically the uncertainties associated to data analysis and experiments.

An excellent agreement (within 1σ) between APOLLO2 calculation results and experimental results is obtained for U-234, Pu-239 and Pu-242, with both JEF2.2 and JEFF3.1 data libraries, except in the case of U-234 with JEFF3.1 which tends to show an underestimation in JEFF3.1 of about 6% of the U-234 resonance integral.

Table 6: Comparison of Experimental and Calculated Results with the APOLLO2 Model [6]

Sample	(C-E)/E in %		σ_d (%) (a)	σ_e (%) (b)	σ_{tot} (%) (c)
	JEF2.2	JEFF3.1			
U-234	0.8%	-6.7%	1.8%	1.0%	2.0%
Pu-239	-2.0%	-0.5%	1.8%	0.4%	1.8%
Pu-242	0.7%	0.4%	1.8%	1.0%	2.1%
Np-237/1	-9.9%	-14.4%	1.8%	1.3%	2.2%
Np-237/2	-7.3%	-12.2%	1.8%	0.3%	1.8%

(a) uncertainty on the data analysis
(b) experimental uncertainty
(c) total uncertainty on (C-E)/E

Table 7: Comparison of Experimental and Calculated results with the DRAGON model

Sample	(C-E)/E in % ENDF-B6.8	σ_d (%) (a)	σ_e (%) (b)	σ_{tot} (%) (c)
U-234	4.3 %	2.3 %	1.0%	2.5 %
Pu-239	0.5 %	2.3 %	0.4%	2.3 %
Pu-242	3.6 %	2.3 %	1.0%	2.5 %
Np-237/1	5.3 %	2.3 %	1.3%	2.6 %
Np-237/2	13.53 %	2.3 %	0.3%	2.3 %

(a) uncertainty on the data analysis
(b) experimental uncertainty
(c) total uncertainty on (C-E)/E

For Np-237, consistent C/E results are obtained for the two samples. They show an underestimation of the calculation of about 8% with JEF2.2 and 13% with JEFF3.1. As the signal of Np-237 is mainly due to both thermal and epithermal captures, it is not possible to identify whether the thermal part or the integral resonance or both, of the Np-237 radiative capture cross section are underestimated. The future trends on C/Es that will be obtained in future core configurations should allow us to identify more precisely the origin of the deviation between calculation and experimental results.

The DRAGON model results appear to show a systematic bias such that all of the calculated values are higher than the experimentally measured values. Otherwise, they are reasonably consistent with the APOLLO2 model results. The DRAGON model has not yet been validated and there are several potential sources of the bias and discrepancy between the results and those from the APOLLO2 model: 1. self-shielding effects may not have been appropriately considered in collapsing from the continuous energy cross-sections to the multi-group cross-sections especially in the case of the minor actinides, 2. the DRAGON model did not account for the slight variation in sample height as discussed in the APOLLO2 model, 3. there may be a small bias in the calibration curve based on the model of the calibration samples, and 4. there may still be some minor differences in the compositions of the samples. The differences in the results are still being investigated.

8. Conclusions

First experimental results were obtained with a very good accuracy around 1% using the oscillation technique for Pu-239, Pu-242, U-234 and Np-237 samples in a PWR-UOx spectrum. An optimized method for data analysis reduces the uncertainties to around 2% for the comparisons of the calculated results to experimental results (C/E ratio).

Consistent results were obtained between the data analysis performed with the French APOLLO2 deterministic code with JEF2.2 and JEFF3.1 and the data analysis with the US DRAGON code with ENDF-B6.8. As noted, the DRAGON results appear to have a systematic bias which is being further investigated.

These preliminary results are based on initial material specifications of the oscillation samples. The associated uncertainties should be reduced in the future taking into account the incoming chemical analysis that will be performed in both ANL and CEA laboratories.

First results show an excellent agreement (within 1σ) between calculated and experimental results for U-234 and Pu-239, for every considered data library. For U-234, a good agreement

is observed with JEF2.2, but a discrepancy is obtained with JEFF3.1 which tends to show an underestimation in JEFF3.1 of about 6% of the U-234 resonance integral.

For Np-237, an underestimation of the calculation of about 8% with JEF2.2 and 13% with JEFF3.1 is found, for the 2 studied samples. The future OSMOSE experiments in other neutron spectra (over-moderated and epithermal spectra) will allow us to identify whether this underestimation is due to the thermal region or the resonant region of the radiative cross section of Np-237.

In the near future, complementary results will be obtained for Th-232, U-233, Pu-238, Pu-240, Pu-241, Am-241, Am-243, Cm-244 and Cm-245. All the studied samples will be studied in the four different neutron spectra, from an over-moderated spectrum to a RSM-epithermal spectrum.

In the end, an exhaustive experimental database will be obtained on the neutronics parameters of actinides (resonance integrals, integral fission and capture cross sections, reproduction factors), and a complete benchmark between the French and US calculations and data libraries will be achieved.

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