THE VALMONT EXPERIMENTAL PROGRAMME FOR THE NEUTRONICS QUALIFICATION OF THE UMO/AL FUEL FOR THE JULES-HOROWITZ-REACTOR

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ABSTRACT

The proper and safe estimation of the uncertainties associated with the results of neutronics calculations is crucial for the design studies of the future Jules Horowitz Reactor (JHR). However, the neutronics characteristics of this innovative core and, in particular, the use of the new UMo/Al fuel preclude the use of the existing qualification databases.
The need for specific experimental data for this fuel was met by the VALMONT programme, which consisted in the precise measurement of the reactivity effect of fuel samples in the MINERVE reactor. These measurements, corroborated by γ-spectroscopic analysis on irradiated UMo/Al fuel, allow to qualify the HORUS3D/N neutronics calculation route for this fuel. Moreover, the application of the representativity method allowed to reduce the uncertainty on the reactivity, due to the uncertainties of the basic nuclear data of the Uranium isotopes, by a factor of 3.

1. Introduction

In the design of a new type of reactor, the uncertainties associated with the results of the neutronics design calculations are a major concern. The consequences of an inexact knowledge of these uncertainties may reach from overly conservative and costly design margins, performance and irradiation quality questions to substantial safety issues.

This is particularly true in the case of the new Jules Horowitz Reactor (JHR), which is going to use the new UMo/Al LEU high-density fuel in an advanced core design [1].

The HORUS3D/N neutronics calculations route [2], used for the development of the JHR core, is being developed within the framework of a rigorous verification-validation-qualification methodology [3], which has been applied with great success in the neutronics domain at CEA: after analytical verification of the neutronics codes and benchmark validation against a continuous energy Monte-Carlo code, the confrontation of the computational results with experimental results allows to qualify the application of the computational route to a given problem. For the qualification of HORUS3D/N, however, it is not possible to use the existing extensive qualification database: as it is focused on UOX and MOX fuels, it lacks representativity with regard to the specific neutronics particularities of the JHR core and its fuel:

- an enrichment close to 20%, compared to 3–5% in common LWR applications,
- the presence of the resonant absorber Molybdenum and its potential interaction with the resonances of the Uranium isotopes (Figure 1),
- a particularly high moderator / fuel volume ratio (JHR: 4.2, PWR ≈ 1.4).

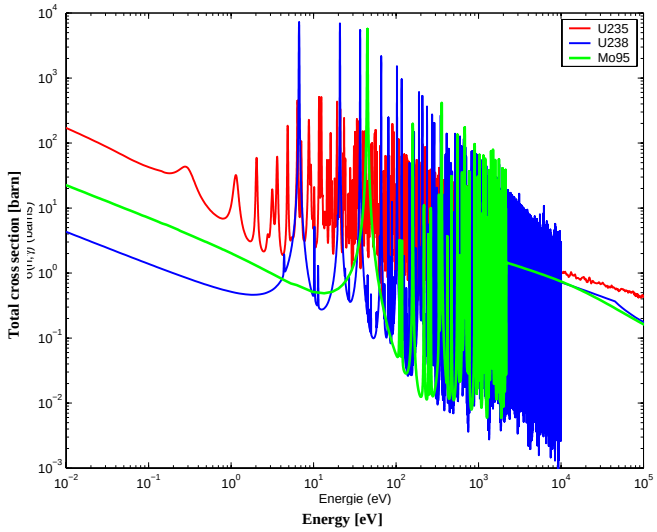

Figure 1: Total neutronics cross sections of ^{235}U (red), ^{238}U (blue) and ^{95}Mo (green)

Furthermore, the statistical evaluation of the uncertainty of the calculated begin-of-life (BOL) reactivity, based on the propagation of the basic nuclear data uncertainties, identified the fuels' Uranium component as critical element (cf. §2.2).

The VALMONT (Validation of Aluminum/Molybdenum/Uranium fuel for Neutronics) programme addressed these needs for representative experimental data with high precision measurements in the MINERVE facility. The programme comprised reactivity effect and γ-spectroscopic measurements on samples and a test rod with the JHR's UMo/Al fuel.

This paper presents the motivation and the background of the VALMONT programme, the experimental techniques employed and the results obtained, and explains the methodology used to transpose the experimental results to the reactor case.

2. Background

2.1. Description of the Jules Horowitz Reactor

The Jules Horowitz Reactor (JHR) is CEA's future reactor for technological irradiations and will be the centerpiece of the future European Fission Platform. Currently in the phase of final definition, it is going to be located in Cadarache (France) and is foreseen to reach first criticality by 2013.

The JHR core will develop a thermal power of about 100 MW and will be cooled and moderated by light water. The preliminary core design (Figure 2) consists of 46 assemblies, arranged in a hexagonal lattice inside a rectangular aluminum matrix with a size of about 70 cm by 70 cm. The fuel assemblies consist of 3 x 6 cylindrical fuel plates, maintained by 3 Aluminum stiffeners (Figure 3).

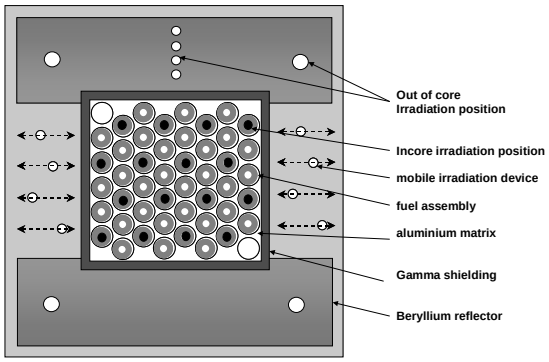

Figure 2 : Cross-section of the JHR core

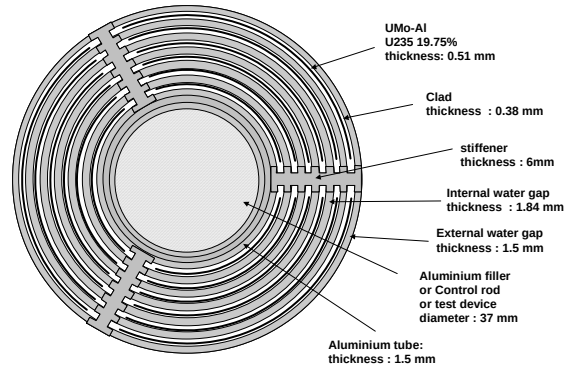

Figure 3: Cross-section of the JHR fuel assembly

The external diameter of the assembly is about 8 cm for an active height of 60 cm. The fuel plates are composed of the UMo7/Al–meat (with an ^{235}U enrichment of less than 20%) and AlFeNi cladding. The central cavity of the assembly can host either an Aluminum filler, a Hafnium control rod or an irradiation test device. Special test devices can take the place of an entire fuel element. The core is bordered on two sides by a Beryllium reflector, which contains out-of-core irradiation device positions. Mobile irradiation devices can approach the core in the water reflector on the remaining two sides.

2.2. Propagation of uncertainties

In order to estimate the uncertainties of the HORUS3D/N results, due to the uncertainties of the basic nuclear data, the propagation of these uncertainties was analyzed. This propagation methodology is based on the linear Law of Error Propagation, which assumes a linear relationship between the basic uncertainty σ_x of a nuclear parameter (i.e. on the cross section of a nuclear reaction *x,* such as absorption, fission, …) and the resulting uncertainty $R_{R,f}$ of a global, calculated parameter *f* (e.g. the reactivity) of the reactor. In multi-energy group representation, the basic uncertainty σ_x takes the form of an variance-covariance matrix and the relationship can be expressed as

$$R_{R,f}^2 = \sum_j \sum_k \left.\frac{\partial f}{\partial x_j}\right|_{<x>} < \sigma_{x,jk}^2 > \left.\frac{\partial f}{\partial x_k}\right|_{<x>} ,$$

with *j, k* as group indices and $\partial f/\partial x$ as sensitivity coefficients of parameter *f* with regard to the reaction *x*. The resulting uncertainties for all nuclei and all reactions are summed up to give the propagated uncertainty of the global parameter:

$$R_{R,f}^2 = \sum_x \left\langle S_x^T \, \underline{\sigma_x^2} \, S_x \right\rangle , \qquad \text{(Eq. 1)}$$

with *S* being the sensitivity vector. The sensitivity coefficients can be obtained by direct calculations or by Standard Perturbation Theory, which is implemented in the neutronics codes.

Ideally, the variance-covariance matrices σ_x are furnished by the evaluator of the nuclear data, as they reflect the experimental uncertainties in the measurement of these data.

During the analysis of the HORUS3D/N propagated uncertainty, however, important uncertainty data turned out to be missing in the JEF-2.2 library and had to be reconstructed with a new methodology [4], based on the comparison of different evaluations.
Concerning the reactivity at begin of life (BOL), the propagation analysis concluded at an uncertainty of 1 700 pcm (2σ), with the sole uncertainty on the ^{235}U cross-sections contributing as much as 1 200 pcm (2σ). The subsequent most important contributing elements were identified as ^{27}Al (the Aluminum components account to 45% of the core volume), light water and Beryllium.

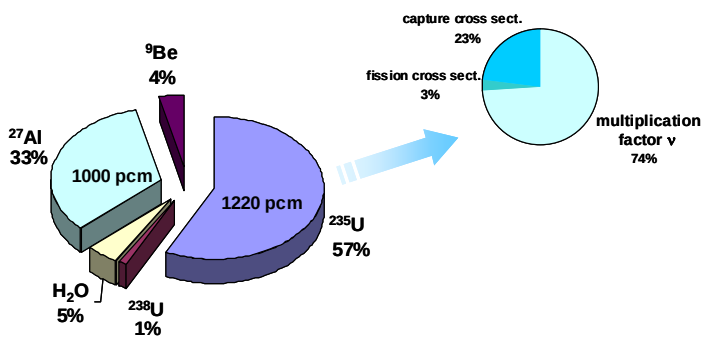

Figure 4: Major contributions to the total propagated uncertainty of the BOL reactivity due to uncertainties of the basic nuclear data (percentages correspond to the fraction of the total variance); the ^{235}U uncertainties (cf. inset) are dominated by the multiplication factor, due to its importance (high sensitivity factor)

To reach the goal of a BOL-reactivity uncertainty of less than 1000 pcm (2σ), as required by the reactor design team, specific experimental measurements were hence needed to reduce the statistical uncertainty.

3. The VALMONT Programme

The basic principle of the VALMONT programme consists in the direct and precise measurement of the reactivity effect of fuel samples, using the MINERVE reactor's oscillation method (see below). In order to differentiate the physical effects of the fuel components and their concentrations, a sequence of 5 samples was devised (Table 1).

Sample	*Caracteristics*
"APur"	neutral Al_2O_3 sample, serving for the normalization of the sequence
"UappAl"	UAl_x sample with depleted Uranium at low density (2.2 gU/cm^3), to asses the effect of the ^{238}U
"UAl20"	UAl_x sample with 20%-enriched Uranium at low density, to measure the effect of enrichment
"UMo/Al 2.2"	UMo/Al sample with 20%-enriched Uranium at low density, to analyze the effect of the Molybdenum component
"UMo/Al 8"	reference JHR-fuel, with 20%-enriched Uranium at high density (8 g/cm^3), to evaluate the effect of the Uranium density

Table 1: Samples of the VALMONT oscillation programme sequence

This sequence was completed by a sample with natural Molybdenum in an Al_2O_3 matrix ("AMo"), to verify the correct treatment of the different resonant Mo-isotopes.

The samples, with a length of 10 cm and a diameter of 8 mm, consisted of circular, compacted pellets in a Zircaloy cladding. An annular form was adapted to the UMo/Al fuel samples (Figure 5), in order to limit their reactivity worth and to achieve the required fuel/moderator ratio and, thereby, spectral representativity. The samples were fabricated by CERCA (Romans), where particular attention was paid to the geometrical and isotopic characterization.

Figure 5: Cylindrical (UAl_x) and annular (UMo/Al) fuel pellets of the oscillation programme

The oscillation programme was supplemented by γ-spectroscopic measurements on a test rod, composed of annular UMo/Al pellets and irradiated in the center of the MINERVE reactor. These measurements included the determination of the modified conversion rate, which is defined as the ratio of capture in ^{238}U to total fission rate. This factor allows to verify the treatment of the self-shielding problem.

The results of the measurements are presented after a brief description of the MINERVE reactor and the oscillation technique.

4. The MINERVE Reactor

The experimental MINERVE reactor is a pool type reactor operating at a maximum power of 100 watts. MINERVE is dedicated to neutronics studies of different reactor types by means of high-precision measurements of the reactivity effects of small fuel or absorber samples.

MINERVE's core (Figure 6) is composed of a driver zone, consisting of HEU plate-type MTR elements and surrounded by a graphite reflector, and a central cavity which houses the experimental zone with a lattice of fuel rods. The use of different lattices allows to simulate the neutronics conditions of a large range of reactors, spanning from PWRs (UOX and MOX) to FBRs. For the VALMONT programme, the "R1-UO2" lattice, consisting of UO_2 rods with an ^{235}U-enrichment of 3% was used.

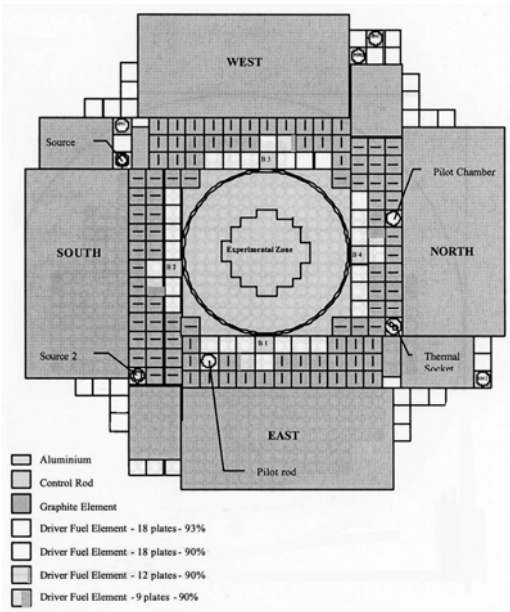

Figure 6: Cross section of the MINERVE reactor

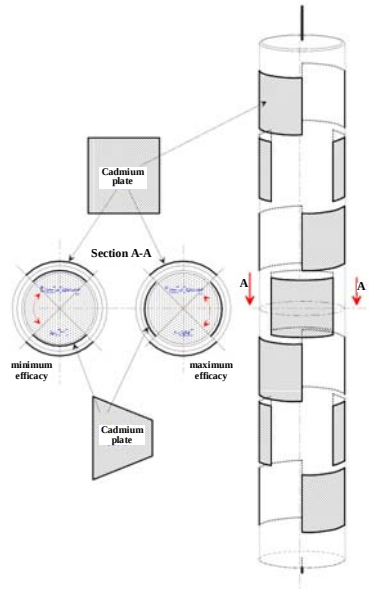

Figure 7: Scheme of the MINERVE rotary absorber

The experimental technique consists in placing alternatively different samples in the center of the core in order to measure the associated reactivity variation. Therefore, the center of the lattice is occupied by the rod-like oscillation device, which permits to place alternatively two different samples in the mid-plane of the reactor. One of these samples is the reference sample, placed in the bottom of the oscillation rod, while the other with the material to be measured is charged in the upper part of the rod.

During the measurement, the oscillation rod moves periodically between an upper and a lower position. A Boron chamber placed in the driver zone, called pilot chamber, detects the small variation of the reactor power induced by the oscillation of the samples. This pilot chamber commands a rotary absorber in such a manner as to compensate the reactivity variation and to maintain criticality. The rotary absorber, called "pilot absorber", consists of two concentric cylinders with overlapping Cadmium sectors (Figure 7). The rotation of the inner cylinder exposes or hides a variable Cd surface area. The shape of the Cd sectors has been chosen in such a way as to assure a constant differential efficiency with regard to the rotation angle of the absorber. The determination of the rotation angle of the absorber hence permits a measurement of the reactivity effect, with an accuracy of about 3% (1σ). The linear range of the rotary absorber is yet relatively small (about ±10 pcm), what limits the maximum reactivity worth of the sample to be analyzed. For each sample, five measurements are performed, each measurement consisting of 20 oscillation cycles with a period of 2 minutes.

As explained above, the reactivity effect is measured in terms of absorber rotation angle (or "pilot units") and is therefore not directly comparable with the results of the neutronics calculations (expressed in pcm or "calculation units"). The normalization is achieved by measuring a series of special, very well characterized samples, representing a very precise variation of a single neutronics parameter, which is supposed to be calculated perfectly. In the case of the VALMONT programme, a series of 7 UO_2 samples with enrichments from

0.72% to 4.9% was used. Figure 8 plots the measured reactivity effect (ordinate) against the calculated reactivity effect (abscissa). The slope of the regression line corresponds to the factor to be used to convert the pilot units to calculation units.

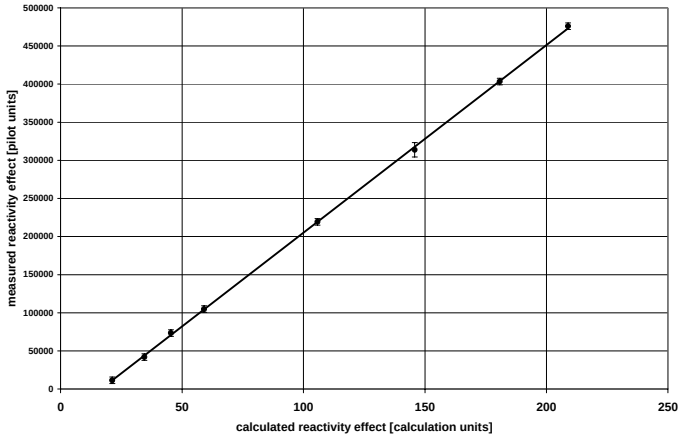

Figure 8: Normalization of the absorber rotation angle (measured in "pilot units", ordinate) with regard to the calculated reactivity effect (in "calculation units", abscissa); error bars correspond to 2σ measurement accuracy.

5. Experimental Results

Figure 9 shows the results of the experimental measurements of the VALMONT samples by plotting the measured reactivity effects (ordinate, converted to calculation units) against the calculated values (abscissa). The y-error bars correspond to the measurement accuracy (2σ); the calculation uncertainties (x-error bars), which are due to uncertainties in the material balance of the samples, are to small to be visible. The plot is normalized on the signal of the inert Al_2O_3 ("APur") sample.

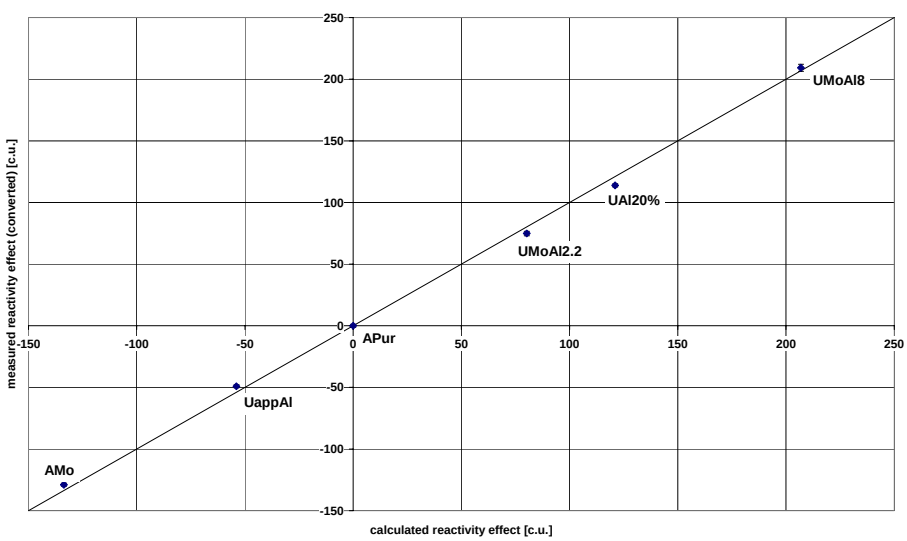

Figure 9: Calculated (abscissa) vs. measured (ordinate) reactivity effects of the VALMONT samples; error bars correspond to 2σ measurement accuracy.

Besides the excellent over-all agreement between measurement and calculation, illustrated by the closely confined scattering of the points around the diagonal, the detailed analysis leads to several comments:

- The absorbing effect of the "AMo" natural Molybdenum sample is calculated with a deviation of only 3.7% (measurement precision: 1.9% at 2σ). This very good result is due to the utilization of a cross-section library, which includes a synthetic "natural" Molybdenum isotope and therefore enables to take into account with high precision the self-shielding interactions of the different natural isotopes.
- The deviations of the different VALMONT fuel samples are depicted in detail in Table 2, along with the experimental uncertainties. One remarks a change of sign in passing from the depleted UO_2 sample (UappAl) to the 20%-enriched UAl_x sample (U20%Al) and from the low- to the high-density UMo/Al samples (UMo/Al2.2 and UMo/Al8); these deviations, however small, are thought to be linked to approximations in the self-shielding calculation scheme. Further analysis is currently being performed.
- The deviations of the UAl_x and UMo/Al fuel samples with the same Uranium loading of 2.2 g/cm^3 are identical within the measurement precision; this testifies that the effect of the Molybdenum is correctly taken into account in the neutronics calculations.
- The deviation experiment-calculation of the RJH reference fuel sample ("UMo/Al8") amounts to 2.4 c.u. and is thereby within the experimental uncertainty of 2.8 c.u. (2σ). From a qualitative point of view, this result marks the qualification of the neutronics route for this fuel.

Sample	*^{235}U-Enrichment [% mass]*	*U density [g/cm^3]*	*Deviation C – M [c.u.]*	*Experimental Uncertainty (2σ) [c.u.]*
"UappAl"	0.47	2.2	– 4.8	± 0.9
"UAl20%"	19.8	2.2	+ 7.2	± 0.9
"UMo/Al 2.2"	19.8	2.2	+ 5.4	± 1.6
"UMo/Al 8"	19.8	8.0	– 2.4	± 2.8

Table 2: Deviation (calculated effect – measured effect) of the four fuel samples of the VALMONT programme

Concerning the γ-spectroscopic measurements, the analysis of the conversion factor is the most informative. A total of three rods were analyzed in the VALMONT programme: the UMo/Al test rod (V), the driver-lattice rod next to the test rod (U0) and another one farther away (U1), supposed to be representative for the unperturbed, homogenous lattice. The results, listed in Table 3, show the usual over-estimation of about 2% for the lattice rods, even for the perturbed spectrum next to the test rod (U0). The deviation for the test rod is well within the measurement uncertainty, what evidences the absence of compensation phenomena with regard to the self-shielding.

Rod	*Measurement*	*Calculation result*	*Deviation (C – M)/M*
UMo/Al test rod	0.1056 ± 3.2%	0.1064	+ 0.7%
lattice rod U0	0.5197 ± 4.4%	0.5293	+ 1.8%
lattice rod U1	0.4985 ± 3.2%	0.5088	+2.1%

Table 3: Measurement and calculation results for the modified conversion factor (exp. uncertainties correspond to 2σ)

6. Transposition to the Reactor Case

The utility of the reactivity effect measurement can be extended beyond the qualitative assertion of qualification by the use of the *representativity method* as defined by ORLOV [5]. This method, which permits to extract a quantitative relationship between the experimental set-up and the reactor case, is based on the similarity of the sensitivity profiles of the experiment and the reactor case with regard to an integral response. The correlation coefficient of this relationship is called *representativity coefficient* r_{RE}, and is defined as:

$$r_{RE} = \frac{\sum_x \left\langle S_{R,x}^T \, \underline{\sigma_x^2} \, S_{E,x} \right\rangle}{\sqrt{\sum_x \left\langle S_{R,x}^T \, \underline{\sigma_x^2} \, S_{R,x} \right\rangle \cdot \left\langle S_{E,x}^T \, \underline{\sigma_x^2} \, S_{E,x} \right\rangle}} \quad , \qquad \text{(Eq. 2)}$$

with S_E as the sensitivity vector of the global parameter (ie. the reactivity) in the experimental set-up, S_R as the sensitivity vector in the reactor case and $\underline{\sigma_x^2}$ as the variance-covariance matrix of the basic nuclear data (cf. Eq. 1).

The numerator of Eq. 2 represents formally the covariance between the experiment and the reactor response to a given perturbation. That means, the higher r_{RE}, the higher is the transferability from the experiment to the reactor case, with a value of 1 in the case of perfect representativity. Considering the Uranium isotopes of the fuel, the r_{RE} coefficient of the VALMONT / RJH configuration amounts to 0.985, what indicates an excellent representativity.

The weighting with the uncertainty matrix $\underline{\sigma_x^2}$ of the nuclear data in the numerator of Eq. 2 allows furthermore a quantitative interpretation of the coefficient: as it compares the effect of the nuclear data uncertainty in the both systems, it enables us to reduce the propagated reactivity uncertainty of the reactor system on the base of the measurements in the experiment.

The propagated uncertainty of the reactor R_R (cf. Eq. 1) has its equivalence in the experiment, named R_E :

$$R_E^2 = \sum_x \left\langle S_{E,x}^T \, \underline{\sigma_x^2} \, S_{E,x} \right\rangle \quad .$$

With an experimental uncertainty σ_E, which represents the precision of the reactivity measurement in the experiment, the reduced reactor uncertainty $\widetilde{R}_R$ can be given as [5]:

$$\widetilde{R}_R^2 = R_R^2 \left(1 - \frac{r_{RE}^2}{1 + \sigma_E^2 / R_E^2} \right).$$

In the VALMONT experiment, the ratio of experimental precision σ_E to propagated uncertainty R_E amounts to $\sigma_E / R_E = 0.25$, what equals to a reduction of the propagated reactor uncertainty to $\widetilde{R}_R \, / \, R_R = 0.3$.

For the reactor case, the uncertainty due to the uncertainties of the basic nuclear data of the Uranium isotopes is hence reduced from 1300 pcm to 400 pcm. Taking into account the remaining uncertainty contributions (cf. Figure 4), the total BOL reactivity uncertainty is reduced to 1200 pcm, dominated now by the Aluminum (responsible for 69% of the total variance).

7. Conclusion and Outlook

The measurements of the VALMONT experimental programme, conducted in CEA's MINERVE reactor, successfully qualified the HORUS3D/N neutronics route for the calculation of the RJH UMo/Al fuel. It allowed furthermore to reduce the uncertainty in the begin-of-life reactivity uncertainty, due to uncertainties in the basic nuclear data of the Uranium isotopes, by a factor of about 3.

Further γ-spectroscopic measurements are being undertaken to investigate the minor deviations observed in the experimental sequence. To this end, the γ-spectroscopic equipment will be fitted to measure directly the samples concerned. Concerning the reduction of the total reactivity uncertainty, the focus shifts now to the Aluminum, were recent re-evaluations of the nuclear data promise to reduce significantly the uncertainties.

The results of the VALMONT programme will be used in the first part of the nuclear licensing procedure of the JHR. The second part of the dedicated experimental programme, named AMMON, is a partial mock-up of the JHR's core, consisting of an array of seven JHR fuel assemblies within a driver core lattice. It is currently in the feasibility study phase and scheduled to take place in the Cadarache-located EOLE reactor in 2008.

8. References

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