NUCLEAR DATA UNCERTAINTY PROPAGATION ON THE JULES HOROWITZ REACTOR NEUTRONIC PARAMETERS

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ABSTRACT

It is crucial for the design studies of the future experimental Jules Horowitz Reactor (JHR) to get an estimate of the uncertainty on main neutronic parameters. Unfortunately, most of covariance information is still missing in the recent evaluated files such as JEF2.2. In order to generate missing covariance matrices, crude method based on the comparison of different independant evaluations was used in this work. A special attention was paid to the determination of sensitivity coefficients using perturbation methods and direct calculations. The initial reactivity uncertainty arising from the nuclear data reaches 900 pcm (1σ). This study points out the importance of the non-diagonal elements of the covariance matrices. The analysis of heavy nuclides and fission products nuclear data (cross-section, multiplicity and fission yields) leads to a cycle length uncertainty of about 3 equivalent full power days (efpd) for a cycle length of 21 efpd. Concerning the integral efficiency of the Hafnium control rod, an uncertainty of 3.4 % is deduced.

1 INTRODUCTION

Part of the uncertainty in a computed value of a nuclear system parameter (eigenvalue, power distribution) comes from the uncertainties associated with the differential nuclear data used in the calculation. During design studies performed for the new experimental Jules Horowitz Reactor (JHR) [1], where all required relevant integral experiment are not availables, an accurate assessment of uncertainties is required in order to avoid large and expensive design margins. Unfortunately, an overview of the available covariance data tabulated in the JEF-2.2 library, which is used in this study, shows that important uncertainty data are missing. Besides, due to time calculation, it is not possible to perform a complete deterministic three dimensional perturbation calculation and a spatial homogeneization and a group collapsing is needed. Straightforward 3D calculations [3] or simplified 2D modeling using perturbation theory [2] were used to get the sensitivity coefficients of the integral parameters to the microscopic nuclear data.
A methodology has been developed on the one hand to obtain covariance data for the reactions and isotopes involved in the JHR neutronic calculations and on the other hand to calculate sensitivity coefficients for initial reactivity, cycle length and control rod integral efficiency. Covariance data and sensitivity coefficients are then combined using the linear Law of Error Propagation.

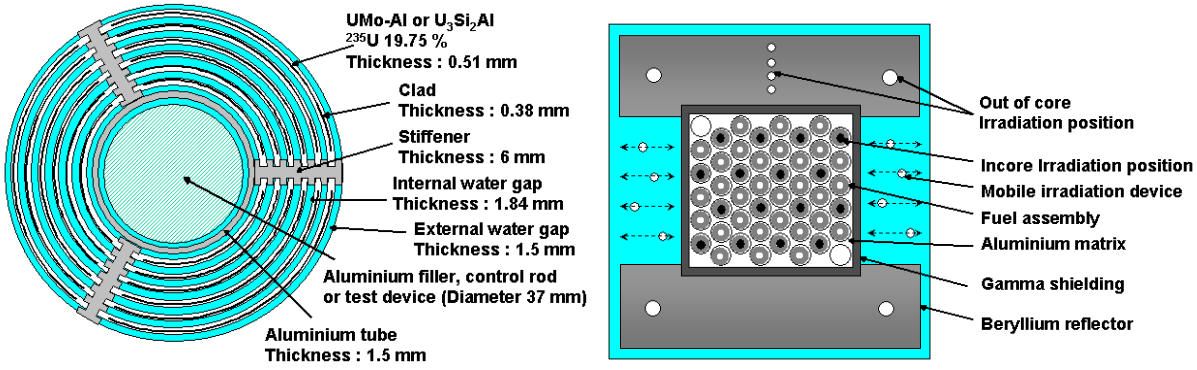

Figure 1: Schematic view of the JHR core

2 JHR DESCRIPTION

The JHR assembly is composed of 3x6 cylindrical fuel plates maintained by 3 stiffeners (see Figure 1). The external diameter of the assembly is close to 8 cm with an active height of 60 cm. The fuel is composed of UMo or U_3Si_2 powder in an aluminium matrix. The uranium-235 enrichment, less than 20 %, respects the non proliferation agreement. The central hole can host either aluminium fillers, hafnium control rods or irradiation test devices.
The core contains 46 assemblies in a triangular lattice, inside a rectangular aluminium matrix with a beryllium reflector on two faces (Figure 1).

3 COVARIANCE MATRIX GENERATION

3.1 JEF-2.2 COVARIANCE DATA

Covariance data from JEF-2.2 are processed through the ERRORR module of the NJOY (97.114) code [4]. The uncertainty data for ^{1}H (σ_s,σ_γ) ; ^{9}Be (σ_s,σ_γ) ; ^{58}Ni (σ_s,σ_γ) ; ^{235}U $(\sigma_f,\sigma_\gamma,\bar{\nu})$ involved in the JHR studies are present in JEF-2.2. Covariance data for ^{238}U in JEF-2.2 are given in the energy range [100 keV - 309 keV] which is unfortunately not interesting for the JHR thermal spectrum. Covariance data are also missing for several isotopes such as molybdenium and hafnium, respectively used in the fuel and for the control rods.
For instance, covariance data for the ^{235}U fission cross sections, processed in the 15 energy mesh structure [5], are shown Figure 2. The analysis of this matrix leads to several comments : in JEF-2.2, the uncertainty is fully correlated in the energy range [10^{-5} eV $-$ 0.625 eV]. Correlations between thermal and epithermal ranges are about 30 %. These correlations originate in the systematic errors on the normalization and background corrections of the experimental data. Moreover, one eigenvalue of this covariance matrix is negative : the matrix is non positive definite. The non positive definiteness disappears when a broader energy groups scheme (eg. 6 instead of 15) is used.
The only rigorous way to provide such information for the missing isotopes (or reactions) is to generate simultaneously the covariance data and the evaluated microscopic nuclear data [6]. However, rather crude methods have already been developped in the past to get rough estimates of cross-section uncertainties.

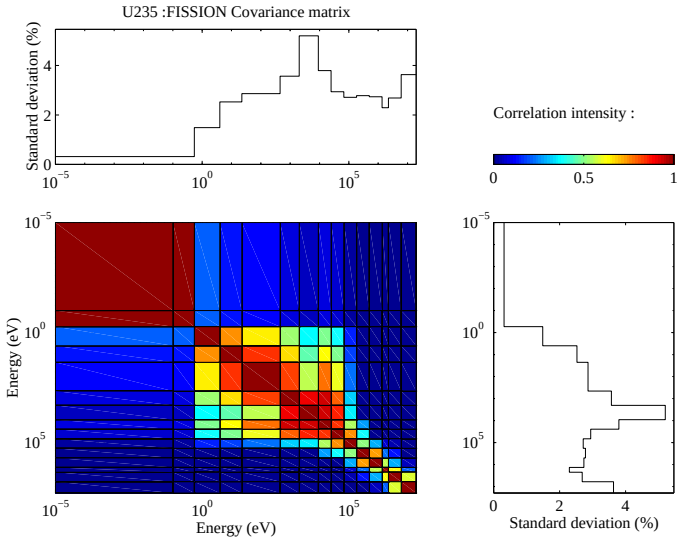

Figure 2: Covariance data for ^{235}U fission cross sections from JEF-2.2

3.2 QUALITATIVE METHODS

This method is based on the simple idea which considers the covariance information as a measurement of the confidence degree in a particular evaluation with respect to the others. Standard errors are calculated with the unbiaised variance estimator, under the assumption that different evaluations consist in a set of independent measurements. This assumption is obviously not always true because evaluations are often built from a common experimental database. However, standards errors obtained with this method are close to those given by the evaluation files and can be considered as an estimation of the missing isotopes uncertainty. In this work, correlation matrices are similar to those given by Reference [7] which considers simple models for the short, medium and long range energetic correlations. Correlations between partial cross-section and isotopes are not taken into account.
To obtain a covariance matrix for the ^{235}U fission spectrum, the simplified Madland-Nix model with a constant inverse compound cross section is used [8] for thermal neutron incident. Uncertainties of the three parameters (average kinetic energy per nucleon of the light - heavy - fragments EFL - EFH - and maximum nuclear temperature T_m), taken from the Reference [9], allow to construct the 15 energy groups covariance matrix. For example,in the important energy range [1 MeV - 2 MeV], an uncertainty of 4 % is deduced from this method. Because of the normalization constraint, the 15 groups correlation matrix consists in two regions fully uncorrelated. Within these two regions, the correlations are close to one.
Concerning the fission yields, uncertainty information is taken from the JEF2.2 library.

4 DETERMINATION OF SENSITIVITY COEFFICIENTS

Sensitivity coefficients are obtained from a two dimensional assembly calculation route, using either the Standard Perturbation Theory implemented in APOLLO2 or direct calculations :

- An assembly calculation is performed to get the uncertainty on the initial reactivity. The direct and adjoint neutron flux is calculated using the 172 XMAS energy-group library based on JEF-2.2 and an accurate space dependent self-shielding formalism, as well as

the collision probability method (P_{ij}) applied on the exact geometry (1/6 of an assembly, designed with the French graphical interface Silene [10]). Furthermore, the sensitivity coefficients accuracy is checked with (direct) three-dimensional deterministic calculations using the CRONOS2 transport code.

- Direct depletion calculations with the above computational options are performed on the assembly to provide the uncertainty on the cycle length. Uncertainties on the fission and the capture cross sections of the major heavy nuclei as well as on the capture cross sections and on the major FPs fission yields are taken into account.
- The core reactivity control is ensured by a system of Hafnium absorbers rods located in the center of several assemblies. The integral efficiency uncertainty is calculated from a model which considers an assembly with a control rod, surrounded by assemblies without control rods (see Figure 3). The integral efficiency sensitivity requires a set of two sensitivity coefficients respectively with and without the control rod (EGPT [11]).

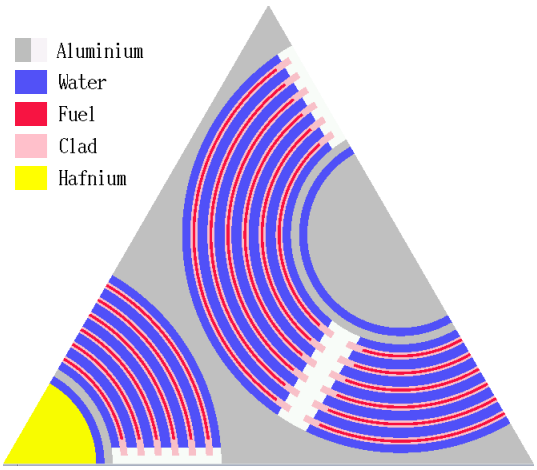

Figure 3: Geometry (1/6) of a control rod assembly next to a standard assembly

5 RESULTS AND ANALYSIS

5.1 INITIAL REACTIVITY UNCERTAINTY

Concerning the initial reactivity, as seen in Table 1, the total uncertainty reaches 876 pcm (1σ). The analysis of these results leads to several comments :

- Neglecting correlations in cross-section covariance matrices can produce a significant underestimation of the final uncertainty (about 20 %).
- In the JHR case, the 3D calculation of the sensitivity coefficients gives a larger uncertainty (26 %) than the assembly calculation approach and is recommended. Nevertheless, it is shown (see Table 1) that the assembly calculation is accurate enough to provide the correct uncertainty for the heavy nuclei (1 %).
- A strong part of the final uncertainty stems from the ^{235}U prompt neutron multiplicity. Whereas the standards [12] give an optimistic uncertainty of 0.14 % in the thermal range, the uncertainty given in JEF2.2 and used in this work is probably more realistic : 0.7 %.

- ^{27}Al cross sections are also responsible for a large part of the initial reactivity uncertainty. About 50 % of the JHR core is made up of aluminium, hence sensitivity coefficients are relatively high in particular for the thermal (< 0.625 eV) capture cross section and for the fast (> 5 keV) scattering cross section. The ^{27}Al uncertainty were deduced from the comparison of different databases, which has pointed out a significant underestimation of the ^{27}Al thermal capture in JEF-2.2 of about 10 %, corrected in the new JEFF-3.0 evaluation. With the more realistic uncertainty of 1 % on the thermal capture, results for initial reactivity are given in Table 1.
- The uncertainty of the ^{235}U neutron fission spectrum does not produce significant uncertainty on reactivity because of the non-diagonal terms of the associated covariance matrix.

		Assembly		Core
		without correlations	with correlations	3D Diffusion
^{235}U	ν	505	544	568
	σ_f	88	113	118
	σ_c	213	346	319
TOTAL		555	655	662
^{238}U	ν	4	4	3
	σ_f	5	5	22
	σ_c	68	95	90
TOTAL		68	95	93
H_2O	σ_c	26	31	49
	σ_s	106	140	185
TOTAL		109	143	191
^{27}Al	σ_c	127	235	216
	σ_s	55	73	457
TOTAL		138	246	505
^{9}Be TOTAL		not present	not present	168
TOTAL		586	720	876

Table 1: Initial reactivity uncertainty in pcm (1 σ) in the JHR core

To illustrate these uncertainty results, 3D heterogeneous, continuous-energy, Monte Carlo (TRIPOLI4 code [13]) calculations of the JHR core with two neutron cross sections libraries (JEF-2.2 versus ENDF/B-VI.2) were performed. This accurate modeling without geometrical approximations (Figure 4) shows a large discrepancy between the two libraries on the initial reactivity calculation (about 1100 pcm), explained partly by differences in the ^{235}U (about 400 pcm) and ^{27}Al (about 860 pcm) cross sections.

5.2 CYCLE LENGTH UNCERTAINTY

For light nuclei (H_2O, ^{27}Al and ^{9}Be), we assume that the neutron spectral change due to the nuclides concentration modification does not change significantly the uncertainty obtained for the initial reactivity (namely 565 pcm at 1σ with 3D diffusion calculations - see Table 2).

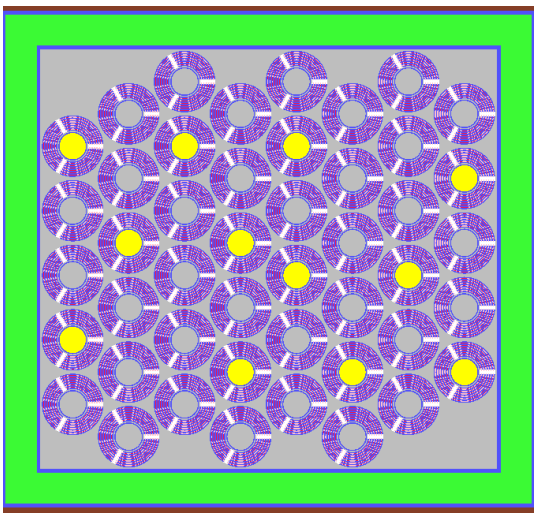

Figure 4: TRIPOLI4 Monte Carlo modeling of the JHR core

As assembly calculations give correct uncertainty results for the heavy nuclei, direct assembly depletion calculations to assess the uncertainty of the cycle length were performed. The nuclear data uncertainties involved were fission and capture cross sections of the major heavy nuclei as well as capture cross sections and fission yields of the major fission products (we have chosen to select 22 fission products that are responsible for 95 % of the FPs capture at the end of the cycle).

	Uncertainty
Heavy nuclei	655
Fission products	104
Light nuclei	565
TOTAL	871

Table 2: Reactivity uncertainty in pcm (1 σ) in the JHR core at the cycle end

For most of the fission products, the capture cross section uncertainties has a small influence on reactivity uncertainty : the increase of a FP capture decreases its concentration, so that its absorption rate remains constant. For example, xenon poisoning :

- depends not on the ^{135}Xe capture cross section for high flux levels ($> 10^{14}$ n/cm^2/s), within the assumption of keeping the power constant during the depletion ;
- depends on the cumulative fission yield of ^{135}I and on the independant fission yield of ^{135}Xe.

The final uncertainty on the cycle end reactivity is close to the initial reactivity uncertainty : 871 pcm (1σ), corresponding to about 3 efpd for a cycle length of 21 efpd.

5.3 ABSORBER INTEGRAL EFFICIENCY

The uncertainty of the absorber integral efficiency is 3.4 %. The uncertainty of ^{177}Hf capture cross section in the resolved range [0.625 eV - 454 eV], given by the qualitative method, is about 6 % and is mainly responsible for this result. The absorber integral efficiency uncertainty is coherent with the systematic overestimation observed by the analysis of slab integral experiments [14].

6 CONCLUSION

The design studies of the future experimental JHR reactor require the estimation of the main neutronic parameter uncertainties. In complement to JEF-2.2 covariance data, a qualitative method, based on the scatter of the cross-section between different evaluations, is used in this study to generate missing covariance information. This systematic method allowed to detect some discrepancies in the nuclear data bases as, for instance, the aluminium cross sections.
For the JHR, the uncertainties of nuclear data lead to a total reactivity uncertainty of about 900 pcm (1σ). This is larger than the uncertainty usually obtained in classic french PWR studies and is partly due to the great amount of aluminium present in the JHR. Concerning the cycle length, the nuclear data are responsible for an uncertainty of about 15 % (1σ).
The qualitative method used to asses nuclear data uncertainties produces rather large uncertainties and points out the importance of the non diagonal elements of the covariance matrices. A significant reduction of the integral parameters uncertainties might be achieved by rigorously generating accurate covariance matrices during the evaluation process. It is emphasized that there still is a strong requirement to have reliable uncertainty and covariance information available in the evaluated files.
In complement to uncertainty studies, it is still necessary to obtain integral experimental validation of the JHR neutronic parameters calculations.

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