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Nuclear Data Impact on ADS Design

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Outline

- Background
- Theory for calculating uncertainties related to nuclear data
- Application to a large system of ATW type
- Application to an experimental simulation: MUSE-3 Program
- Conclusions

Background

The concept of a subcritical system driven by an external source of neutrons provided by an accelerator ADS (Accelerator Driven System) has become the object of active programs in Europe, Russia, Japan, and U.S.A.

A general consensus has been reached in adopting for the subcritical component a fast spectrum liquid metal cooled configuration. Both a lead-bismuth eutectic, sodium and gas are being considered as a coolant; each has advantages and disadvantages.

In the ADS the major expected advantage is that the subcriticality avoids reactivity induced transients. The potentially large subcriticality margin also should allow for the introduction of very significant quantities of waste (Minor Actinides and Fission Products) which negatively impact the safety characteristics of standard cores (e. g. β_{eff} and Doppler effect)

Background

In the U.S.A. these are arguments are the basis for the development of the Accelerator Transmutation of Waste (ATW), which has significant potential in reducing nuclear waste levels. Today ATW is part of the more comprehensive AAA (Advanced Accelerator Application) program.

In general neutronic calculations for ADS design do not attach uncertainties on the values of the main nuclear integral parameters that characterize the system. Many of these parameters (e. g. degree of subcriticality) are crucial to demonstrate the validity and feasibility of this concept.

The object of this lecture is to present a methodology and its application that allows to quantify the impact of the nuclear data in terms of uncertainties on the main neutronic design parameters of an ADS.

Background

The present knowledge of the cross sections of many isotopes that are not usually utilized in existing reactors (e. g. Bi, Pb, and also Minor Actinides and Fission Products) indicates that uncertainties in the integral parameters can be significantly larger than for conventional reactor systems, and this raises concerns on the neutronic performances of those systems.

As an example, the multiplication factor in many designs of subcritical systems are envisioned to be around 0.98 because of the need to massively multiply the spallation source. If uncertainties on cross sections lead to a significant variation of this value, a modification in the planned core layout or additional margin in the accelerator size will be required.

Background

Predictions of reactivity variations during operation are also crucial and significant uncertainty on this value is expected for a typical ADS, which can create problems on fuel inventory, safety issues, control requirements, and accelerator dimensioning.

The power distribution in such a system is quite different from that in the standard reactor situation because of the presence of the external source that tends to peak the power toward the source region. A partial flattening is obtained through inward shuffling of irradiated fuel and the use of lead,which also serve as reflector. Elevated uncertainty on this parameter can lead to power derating or overdimensioning of the accelerator.

In the following we will assess the effects of nuclear data uncertainties on an ADS performances and define the major contributors to these uncertainties.

Theory

In order to obtain uncertainties on ADS, first sensitivities coefficients for each integral parameter of interest have to be evaluated. If calculations were done by "brute force" variation, thousand of calculations would be necessary, because it is difficult to know "a priori" which cross section is more sensitive for the specific integral parameter.

For calculating the sensitivity coefficients we make use of the Classical Perturbation Theory (CPT), Generalized Perturbation Theory (GPT), and Equivalent Perturbation Theory (EGPT). This methodology is based on the use of a specific adjoint function that identifies the importance of neutrons with respect of the integral parameter of interest. CPT uses the adjoint importance of K_{eff}, GPT uses importance of linear or bilinear functionals of the direct and adjoint flux, and EGPT is used for reactivity coefficients.

Theory

Homogeneous and inhomogeneous Boltzmann equations:

$$A\Phi = \frac{F\Phi}{K_{eff}} \quad \textbf{(1)} \qquad A^*\Phi^* = \frac{F^*\Phi^*}{K_{eff}} \quad \textbf{(2)} \qquad A\Phi_s = F\Phi_s + S \quad \textbf{(3)}$$

Where in multigroup notation:

$$A_g = \Omega\Delta\psi_g + \sigma_t\psi_g - {}_{g}\,\sigma_{g\blacklozenge g'}\Phi_{g'} \qquad \textbf{(4)}$$

$$F_g = \chi_g \; {}_{g'}\, \nu\sigma_f^{g'}\Phi_{g'} \qquad \textbf{(5)}$$

Theory

and

$$\Phi = \quad \psi d\Omega \qquad (6)$$

The inhomogeneous multiplication factor is defined as:

$$k_S = \frac{\langle F\Phi_S \rangle}{\langle A\Phi_S \rangle} \qquad (7)$$

Theory

In a source driven system with a multiplication medium the neutr of the source are multiplied as:

$$S_m = \frac{S}{1-k_S} \qquad (8)$$

The inhomogeneous reactivity is defined as:

$$\rho_S = 1 - \frac{1}{k_s} = \frac{\langle F\Phi_S \rangle - \langle A\Phi_S \rangle}{\langle F\Phi_S \rangle} = -\frac{\langle S \rangle}{\langle F\Phi_S \rangle} \qquad (9)$$

Theory

Classical Perturbation Theory

We consider the perturbed equation:

$$A'\Phi' = \frac{F'\Phi'}{K'_{eff}} \qquad \textbf{(10)}$$

Multiplying Eq. (2) by Φ' and Eq. (10) by Φ* and then subtracting, we obtain:

$$\delta\rho = \frac{1}{k'} - \frac{1}{k} = \frac{\langle \Phi^*, (\delta A - \delta F)\Phi' \rangle}{\langle \Phi^*, \frac{1}{k'} F'\Phi' \rangle} \qquad \textbf{(11)}$$

For the first order approximation we consider $\Phi' \cong \Phi$

Theory

For an integral parameter:

$$I_S = \langle \sigma_f \Phi_S \rangle \qquad \textbf{(12)}$$

Sensitivity coefficients are calculated using GPT (Generalized Importance Theory). :

$$\frac{\sigma}{\langle \sigma_f \Phi_S \rangle} \frac{d\langle \sigma_f \Phi_S \rangle}{d\sigma} = \sigma \left[\frac{\left\langle \left(\frac{\partial \sigma_f}{\partial \sigma} \right) \Phi_S \right\rangle}{\langle \sigma_f \Phi_S \rangle} - \left\langle \tilde{\Psi}^*, \left(\frac{\partial A}{\partial \sigma} - \frac{\partial F}{\partial \sigma} \right) \Phi_S \right\rangle \right] \qquad \textbf{(13)}$$

Theory

The Generalized Importance Function Ψ* satisfies the equation:

$$\left(A^* - F^*\right)\widetilde{\Psi}^* = \frac{fI_S}{f\Phi_S} = \sigma_f(r,E) \qquad \textbf{(14)}$$

Using Eq. (3) and Eq. (14) we can establish the principle of conservation of importance:

$$I_S = \left\langle \sigma_f \Phi_S \right\rangle = \left\langle S\widetilde{\Psi}^* \right\rangle \qquad \textbf{(15)}$$

When a perturbation is made:

$$A'\Phi'_s = F'\Phi'_s + S \qquad \textbf{(16)}$$

Theory

We can calculate the variation of the integral parameter as:

$$\delta I_S = I'_S - I_S = \left\langle \tilde{\Psi}^*, (fA - fF)\Phi' \right\rangle \qquad \textbf{(17)}$$

In the case of a reaction rate ratio:

$$I_S = \frac{\left\langle \sigma_f \Phi_1 \right\rangle}{\left\langle \sigma_f \Phi_2 \right\rangle} \qquad \textbf{(18)}$$

The adjoint importance satisfies the following equation:

$$\left(A^* - F^*\right)\tilde{\Psi}^* = \frac{\sigma_f(r,E)}{\left\langle \sigma_f \Phi_1 \right\rangle} - \frac{\sigma_f(r,E)}{\left\langle \sigma_f \Phi_2 \right\rangle} \qquad \textbf{(19)}$$

Theory

The external source importance is defined as:

$$\varphi^* = \frac{\overline{s}^*}{\overline{\chi}^*} = \frac{\langle \Phi^*, S \rangle}{\langle S \rangle} \Big/ \frac{dr\,[\Phi^* \chi][\Sigma_f \Phi_S]}{\langle \Sigma_f \Phi_S \rangle} \qquad \textbf{(20)}$$

For the sensitivity analysis we introduce the function:

$$G = I_S - \langle \Psi^*, (A-F)\Phi_S - S \rangle - \langle \Psi, (A^* - \tfrac{1}{k}F^*)\Phi^* \rangle \qquad \textbf{(21)}$$

Requiring this function to be stationary with respect to the of Φ_s and Φ^* leads to the equations for the direct and adjoint variation importance functions:

Theory

$$\left(A^* - F^*\right)\tilde{\Psi}^* = \frac{1}{I_S}\frac{fI_S}{f\Phi_S} = -\frac{\left[\Phi^*\chi\right]\Sigma_f(r,E)}{dr\left[\Phi^*\chi\right]\left[\Sigma_f\Phi_S\right]} + \frac{\Sigma_f(r,E)}{\left\langle \Sigma_f\Phi_S\right\rangle}$$

$$\left(A - \tfrac{1}{k}F\right)\tilde{\Psi} = \frac{1}{I_S}\frac{fI_S}{f\Phi^*} = \frac{S(r,E)}{\left\langle \Phi^* S\right\rangle} - \frac{\left[\Sigma_f\Phi_S\right]\chi(r,E)}{dr\left[\Phi^*\chi\right]\left[\Sigma_f\Phi_S\right]} \qquad \textbf{(22)}$$

The sensitivity coefficients for the source importance are calculated as:

$$\frac{\sigma}{I_S}\frac{dI_S}{d\sigma} = \frac{\sigma}{I_S}\frac{fI_S}{f\sigma} - \left\langle \tilde{\Psi}^*, \left(\frac{fA}{f\sigma} - \frac{fF}{f\sigma}\right)\Phi_S - \frac{fS}{f\sigma}\right\rangle - \left\langle \tilde{\Psi}, \left(\frac{fA}{f\sigma} - \frac{1}{k}\frac{fF}{f\sigma}\right)\Phi^*\right\rangle ? \qquad \textbf{(23)}$$

Theory

The generalized importance for the inhomogeneous reactivity is calculated as:

$$\left(A^* - F^*\right)\tilde{\Psi}^* = \frac{1}{I_S}\frac{f I_S}{f \Phi_s} = -\frac{S(r,E)}{\Phi_s(r,E)\langle S\rangle} + \frac{\left[\nu\Sigma_f \Phi_S(r)\right]\chi(r,E)}{\Phi_s(r,E)\, F\Phi_s} \qquad \textbf{(24)}$$

Sensitivity coefficients are calculated as:

$$\frac{\sigma}{I_S}\frac{dI_S}{d\sigma} = \frac{\sigma}{I_S}\;\frac{\rho_s \quad f\nu\,\Sigma_f \Phi_s}{F\,\Phi_s} - \left\langle \tilde{\Psi}^*, \frac{fA}{f\sigma} - \frac{fF}{f\sigma}\sqrt{}\Phi_S \right\rangle ? ? \qquad \textbf{(25)}$$

Theory

For the Equivalent Generalized Perturbation Theory the integral parameter is defined as:

$$I_s = \frac{1}{k'} - \frac{1}{k} = \frac{\langle \Phi^*, (\text{f}A - \text{f}F)\Phi' \rangle}{\langle \Phi^*, \frac{1}{k'} F' \Phi' \rangle} \qquad \textbf{(26)}$$

Where $(\text{f}A - \text{f}F)$ **characterizes the reactivity coefficient and the sensitivity coefficients are calculated using the fact that changing the order of the derivatives does not change the results:**

$$\frac{\sigma}{I_s}\frac{dI_s}{d\sigma} = \frac{\langle \Phi'^*, (\text{f}A' - \text{f}F')\Phi' \rangle}{\langle \Phi'^*, \frac{1}{k'} F' \Phi' \rangle} - \frac{\langle \Phi^*, (\text{f}A - \text{f}F)\Phi \rangle}{\langle \Phi^*, \frac{1}{k} F \Phi \rangle} \qquad \textbf{(27)}$$

Theory

Once the sensitivity coefficient matrix *S* and the dispersion matrix *D* are available, the uncertainty on the integral parameter can be evaluated:

$$\Delta R_0^2 = S_R^+ D S_R \qquad (28)$$

The representativity factor:

$$r_{RE} = \frac{\left(S_R^+ D S_E\right)}{\left[\left(S_R^+ D S_R\right)\left(S_E^+ D S_E\right)\right]^{1/2}} \qquad (29)$$

allows to reduce the uncertainty by:

$$\Delta R_1^2 = \Delta R_0^2 (1 - r_{RE}^2) \qquad (30)$$

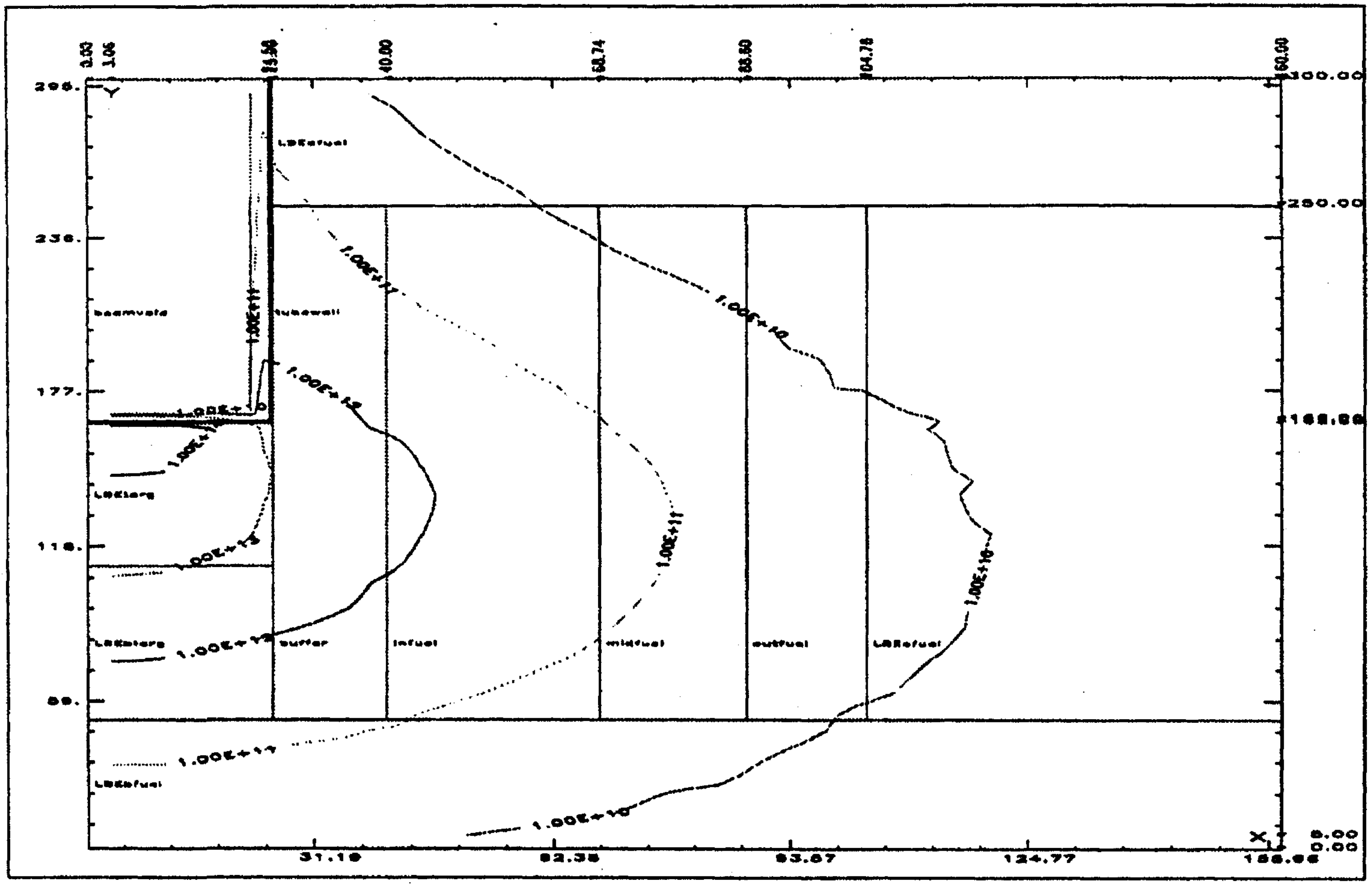
ATW model characteristics

- 2000 MWth Pb-Bi cooled system with three equivolume fuel zones (~1 meter radius over an height of 2 meters).
- 15 cm radius for accelerator beam and 40 cm for buffer.
- Volumetric fractions are: 25.7% fuel, 59.3% coolant, and 15% structure.
- The metal alloy fuel is composed of 70% Zr, 25% TRU (Pu dominated with significant amount of MA) and 5% of ^{99}Tc by weight.

ATW calculation characteristics

- The LCS system code was used to evaluate the neutron spallation source. Source values under the threshold energy of 20 MeV were stored and provided for the deterministic neutronic calculations
- JEF2.2 files and ECCO cell code were used to generate 33 group cross sections
- The ERANOS code system, and in particular the BISTRO S_n transport module was used to calculate neutron fluxes, importances, sensitivity coefficients and uncertainty values

ATW Model



G. Palmiotti "Nuclear Data Impact on ADS Design", ICTP Trieste, September 2001

ATW Uncertainty

Calculated integral parameters considered for the uncertainty analysis

Calculation Type	Parameter					
	K_{eff}	Max DPA[a)]	Peak Power	Φ^*	Loss of Coolant Reactivity[b)]	Burn-up Swing[c)]
Inhomogeneous	0.96056	99.1	1.67	1.05	0.578%	10.609%
Homogeneous	0.95859	-	-	-	0.666%	10.781%

[n)] Max DPA on the fuel regions for an irradiation time of 300 days of full power

[o)] Reactivity variation, expressed in terms of $\Delta k_{eff}/K_{eff}$, due to the loss of coolant in the fuel regions

[p)] Reactivity loss due to a cycle time of 100 days of full power.

ATW Uncertainty

Cross section variances (%) applied in the uncertainty analysis. Complete correlation applied over a six group energy structure.

Isotopes	σ_{cap}	σ_{frs}	ν	σ_{el}	σ_{inel}	$\sigma_{n,2n}$
U^{235}	10	4	1	5	20	-
U^{238}	5	8	1	5	15	30
Pu^{239}	10	4	1	5	20	-
Pu^{240}, Pu^{241}	20	10	5	5	40	-
Pu^{238}, Pu^{242} Np^{237}, Am^{247}, Am^{243}, Cm^{244}	40	30	5	5	50	-
Tc^{99}	20	-	-	20	50	-
Pb, Bi^{209}	20	-	-	20	40	100
Fe^{56}, Fe^{57}, Cr^{52}, Ni^{56}, Zr	20	-	-	10	15	-

ATW Uncertainty

Subcriticality Level

- The uncertainty results for the homogeneous and inhomogeneous reactivity are very similar. This is to be related to the fact that the two K_{eff} do not differ too much
- Total uncertainty is of the order of 2% and is about a factor two larger than values found for large size fat reactors
- The increase in the uncertainty is to be attributed to the Pb and Bi data, to the different isotopics of the transuranic element, and to the presence of a significant amount of ^{99}Tc

ATW Uncertainty

Uncertainty on inhomogeneous reactivity (%)

Isotope	σ_{cap}	σ_{fis}	ν	σ_{el}	σ_{inel}	$\sigma_{n,2n}$	Total
Pu^{239}	0.304	1.135	0.403	0.001	0.021	–	1.242
Pb	0.204	–	–	0.718	0.219	0.099	0.784
Bi^{209}	0.365	–	–	0.948	0.223	0.147	1.050
Tc^{99}	0.675	–	–	0.002	0.059	–	0.677
Pu^{240}	0.305	0.281	0.207	–	0.022	–	0.464
Pu^{241}	0.105	0.613	0.427	–	0.005	–	0.754
Np^{237}	0.336	0.090	0.034	–	0.006	–	0.350
Am^{241}	0.489	0.111	0.037	–	0.080	–	0.503
Zr	0.365	–	–	0.013	0.080	–	0.374
Total	1.176	1.339	0.627	1.191	0.342	0.177	2.267

ATW Uncertainty

Uncertainty on homogeneous reactivity (%)

Isotope	σ_{cap}	σ_{fis}	ν	σ_{el}	σ_{inel}	$\sigma_{n,2n}$	Total
Pu^{239}	0.302	1.140	0.405	0.001	0.021	-	1.247
Pb	0.200	-	-	0.762	0.211	0.098	0.822
Bi^{209}	0.357	-	-	1.001	0.220	0.147	1.095
Tc^{99}	0.670	-	-	0.002	0.060	-	0.672
Pu^{240}	0.304	0.287	0.211	-	0.023	-	0.469
Pu^{241}	0.105	0.614	0.428	-	0.005	-	0.756
Np^{237}	0.335	0.092	0.351	-	0.006	-	0.349
Am^{241}	0.488	0.114	0.387	-	0.006	-	0.502
Zr	0.361	-	-	0.013	0.083	-	0.371
Total	1.167	1.346	0.630	1.260	0.337	0.177	2.303

ATW Uncertainty

Power Peak

- The total uncertainty (~ 7%) is more than double of one used for typical large size fast reactors

Max DPA in Core

- A very large uncertainty is found for this parameter (~44%) . This is to be related to the uncertainty on the flux level via the sensitivity on K_{eff}
- The main contributions are coming from the fissile Pu isotopes and the coolant isotopes

ATW Uncertainty

Uncertainty on peak power (%)

Isotope	σ_{cap}	σ_{fis}	ν	σ_{el}	σ_{inel}	$\sigma_{n,2n}$	Total
Pu^{239}	1.01	3.64	1.31	–	0.07	–	4.00
Pb	0.61	–	–	2.04	0.87	0.31	2.32
Bi^{209}	1.03	–	–	2.81	0.84	0.47	3.14
Tc^{99}	2.19	–	–	–	0.21	–	2.20
Pu^{240}	1.02	0.90	0.68	–	0.08	–	1.52
Pu^{241}	0.36	1.96	1.39	–	0.02	–	2.43
Np^{237}	1.13	0.29	0.11	–	0.02	–	1.17
Am^{241}	1.65	0.36	0.12	–	0.02	–	1.69
Zr^{237}	1.18	–	–	0.27	0.28	–	1.24
Total	3.81	4.29	2.04	3.50	1.31	5.62	7.17

ATW Uncertainty

Uncertainty on max DPA in fuel regions (%)

Isotope	σ_{cap}	σ_{fis}	ν	σ_{el}	σ_{inel}	$\sigma_{n,2n}$	Total
Pu^{239}	6.0	21.9	7.8	-	0.5	-	24.0
Pb	4.1	-	-	13.6	5.9	2.0	15.5
Bi^{209}	7.2	-	-	18.1	6.4	3.0	20.7
Tc^{99}	13.3	-	-	-	1.4	-	13.4
Pu^{240}	6.0	5.4	4.0	-	0.5	-	9.0
Pu^{241}	2.1	11.8	8.3	-	0.1	-	14.6
Np^{237}	6.6	1.7	0.7	-	0.1	-	6.9
Am^{241}	9.7	2.1	0.7	-	0.1	-	9.9
Zr	7.2	-	-	0.2	2.0	-	7.4
Total	23.2	25.8	12.2	22.6	9.3	3.6	44.3

ATW Uncertainty

Source importance factor Φ^*

- A very low uncertainty (~1.7%) has been observed for this parameter. This indicates that Φ^* has very low sensitivity to basic data, and the main dependence will come from the spallation source spatial and energy distribution. Neutrons, after one mean free path "lose memory" of their origin and become assimilated to the standard fission neutrons. This is a consequence of the specific design adopted for this study. Changing the thickness of the buffer will have an impact on the uncertainty values for the source importance factor

ATW Uncertainty

Uncertainty on source importance (%)

Isotope	σ_{cap}	σ_{fis}	ν	σ_{el}	σ_{inel}	$\sigma_{n,2n}$	Total
Pu^{239}	0.14	0.33	0.11	-	-	-	0.38
Pb	0.17	-	-	0.84	0.42	0.04	0.96
Bi^{209}	0.29	-	-	1.03	0.44	0.05	1.16
Tc^{99}	0.33	-	-	-	0.02	-	0.33
Pu^{240}	0.13	0.07	0.05	-	-	-	0.15
Pu^{241}	0.03	0.21	0.16	-	-	-	0.25
Np^{237}	0.13	0.02	-	-	-	-	0.14
Am^{241}	0.17	0.06	0.01	-	-	-	0.18
Zr	0.19	-	-	0.04	0.03	-	0.20
Total	0.59	0.40	0.19	1.36	0.61	0.07	1.65

ATW Uncertainty

Reactivity Variation Due to a Loss of Coolant in the Fuel Region

- A large uncertainty (~220%) has been calculated for this parameter. This is due to the relative small reference value and the large sensitivity to Pb and Bi data that contributes to the total uncertainty also through the direct effects on this parameter

ATW Uncertainty

Uncertainty on loss of coolant

Isotope	σ_{cap}	σ_{fis}	ν	σ_{el}	σ_{inel}	$\sigma_{n,2n}$	Total
Pu^{239}	10.1	21.9	7.4	0.3	0.5	-	25.2
Pb	26.7	-	-	151.4	42.3	28.9	162.1
Bi^{209}	40.9	-	-	191.5	53.2	43.3	207.5
Tc^{99}	20.8	-	-	1.1	1.8	-	20.9
Pu^{240}	8.7	9.9	7.2	0.2	0.5	-	15.0
Pu^{241}	2.2	14.8	9.8	-	0.2	-	17.8
Np^{237}	9.3	3.2	1.2	-	0.2	-	9.9
Am^{241}	11.2	5.5	1.9	-	0.2	-	12.6
Zr	10.3	-	-	12.5	3.7	-	16.6
Total	58.0	29.3	14.5	244.5	68.2	52.1	267.6

ATW Uncertainty

Reactivity Loss Through Fuel Cycle

- Only about 3% of relative variation of this parameter (i. e. ~0.3% of absolute reactivity) has been calculated. This is mainly due to the fairly large reference value, that, consequently, results quite insensitive to cross section data. Also BOC (Beginning Of Cycle) and EOC (End Of Cycle) K_{eff} are presumably very correlated.
- In this study the uncertainty on isotope density variation due to the cross section dispersion matrix has not been included. This requires use of time dependent sensitivity theory

ATW Uncertainty

Uncertainty on reactivity loss through fuel cycle (%)

Isotope	σ_{cap}	σ_{fis}	ν	σ_{el}	σ_{inel}	$\sigma_{n,2n}$	Total
Pu^{239}	0.67	2.06	0.72	-	0.04	-	2.28
Pb	0.04	-	-	0.16	0.01	0.05	0.17
Bi^{209}	0.10	-	-	0.19	0.01	0.07	0.22
Tc^{99}	0.54	-	-	-	0.04	-	0.55
Pu^{240}	0.12	0.17	0.11	-	-	-	0.23
Pu^{241}	0.12	0.74	0.51	-	-	-	0.91
Np^{237}	0.56	0.09	0.04	-	-	-	0.57
Am^{241}	0.79	0.12	0.04	-	-	-	0.80
Zr	0.18	-	-	0.05	-	-	0.18
Total	1.33	2.26	0.89	0.25	0.06	0.08	2.77

ATW Uncertainty

Subcriticality Level for a MA Dominated Fuel

- As for the previous fuel the total uncertainty is larger than standard fast reactors (~2%)
- As expected the main contributions to the uncertainty are now coming from the Minor Actinides. In particular ^{241}Am and ^{245}Cm (fission)

ATW Uncertainty

Decomposition of $\frac{\Delta K}{K}$ uncertainty for a dedicated core

(fuel : (Pu+MA)N particles surrounded by TiN layers. Ratio Pu/MA = 0.6)

Isotope	Capture[a]	Fission[a]	Total Isotope
Pu-238	0.0017	0.0097	0.0099
Am-241	0.0099	0.0062	0.0117
Am-242m	0.0001	0.0053	0.0053
Am-243	0.0054	0.0026	0.0060
Cm-244	0.0015	0.0046	0.0048
Cm-245	0.0003	0.0114	0.0114
Total	0.0116	0.0178	0.0213

(a) Uncertainties on σ vary between 5 and 30 % according to the energy range, type of cross-section and isotope.

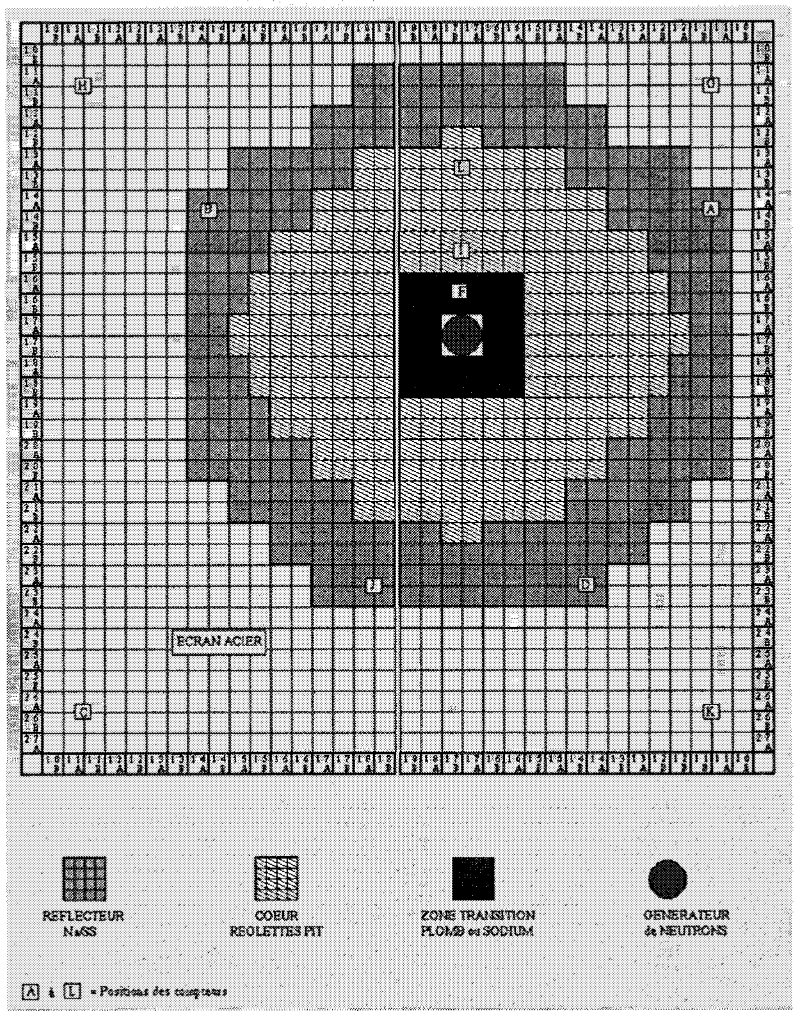
MUSE Experiment

- The MUSE3 experiments consisted of inserting a standard commercial *(d,t)* 14 MeV neutron generator, loaded inside a standard MASURCA subassembly, at the core center of different subcritical configurations, the tritium target being located at the core midplane. These subcritical configurations are loaded with UO_2-PuO_2 fuel (Pu enrichment ≈ 25%) with sodium coolant. The core height was 60 cm and the fuel radius ranged from 45 to 51 cm depending on reactivity. The 14 MeV neutron emission was isotropic, with an emission level of 3. 10^8 n/s in the continuous mode and 10^5 n/µs in the pulsed situation. The neutrons of spontaneous fissions or *(_,n)* reactions origin create an inherent source in the subcritical core and induce an initial power.

MUSE Experiment

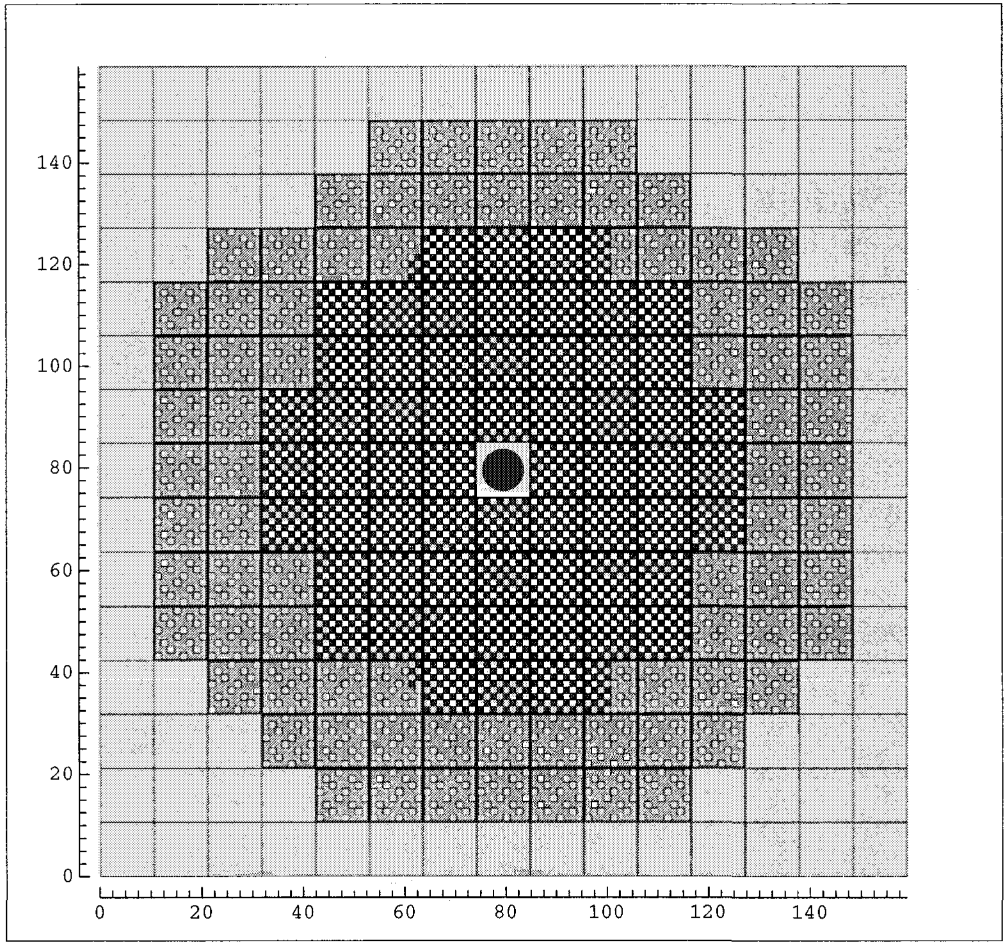
- The MUSE3 experiments started with a critical reference followed by three subcritical configurations called SC1, SC2 and SC3 of about -500, -1000 and -1500 pcm (1pcm=0.001% of $\Delta k/k$) respectively, which were obtained by unloading peripheral MASURCA subassemblies from the critical reference. Some measurements were performed with the generator wrapped in a 1 mm thick cadmium layer, to prevent the neutrons moderated by the generator's light materials from entering the core. In a later phase, the neutron generator was surrounded successively by sodium and pure lead buffers of about 12 cm radius, to simulate the diffusing properties of a spallation source and to modify the importance of the 14 MeV neutrons emitted by the generator. In these two configurations, a subcriticality level of about - 4500 pcm was obtained by adjusting the external fuel loading

The MUSE Experiment



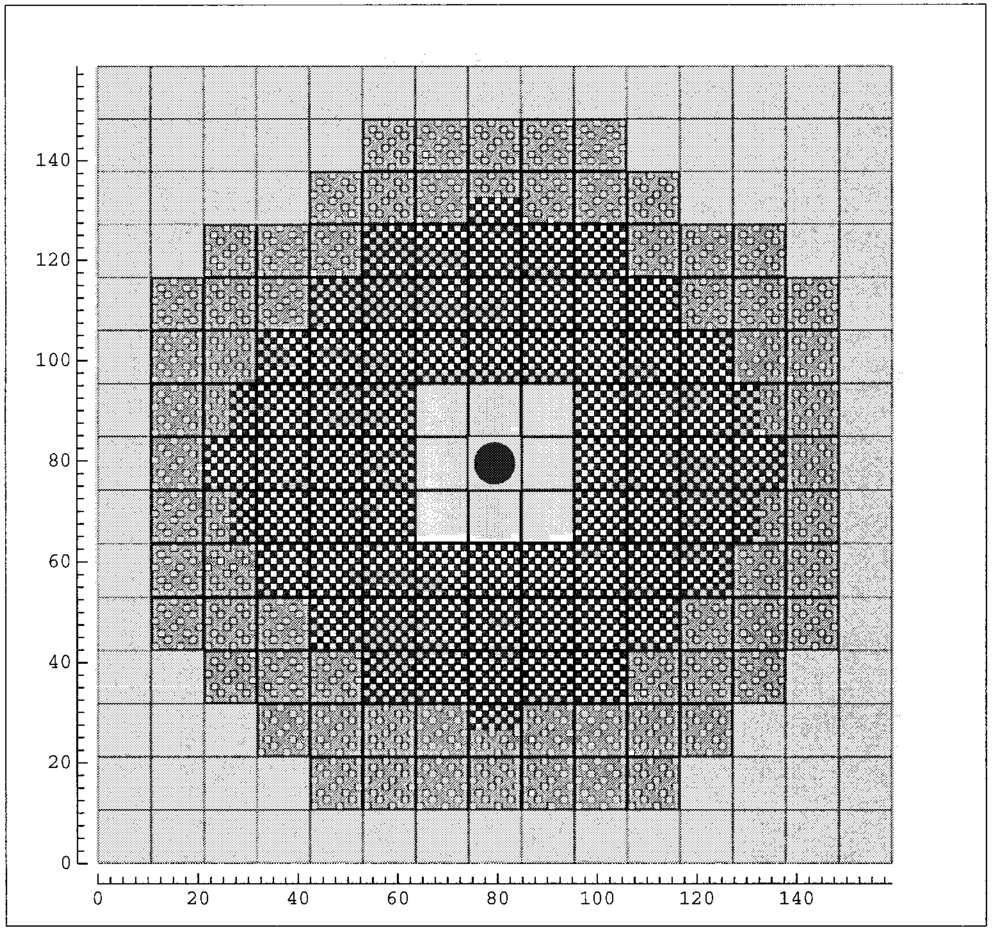
The MUSE Experiment

Monte Carlo model for the reference configuration

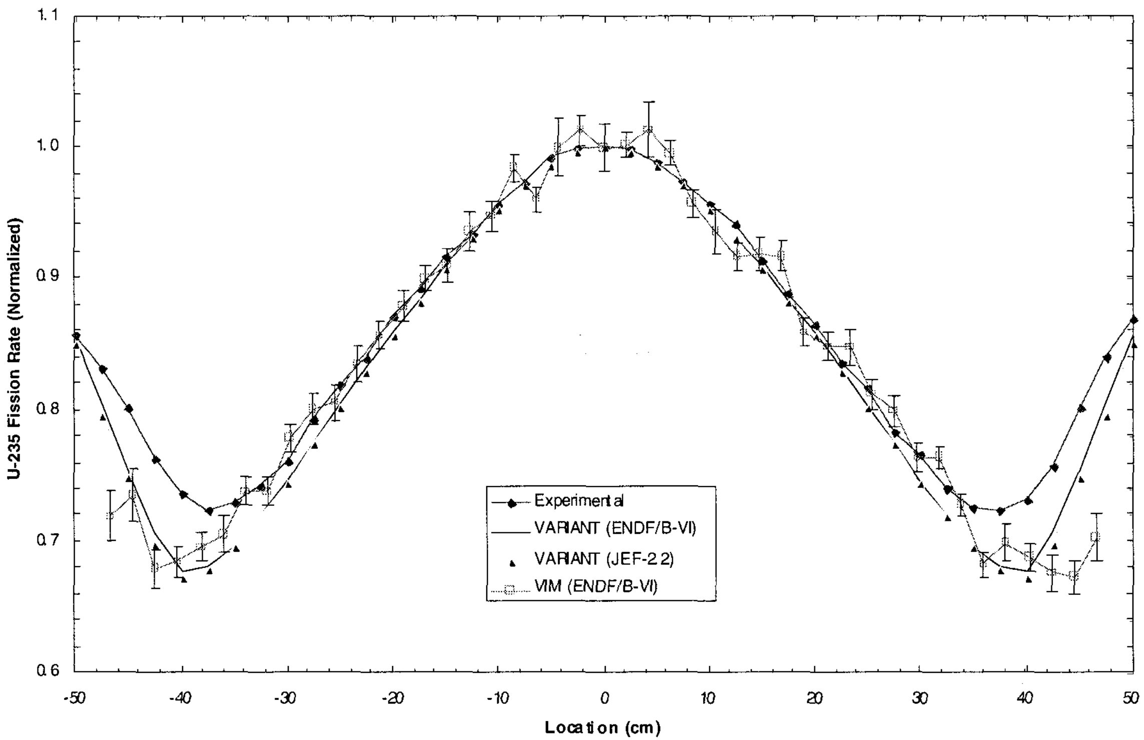


The MUSE Experiment

Monte Carlo model for the buffer configuration



The MUSE Experiment



Fission rate radial distribution

MUSE Experiment

Reactivity level comparison between experiment and calculations

Experimental Configuration	Measured Experimental Reactivity	Monte Carlo Calculations ENDF/B-VI	Deterministic Transport ENDF/B-VI	Deterministic Transport JEF2.2
Reference	-112 ±60	+666 ±23	+1342	+327
Subcritical level 3	-1579 ±90	-812 ±30	-50	-1053
Subcritical with Pb buffer	-5687 ±120	-4564 ±28	-4268	-5398
Subcritical with Na buffer	-5893 ±120	-4977 ±26	-4232	-5270

MUSE Experiment

Perturbation breakdown of isotopes and components of the reactivity (expressed in p.c.m) difference between JEF2.2 and ENDF/B-VI

ISOTOPE	Perturbation Components					
	Capture	Fission	Elastic	Inelastic	N♦ 2N	SUM
U^{238}	134	11	- 56	- 369	110	- 170
Pu^{239}	- 290	- 9	57	-37	10	- 269
Pu^{240}	- 188	- 19	18	- 9	2	- 196
Am^{241}	- 102	15	- 3	3	-	- 87
Fe^{56}	35	-	- 91	- 47	3	- 100
O^{16}	2	-	- 129	-	-	- 127

MUSE Experiment

1easured and calculated (ERALIB1)reactivities (1σ uncertainty)

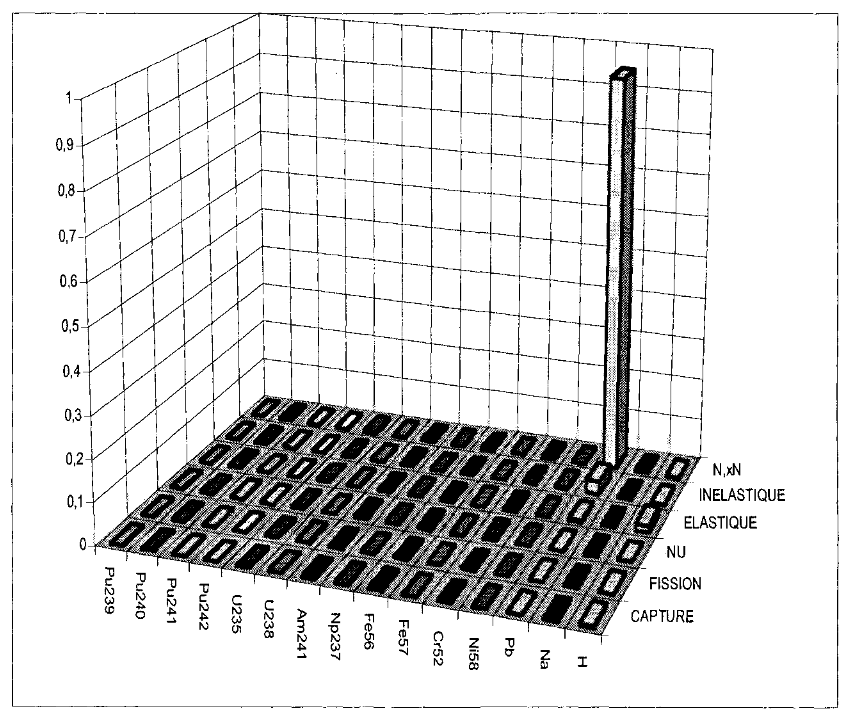
	MUSE3 REF	MUSE3 SC1	MUSE3 SC2	MUSE3 SC3	MUSE3+Cd	MUSE3 Pb	MUSE Na
MSM corrected measured reactivity : E [pcm]	- 112 ± 60	- 467 ± 70	- 1202 ± 80	- 1579 ± 90	- 2151 ± 100	- 5687 ± 120	-5893 ± 120
Calculated reactivity : C [pcm]	+ 206 ± 360	- 124 ± 360	- 806 ± 370	- 1170 ± 380	- 2130 ± 510	- 5500 ± 400	- 5438 ± 411
E-C	-318	-343	-396	-409	-21	-187	-455

MUSE Experiment

- The uncertainty on parameter φ^* in the MUSE3 Pb configuration with the neutron generator switched on (calculated absolute value φ^*=1.42) has been calculated using the dispersion matrix of the unadjusted library JEF2.2 and the adjusted library ERALIB1. The absolute value of the uncertainty is 6.5% using JEF2.2 data and the most important contribution to the uncertainty is due to lead, particularly the *(n,2n)* reaction. Using the ERALIB1 data the uncertainty does not change too much with respect to the unadjusted library because the most important contribution to the uncertainty is due to the non-adjusted lead.

The MUSE Experiment

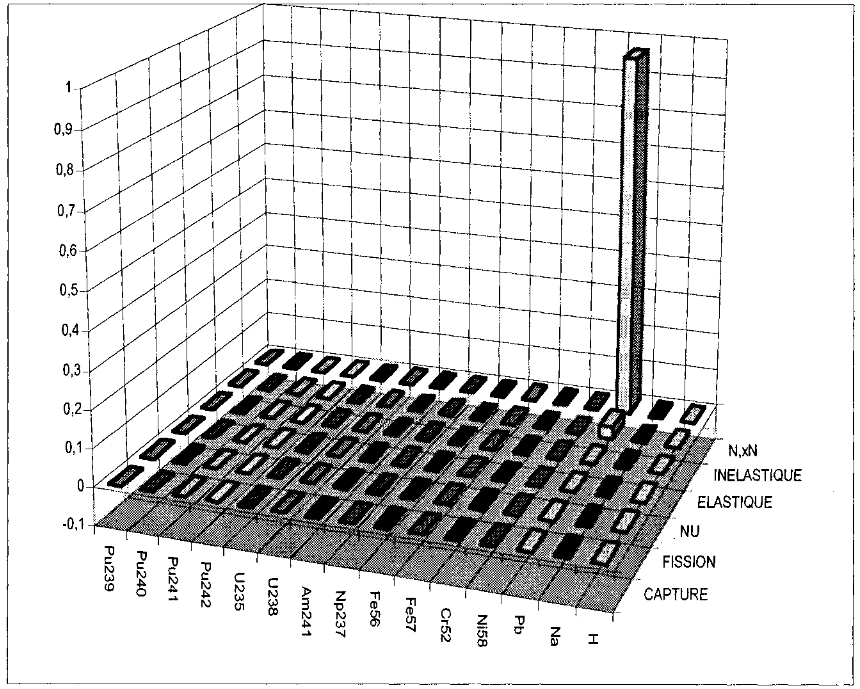
Isotope	σ_{cap}	σ_{fiss}	ν	σ_{el}	σ_{inel}	$\sigma_{n,2n}$	Total
Pu239	5.3E-2	1.1E-1	2.2E-2	4.7E-3	9.4E-3	6.4E-3	1.2E-1
Pu240	2.3E-2	2.5E-2	6.6E-3	2.5E-3	3.7E-3	3.4E-3	3.5E-2
Pu241	2.4E-3	6.4E-3	1.1E-3	2.1E-4	3.0E-4	1.8E-4	6.9E-3
Pu242	9.2E-4	7.6E-4	2.2E-4	9.8E-5	1.4E-4	3.0E-4	1.3E-3
U235	7.0E-4	4.0E-3	1.9E-4	8.1E-5	9.2E-5	6.2E-5	4.1E-3
U238	1.4E-2	8.9E-2	2.3E-2	1.2E-2	4.0E-2	4.9E-2	1.1E-1
Am241	2.9E-2	2.0E-2	6.6E-3	9.2E-5	1.1E-3	0.0E+0	3.6E-2
Np237	3.8E-8	7.2E-9	2.8E-9	3.1E-11	3.7E-10	0.0E+0	3.9E-8
Fe56	1.5E-1	0.0E+0	0.0E+0	8.3E-2	9.6E-2	0.0E+0	2.0E-1
Fe57	3.0E-3	0.0E+0	0.0E+0	3.5E-3	3.4E-2	0.0E+0	3.4E-2
Cr52	2.8E-2	0.0E+0	0.0E+0	2.5E-2	1.7E-1	0.0E+0	1.8E-1
Ni58	3.7E-2	0.0E+0	0.0E+0	1.7E-2	2.5E-2	0.0E+0	4.8E-2
Pb	7.4E-2	0.0E+0	0.0E+0	2.2E-1	1.1E+0	6.3E+0	6.4E+0
Na	4.3E-2	0.0E+0	0.0E+0	2.1E-2	5.5E-2	0.0E+0	7.3E-2
H	3.8E-1	0.0E+0	0.0E+0	8.2E-1	0.0E+0	0.0E+0	9.0E-1
Total	4.3E-1	1.4E-1	3.3E-2	8.5E-1	1.2E+0	6.3E+0	6.5E+0



φ^* Uncertainties (%) in the MUSE3 Pb Configuration with Generator ON - JEF2

The MUSE Experiment

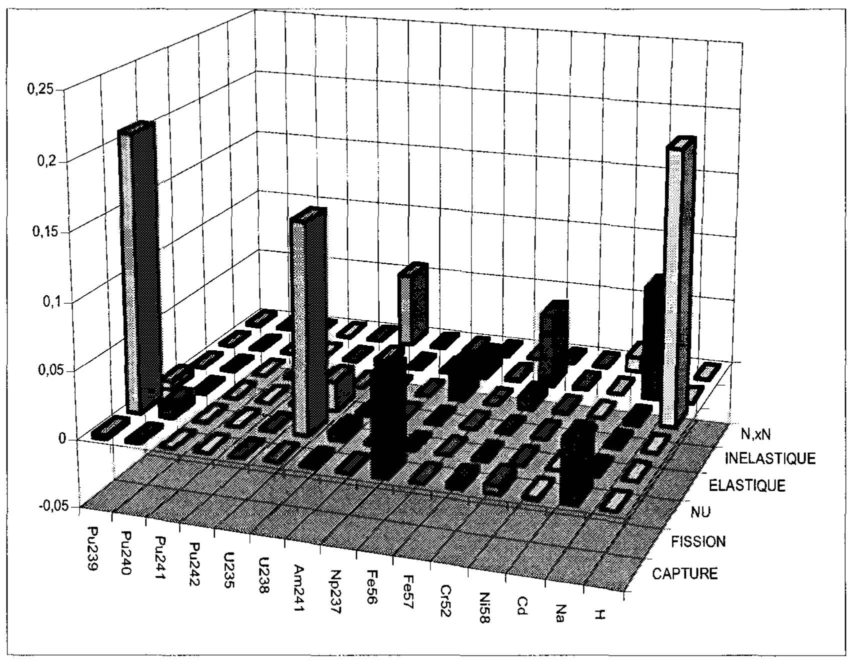
Isotope	σ_{cap}	σ_{fiss}	ν	σ_{el}	σ_{inel}	$\sigma_{n,2n}$	Total
Pu239	2.1E-2	3.9E-2	1.5E-2	5.9E-3	9.4E-3	8.1E-3i	4.7E-2
Pu240	1.2E-2	1.4E-2	4.3E-3	3.1E-3	3.7E-3	5.5E-3i	1.9E-2
Pu241	2.5E-3i	3.2E-3	1.2E-3i	3.1E-4	2.8E-4	1.8E-4	1.6E-3
Pu242	1.4E-3	2.8E-4	2.1E-4	9.7E-5	1.4E-4	0.0E+0	1.5E-3
U235	3.8E-4	5.3E-3	8.7E-4	4.4E-4	4.7E-4	1.4E-3i	5.3E-3
U238	8.6E-3	6.3E-2	2.3E-2	1.8E-3	9.0E-3i	4.8E-2	8.2E-2
Am241	0.0E+0	7.4E-3	0.0E+0	0.0E+0	0.0E+0	0.0E+0	7.4E-3
Np237	3.8E-8	7.2E-9	2.8E-9	3.1E-11	3.7E-10	0.0E+0	3.9E-8
Fe56	1.5E-1	0.0E+0	0.0E+0	2.2E-2	4.4E-2	0.0E+0	1.5E-1
Fe57	3.0E-3	0.0E+0	0.0E+0	3.5E-3	3.4E-2	0.0E+0	3.4E-2
Cr52	2.7E-2	0.0E+0	0.0E+0	2.0E-2	1.6E-1	0.0E+0	1.6E-1
Ni58	3.4E-2	0.0E+0	0.0E+0	1.4E-2	2.0E-2	0.0E+0	4.2E-2
Pb	7.4E-2	0.0E+0	0.0E+0	2.2E-1	1.1E+0	6.3E+0	6.4E+0
Na	4.3E-2	0.0E+0	0.0E+0	1.1E-2	3.6E-2	0.0E+0	5.7E-2
H	2.9E-2	0.0E+0	0.0E+0	4.2E-2	0.0E+0	0.0E+0	5.2E-2
Total	1.8E-1	7.6E-2	2.7E-2	2.3E-1	1.2E+0	6.3E+0	6.4E+0



φ* Uncertainties (%) in the MUSE3 Pb Configuration with Generator ON - ERALIB1

The MUSE Experiment

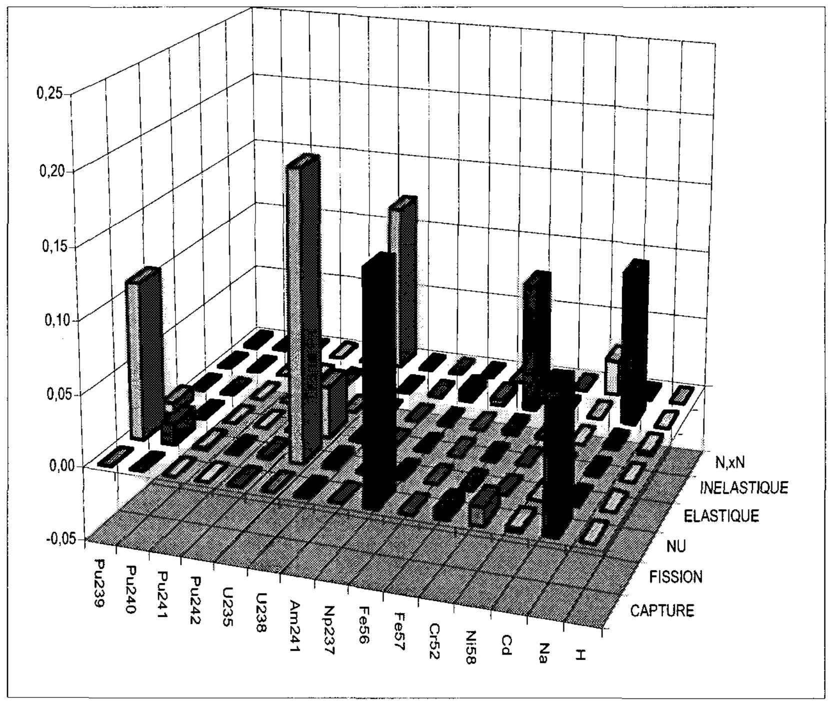
Isotope	σ_{cap}	σ_{fiss}	ν	σ_{el}	σ_{inel}	$\sigma_{n,2n}$	Total
Pu239	4.4E-2	4.5E-1	7.9E-2	2.6E-3	1.0E-2	2.9E-2	4.6E-1
Pu240	2.6E-2	9.5E-2	1.9E-2	2.3E-3	3.9E-3	1.6E-2	1.0E-1
Pu241	3.8E-3	2.6E-2	2.0E-3	2.2E-4	3.1E-4	1.2E-3	2.7E-2
Pu242	7.8E-4	3.0E-3	6.5E-4	8.4E-5	1.4E-4	1.4E-3	3.4E-3
U235	6.2E-4	1.5E-2	4.8E-4	5.4E-5	1.1E-4	3.1E-4	1.5E-2
U238	2.4E-2	3.9E-1	1.5E-1	8.6E-3	5.7E-2	2.3E-1	4.8E-1
Am241	2.6E-2	7.1E-2	2.3E-2	7.7E-5	1.3E-3	0.0E+0	7.9E-2
Np237	2.0E-9	2.4E-9	8.7E-10	4.8E-11	1.5E-10	0.0E+0	3.3E-9
Fe56	2.6E-1	0.0E+0	0.0E+0	1.6E-1	1.2E-1	0.0E+0	3.3E-1
Fe57	4.4E-3	0.0E+0	0.0E+0	7.5E-3	4.3E-2	0.0E+0	4.4E-2
Cr52	5.0E-2	0.0E+0	0.0E+0	8.4E-2	2.3E-1	0.0E+0	2.5E-1
Ni58	7.7E-2	0.0E+0	0.0E+0	2.9E-2	3.5E-2	0.0E+0	8.9E-2
Cd	2.9E-2	0.0E+0	0.0E+0	7.5E-3	9.2E-3	1.0E-1	1.1E-1
Na	2.1E-1	0.0E+0	0.0E+0	4.3E-2i	2.8E-1	0.0E+0	3.5E-1
H	3.3E-3	0.0E+0	0.0E+0	4.4E-1	0.0E+0	0.0E+0	4.4E-1
Total	3.5E-1	6.1E-1	1.7E-1	4.8E-1	3.9E-1	2.6E-1	9.8E-1



φ^* Uncertainties (%) in the MUSE3 Cd Configuration with Generator ON - JEF2.2

The MUSE Experiment

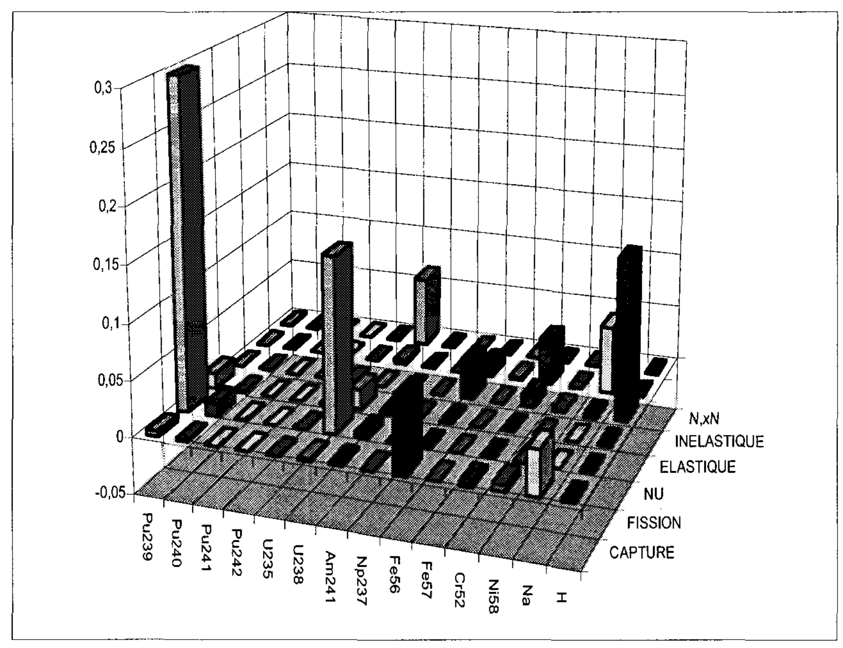
Isotope	σ_{cap}	σ_{fiss}	ν	σ_{el}	σ_{inel}	$\sigma_{n,2n}$	Total
Pu239	9.2E-3	2.2E-1	5.9E-2	3.9E-3i	8.4E-3i	1.8E-2i	2.3E-1
Pu240	2.2E-3	7.9E-2	1.8E-2	1.3E-3i	1.9E-3	1.4E-2i	8.0E-2
Pu241	1.5E-3i	2.0E-2	2.8E-3	2.4E-4	2.9E-4	1.2E-3	2.0E-2
Pu242	9.2E-4i	2.7E-3i	7.6E-4	8.2E-5	1.3E-4	0.0E+0	2.7E-3i
U235	2.2E-3	2.5E-2	2.2E-3	6.9E-4	1.4E-3	4.3E-3i	2.5E-2
U238	3.5E-3	2.9E-1	1.2E-1	4.3E-3	9.6E-3i	2.3E-1	3.9E-1
Am241	0.0E+0	2.5E-2	0.0E+0	0.0E+0	0.0E+0	0.0E+0	2.5E-2
Np237	2.0E-9	2.4E-9	8.7E-10	4.8E-11	1.5E-10	0.0E+0	3.3E-9
Fe56	2.6E-1	0.0E+0	0.0E+0	1.1E-2	5.3E-2	0.0E+0	2.7E-1
Fe57	4.4E-3	0.0E+0	0.0E+0	7.5E-3	4.3E-2	0.0E+0	4.4E-2
Cr52	4.9E-2	0.0E+0	0.0E+0	2.4E-2	2.0E-1	0.0E+0	2.0E-1
Ni58	7.3E-2	0.0E+0	0.0E+0	1.4E-2	2.6E-2	0.0E+0	7.8E-2
Cd	2.9E-2	0.0E+0	0.0E+0	7.5E-3	9.2E-3	1.0E-1	1.1E-1
Na	2.0E-1	0.0E+0	0.0E+0	1.5E-2	2.1E-1	0.0E+0	2.9E-1
H	4.6E-4i	0.0E+0	0.0E+0	2.8E-2	0.0E+0	0.0E+0	2.8E-2
Total	3.4E-1	3.8E-1	1.4E-1	4.5E-2	3.0E-1	2.5E-1	6.6E-1



φ^* Uncertainties (%) in the MUSE3 Cd Configuration with Generator ON - ERALIB1

The MUSE Experiment

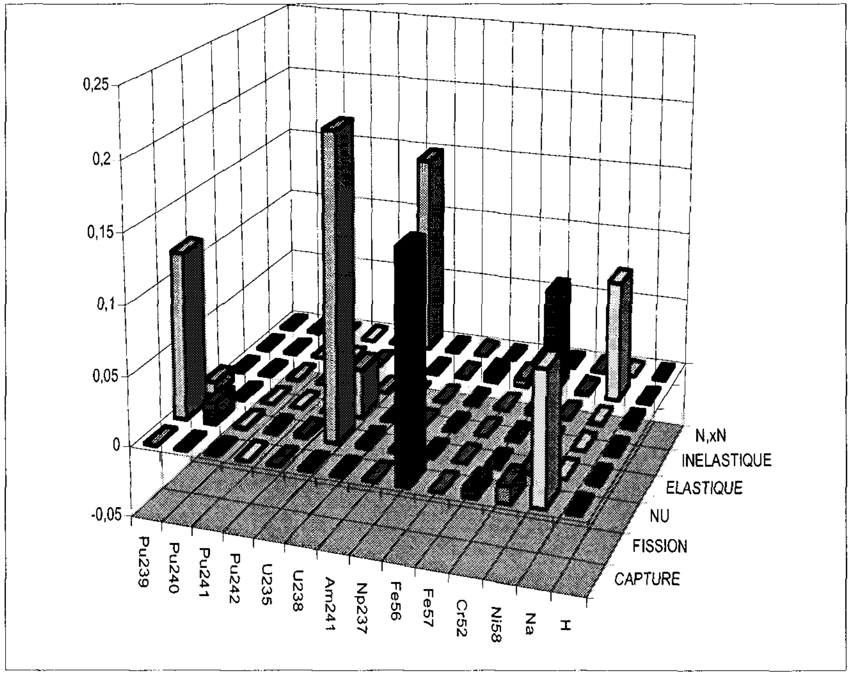
Isotope	σ_{cap}	σ_{fiss}	ν	σ_{el}	σ_{inel}	$\sigma_{n,2n}$	Total
Pu239	7.0E-2	5.6E-1	1.2E-1	2.3E-3	1.4E-2	3.3E-2	5.8E-1
Pu240	3.9E-2	1.1E-1	2.0E-2	2.1E-3	5.3E-3	1.7E-2	1.2E-1
Pu241	5.6E-3	3.2E-2	3.3E-3	2.1E-4	4.3E-4	1.3E-3	3.3E-2
Pu242	1.2E-3	3.3E-3	6.1E-4	8.0E-5	1.9E-4	1.5E-3	3.9E-3
U235	9.5E-4	1.7E-2	6.3E-4	4.8E-5	1.5E-4	3.3E-4	1.7E-2
U238	3.6E-2	4.0E-1	1.4E-1	8.0E-3	6.6E-2	2.6E-1	5.0E-1
Am241	3.8E-2	7.4E-2	2.4E-2	7.5E-5	1.7E-3	0.0E+0	8.7E-2
Np237	2.9E-9	2.7E-9	9.4E-10	5.6E-11	1.6E-10	0.0E+0	4.0E-9
Fe56	2.7E-1	0.0E+0	0.0E+0	1.9E-1	1.1E-1	0.0E+0	3.4E-1
Fe57	4.8E-3	0.0E+0	0.0E+0	8.7E-3	4.8E-2	0.0E+0	4.9E-2
Cr52	5.0E-2	0.0E+0	0.0E+0	1.0E-1	2.1E-1	0.0E+0	2.4E-1
Ni58	7.6E-2	0.0E+0	0.0E+0	3.4E-2	3.1E-2	0.0E+0	8.9E-2
Na	2.0E-1	0.0E+0	0.0E+0	4.4E-2i	2.5E-1	0.0E+0	3.2E-1
H	3.0E-2	0.0E+0	0.0E+0	3.9E-1	0.0E+0	0.0E+0	3.9E-1
Total	3.6E-1	7.0E-1	1.9E-1	4.4E-1	3.5E-1	2.6E-1	1.0E+0



φ^* Uncertainties (%) in the MUSE3 SC3 Configuration with Generator ON – JEF2.2

The MUSE Experiment

Isotope	σ_{cap}	σ_{fiss}	ν	σ_{el}	σ_{inel}	$\sigma_{n,2n}$	Total
Pu239	1.0E-2	2.3E-1	6.4E-2	2.6E-3i	8.6E-3i	1.5E-2i	2.4E-1
Pu240	3.7E-3i	8.1E-2	1.8E-2	1.4E-3	3.1E-3	1.3E-2i	8.2E-2
Pu241	2.0E-3i	2.2E-2	3.7E-3	2.8E-4	3.9E-4	1.3E-3	2.2E-2
Pu242	1.3E-3i	2.7E-3i	7.2E-4	7.9E-5	1.9E-4	0.0E+0	3.0E-3i
U235	2.3E-3	2.6E-2	3.4E-3	6.7E-4	1.7E-3	4.1E-3i	2.6E-2
U238	4.0E-3i	3.1E-1	1.2E-1	5.6E-3	6.9E-3	2.5E-1	4.1E-1
Am241	0.0E+0	2.7E-2	0.0E+0	0.0E+0	0.0E+0	0.0E+0	2.7E-2
Np237	2.9E-9	2.7E-9	9.4E-10	5.6E-11	1.6E-10	0.0E+0	4.0E-9
Fe56	2.6E-1	0.0E+0	0.0E+0	1.6E-2	4.8E-2	0.0E+0	2.7E-1
Fe57	4.8E-3	0.0E+0	0.0E+0	8.7E-3	4.8E-2	0.0E+0	4.9E-2
Cr52	4.9E-2	0.0E+0	0.0E+0	3.0E-2	1.8E-1	0.0E+0	1.9E-1
Ni58	7.2E-2	0.0E+0	0.0E+0	1.7E-2	2.3E-2	0.0E+0	7.8E-2
Na	2.0E-1	0.0E+0	0.0E+0	1.4E-2	1.9E-1	0.0E+0	2.8E-1
H	2.3E-3	0.0E+0	0.0E+0	2.3E-2	0.0E+0	0.0E+0	2.3E-2
Total	3.4E-1	3.9E-1	1.4E-1	4.8E-2	2.7E-1	2.5E-1	6.5E-1



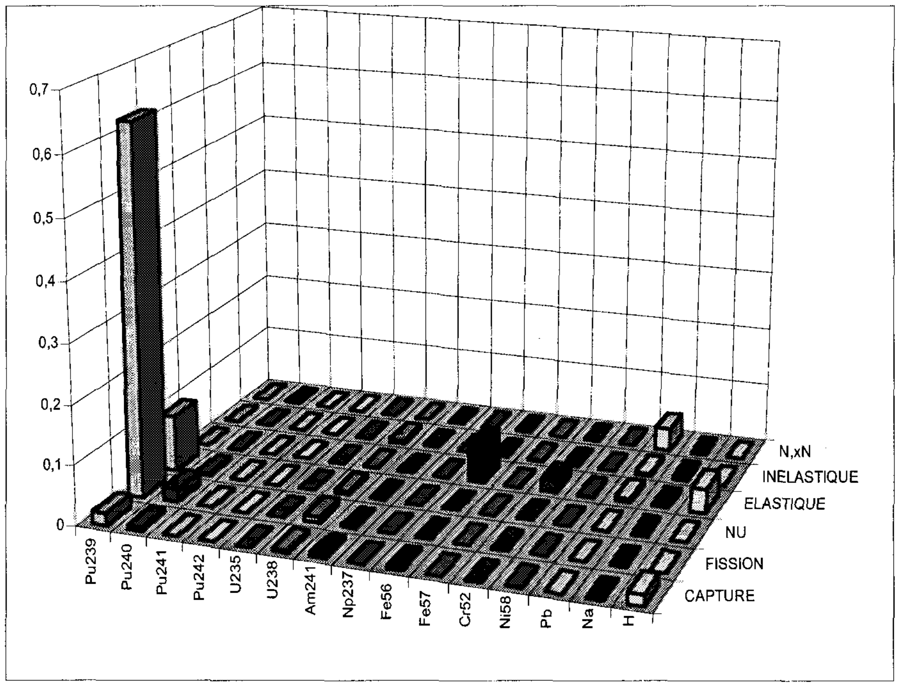
φ^* Uncertainties (%) in the MUSE3 SC3 Configuration with Generator ON - ERALIB1

MUSE Experiment

- The calculated uncertainties for the integral fission rate $<\Sigma_f \Phi_S>$ in the MUSE3 Pb configuration with the neutron generator switched on (absolute calculated value $<\Sigma_f \Phi_S>$=5.39E+9 *fiss/sec*) using the JEF2.2 dispersion matrix is quite large (41%). This is mainly due to the fact that the integral fission rate change the K_{eff} and consequently the flux level. The uncertainty profiles are dominated by the contribution due to the Pu239 cross sections, but using the ERALIB1 adjusted library, we reduce the uncertainty on the integral fission rate to 8.5% In fact after the adjustment of cross sections of the fissile isotopes, the absolute value of the uncertainty is dominated by the contribution due to the unadjusted lead cross sections, particularly the lead *(n,2n)* reaction.

The MUSE Experiment

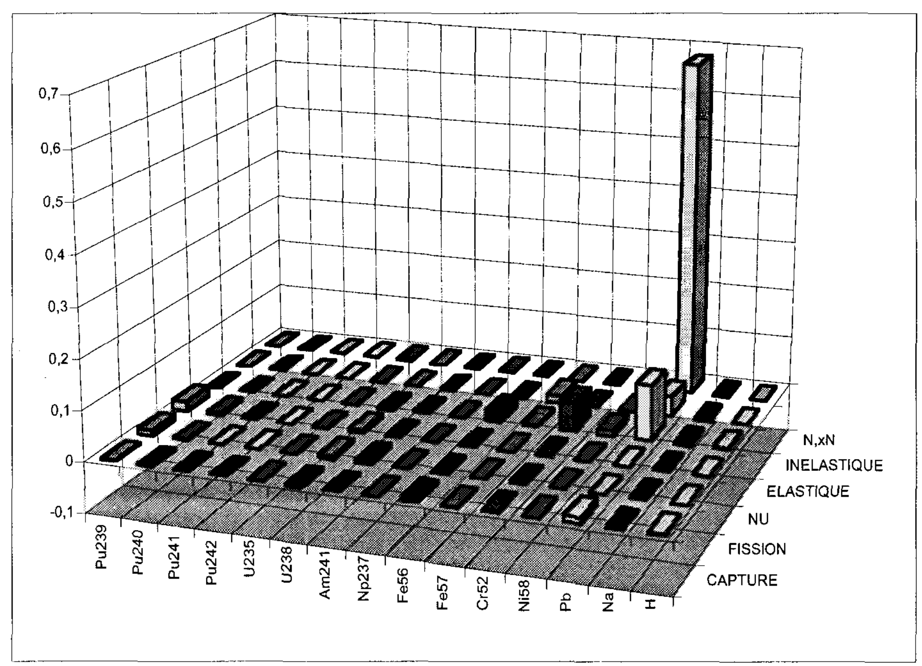
Isotope	σ_{cap}	σ_{fiss}	ν	σ_{el}	σ_{inel}	$\sigma_{n,2n}$	Total
Pu239	5.4E+0	3.4E+1	1.3E+1	3.3E-1	5.3E-1	2.7E-2	3.6E+1
Pu240	2.8E+0	6.3E+0	2.2E+0	1.9E-1	1.9E-1	1.1E-2	7.2E+0
Pu241	3.7E-1	1.9E+0	3.5E-1	1.5E-2	1.7E-2	6.4E-3	2.0E+0
Pu242	8.4E-2	1.7E-1	5.7E-2	7.3E-3	7.9E-3	1.0E-3	2.0E-1
U235	7.2E-2	7.7E-1	6.9E-2	5.8E-3	4.8E-3	4.8E-4	7.8E-1
U238	2.4E+0	4.2E+0	3.2E+0	8.1E-1	2.5E+0	1.9E-1	6.4E+0
Am241	2.7E+0	1.4E+0	4.7E-1	6.3E-3	6.4E-2	0.0E+0	3.1E+0
Np237	9.0E-7	7.3E-8	2.8E-8	2.9E-9	2.6E-9	0.0E+0	9.0E-7
Fe56	1.8E+0	0.0E+0	0.0E+0	9.9E+0	9.2E-1	0.0E+0	1.0E+1
Fe57	2.6E-1	0.0E+0	0.0E+0	5.1E-1	1.0E+0	0.0E+0	1.2E+0
Cr52	5.0E-1	0.0E+0	0.0E+0	5.4E+0	2.5E-1	0.0E+0	5.4E+0
Ni58	8.2E-1	0.0E+0	0.0E+0	1.6E+0	1.2E-1	0.0E+0	1.8E+0
Pb	8.6E-1	0.0E+0	0.0E+0	2.8E+0	1.7E+0	6.8E+0	7.6E+0
Na	2.0E-1	0.0E+0	0.0E+0	1.9E+0	2.0E+0	0.0E+0	2.8E+0
H	4.6E+0	0.0E+0	0.0E+0	7.1E+0	0.0E+0	0.0E+0	8.4E+0
Total	8.8E+0	3.5E+1	1.3E+1	1.4E+1	3.9E+0	6.8E+0	4.1E+1



Integral Fission Rate Uncertainties (%) in the MUSE3 Pb Configuration with Generator ON – JEF2.2

The MUSE Experiment

Isotope	σ_{cap}	σ_{fiss}	ν	σ_{el}	σ_{inel}	$\sigma_{n,2n}$	Total
Pu239	8.3E-1i	2.1E+0	1.2E+0	2.2E-1i	1.4E-1	4.3E-2	2.2E+0
Pu240	5.3E-1i	4.7E-1	6.4E-1	1.6E-1i	5.6E-2i	2.1E-2	5.7E-1
Pu241	1.8E-1i	4.3E-1	1.2E-1i	1.9E-2i	1.6E-2	6.3E-3	3.7E-1
Pu242	9.0E-2i	7.9E-2	4.2E-2	7.2E-3	7.8E-3	0.0E+0	4.9E-3
U235	6.9E-2i	2.0E-1	2.7E-2	2.7E-2i	3.0E-2	6.9E-3	1.9E-1
U238	8.8E-1i	7.4E-1	7.9E-1	6.2E-1i	3.5E-2	1.7E-1	2.1E-1
Am241	0.0E+0	7.5E-1	0.0E+0	0.0E+0	0.0E+0	0.0E+0	7.5E-1
Np237	9.0E-7	7.3E-8	2.8E-8	2.9E-9	2.6E-9	0.0E+0	9.0E-7
Fe56	6.7E-1	0.0E+0	0.0E+0	1.3E+0	1.4E-1	0.0E+0	1.4E+0
Fe57	2.6E-1	0.0E+0	0.0E+0	5.1E-1	1.0E+0	0.0E+0	1.2E+0
Cr52	2.5E-1	0.0E+0	0.0E+0	2.0E+0	2.2E-1	0.0E+0	2.0E+0
Ni58	3.3E-1	0.0E+0	0.0E+0	8.6E-1	7.1E-2	0.0E+0	9.2E-1
Pb	8.6E-1	0.0E+0	0.0E+0	2.8E+0	1.7E+0	6.8E+0	7.6E+0
Na	1.6E-1	0.0E+0	0.0E+0	6.5E-1i	4.8E-1i	0.0E+0	7.9E-1i
H	3.6E-1	0.0E+0	0.0E+0	3.3E-1	0.0E+0	0.0E+0	4.9E-1
Total	4.6E-1i	2.4E+0	1.5E+0	3.7E+0	2.0E+0	6.8E+0	8.5E+0



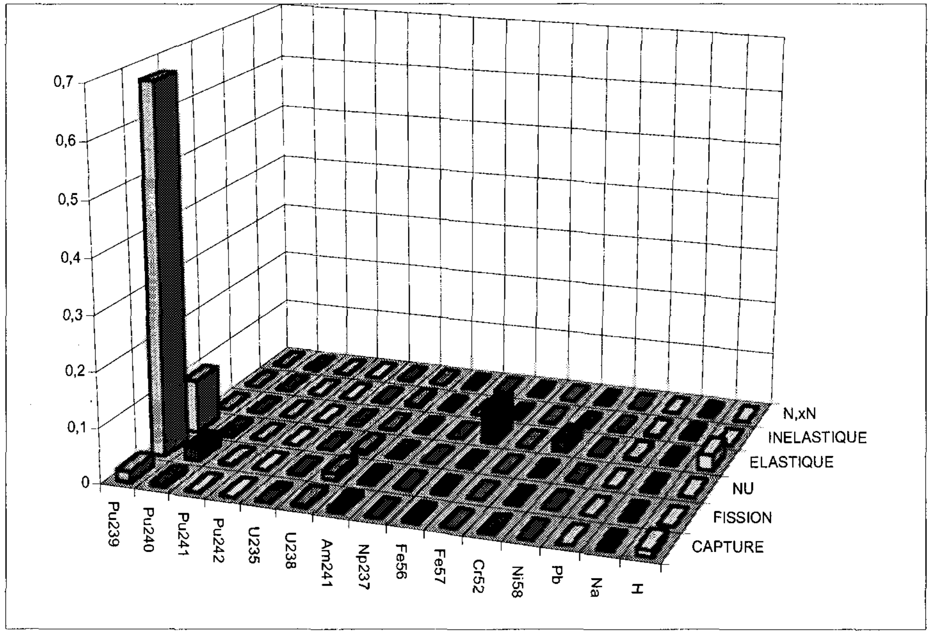
Integral Fission Rate Uncertainties (%) in the MUSE3 Pb Configuration with Generator ON - ERALIB1

MUSE Experiment

- The calculated uncertainties on the K_{eff} for the MUSE3 Pb configuration (absolute calculated value K_{eff} =.95633) using the unadjusted library JEF2.2 the absolute value of uncertainty is 1.7%. The most important contribution to the uncertainty is due to the Pu239, but using the adjusted library ERALIB1 the uncertainty is reduced to the value of 0.2% and the uncertainty profiles are dominated by the contribution due to the elastic lead cross section. Compared with the previous uncertainty on the integral fission rate, the uncertainty on K_{eff} is significantly lower because this parameter is a ratio and consequently compensation effects take place (e. g. flux level).

The MUSE Experiment

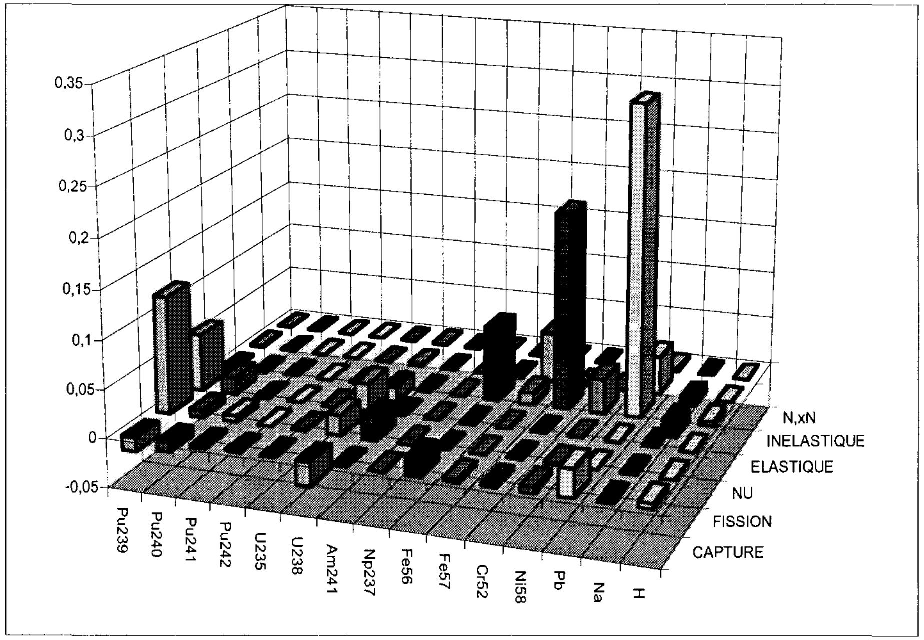
Isotope	σ_{cap}	σ_{fiss}	ν	σ_{el}	σ_{inel}	$\sigma_{n,2n}$	Total
Pu239	2.3E-1	1.4E+0	5.2E-1	1.4E-2	2.3E-2	8.8E-4	1.5E+0
Pu240	1.2E-1	2.6E-1	9.0E-2	8.0E-3	8.3E-3	3.1E-4	3.0E-1
Pu241	1.6E-2	7.9E-2	1.5E-2	6.3E-4	7.6E-4	2.7E-4	8.2E-2
Pu242	3.6E-3	6.9E-3	2.4E-3	3.1E-4	3.5E-4	3.0E-5	8.2E-3
U235	3.1E-3	3.2E-2	2.9E-3	2.5E-4	2.1E-4	1.8E-5	3.2E-2
U238	1.1E-1	1.7E-1	1.3E-1	3.5E-2	1.1E-1	5.8E-3	2.7E-1
Am241	1.2E-1	5.8E-2	2.0E-2	2.7E-4	2.8E-3	0.0E+0	1.3E-1
Np237	3.7E-8	3.2E-9	1.2E-9	1.3E-10	1.1E-10	0.0E+0	3.7E-8
Fe56	7.7E-2	0.0E+0	0.0E+0	4.3E-1	4.0E-2	0.0E+0	4.4E-1
Fe57	1.1E-2	0.0E+0	0.0E+0	2.2E-2	4.6E-2	0.0E+0	5.2E-2
Cr52	2.1E-2	0.0E+0	0.0E+0	2.3E-1	5.0E-3	0.0E+0	2.3E-1
Ni58	3.5E-2	0.0E+0	0.0E+0	7.2E-2	4.6E-3	0.0E+0	8.0E-2
Pb	3.4E-2	0.0E+0	0.0E+0	1.1E-1	4.0E-2	1.1E-2	1.3E-1
Na	7.3E-3	0.0E+0	0.0E+0	8.1E-2	8.8E-2	0.0E+0	1.2E-1
H	1.8E-1	0.0E+0	0.0E+0	2.8E-1	0.0E+0	0.0E+0	3.3E-1
Total	3.7E-1	1.4E+0	5.5E-1	5.8E-1	1.6E-1	1.3E-2	1.7E+0



Keff Uncertainties (%) in the MUSE3 Pb Configuration - JEF2

The MUSE Experiment

Isotope	σ_{cap}	σ_{fiss}	ν	σ_{el}	σ_{inel}	$\sigma_{n,2n}$	Total
Pu239	2.4E-2i	7.0E-2	4.9E-2	8.7E-3i	7.8E-3	1.7E-3	8.2E-2
Pu240	2.0E-2i	1.7E-2	2.7E-2	6.7E-3i	1.7E-3i	8.0E-4	2.4E-2
Pu241	7.2E-3i	1.6E-2	4.9E-3i	7.9E-4i	6.9E-4	2.7E-4	1.3E-2
Pu242	3.6E-3i	3.0E-3	1.7E-3	3.1E-4	3.4E-4	0.0E+0	9.5E-4i
U235	2.3E-3i	6.9E-3	1.6E-3	1.1E-3i	1.3E-3	3.1E-4	6.7E-3
U238	3.1E-2i	2.9E-2	3.4E-2	2.4E-2i	8.7E-3	5.0E-3	2.3E-2
Am241	0.0E+0	3.1E-2	0.0E+0	0.0E+0	0.0E+0	0.0E+0	3.1E-2
Np237	3.7E-8	3.2E-9	1.2E-9	1.3E-10	1.1E-10	0.0E+0	3.7E-8
Fe56	2.7E-2	0.0E+0	0.0E+0	5.5E-2	5.4E-3	0.0E+0	6.2E-2
Fe57	1.1E-2	0.0E+0	0.0E+0	2.2E-2	4.6E-2	0.0E+0	5.2E-2
Cr52	1.1E-2	0.0E+0	0.0E+0	9.0E-2	3.8E-3	0.0E+0	9.1E-2
Ni58	1.4E-2	0.0E+0	0.0E+0	3.8E-2	2.7E-3	0.0E+0	4.0E-2
Pb	3.4E-2	0.0E+0	0.0E+0	1.1E-1	4.0E-2	1.1E-2	1.3E-1
Na	5.7E-3	0.0E+0	0.0E+0	2.5E-2i	1.8E-2i	0.0E+0	3.1E-2i
H	1.4E-2	0.0E+0	0.0E+0	1.3E-2	0.0E+0	0.0E+0	2.0E-2
Total	2.3E-2	8.5E-2	6.5E-2	1.6E-1	5.9E-2	1.2E-2	2.0E-1



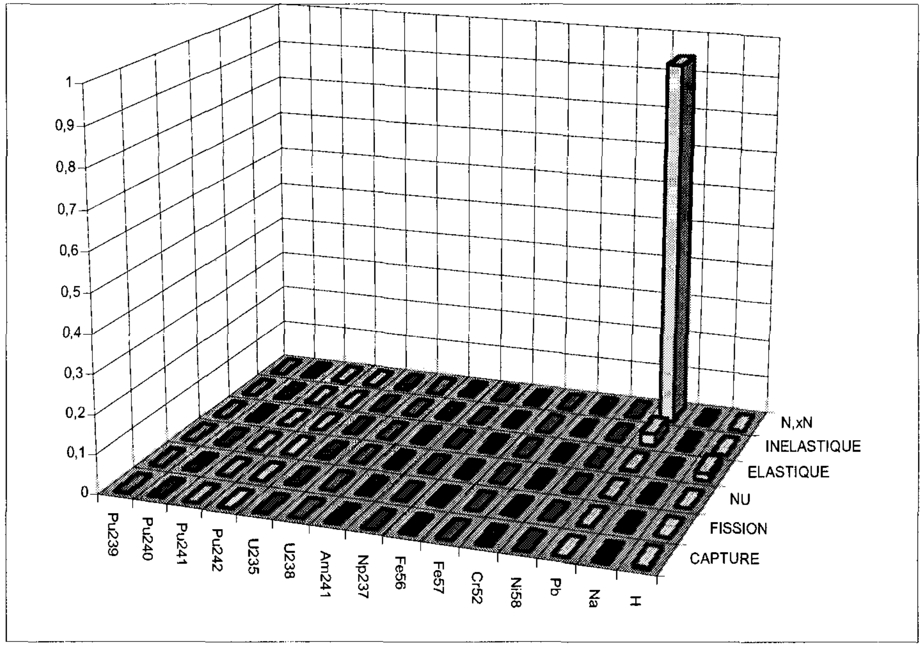
Keff Uncertainties (%) in the MUSE3 Pb Configuration - ERALIB1

MUSE Experiment

- Uncertainty on the integral fission rate ratio in the MUSE3 Pb configuration for the situations where the generator is successively on and off has been calculated using the dispersion matrices from JEF2.2 and ERALIB1.The absolute value of the uncertainty is 6.7% when using the JEF2.2 dispersion matrix; and 6.6% when using the ERALIB1 dispersion matrix. The most important contribution to the uncertainty in the two cases is due to the lead, particularly the *(n,2n)* reactions. As in the previous case (K_{eff}) when calculating the uncertainty of the ratio of two quantities, we eliminate most of the uncertainty coming from both the numerator and the denominator. In this specific case, we eliminate the uncertainty component due to the fissile isotopes. What is left consists of the uncertainty contributions that are not common to both the numerator and the denominator, e.g. the uncertainty due to the cross sections of lead, particularly the *(n,2n)* reaction that has an effect on the fission rate only when the generator is on (multiplication of the external source neutrons in the buffer zone).

The MUSE Experiment

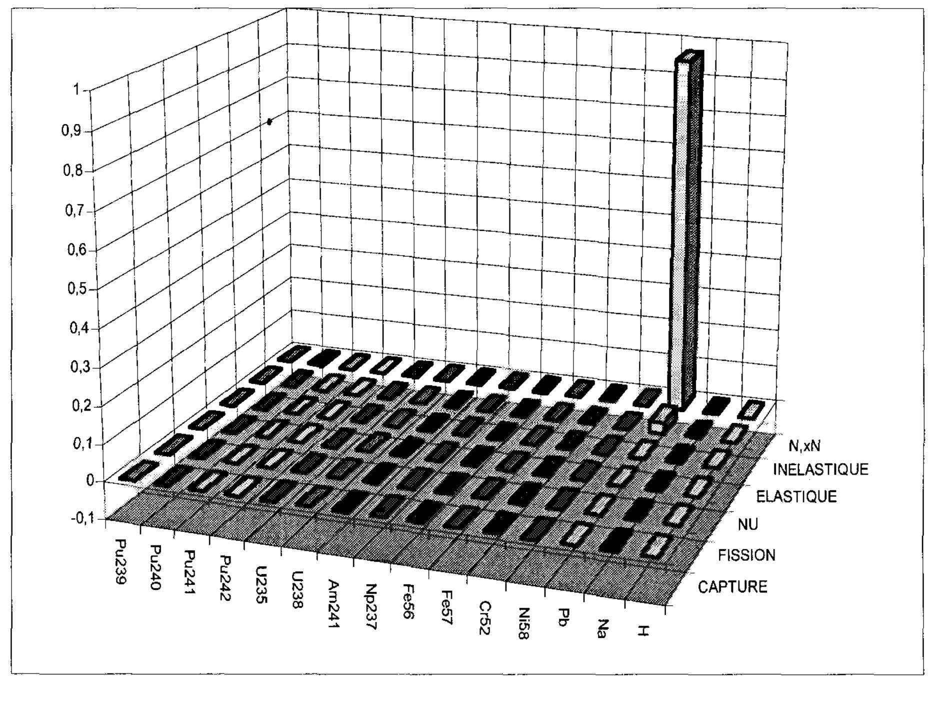
Isotope	σ_{cap}	σ_{fiss}	ν	σ_{el}	σ_{inel}	$\sigma_{n,2n}$	Total
Pu239	5.9E-2	1.8E-1	5.6E-2	1.3E-2	1.9E-2	7.4E-3	2.0E-1
Pu240	2.7E-2	3.3E-2	8.5E-3	7.0E-3	7.1E-3	3.8E-3	4.5E-2
Pu241	3.1E-3	1.3E-2	2.1E-3	5.6E-4	5.7E-4	3.6E-4	1.4E-2
Pu242	1.1E-3	9.8E-4	3.0E-4	2.7E-4	2.7E-4	3.3E-4	1.6E-3
U235	7.9E-4	6.6E-3	3.8E-4	2.2E-4	1.8E-4	8.0E-5	6.7E-3
U238	1.9E-2	1.3E-1	3.5E-2	3.2E-2	8.9E-2	5.6E-2	1.7E-1
Am241	3.2E-2	3.0E-2	1.0E-2	2.4E-4	2.3E-3	0.0E+0	4.5E-2
Np237	3.8E-8	7.2E-9	2.8E-9	4.3E-11	3.8E-10	0.0E+0	3.9E-8
Fe56	1.5E-1	0.0E+0	0.0E+0	1.3E-1	9.6E-2	0.0E+0	2.3E-1
Fe57	2.6E-3	0.0E+0	0.0E+0	5.8E-3	2.9E-2	0.0E+0	3.0E-2
Cr52	2.9E-2	0.0E+0	0.0E+0	3.1E-2	1.7E-1	0.0E+0	1.8E-1
Ni58	4.1E-2	0.0E+0	0.0E+0	2.7E-2	2.4E-2	0.0E+0	5.4E-2
Pb	8.8E-2	0.0E+0	0.0E+0	2.5E-1	1.2E+0	6.5E+0	6.6E+0
Na	4.8E-2	0.0E+0	0.0E+0	5.9E-2	7.2E-2	0.0E+0	1.0E-1
H	4.6E-1	0.0E+0	0.0E+0	9.0E-1	0.0E+0	0.0E+0	1.0E+0
Total	5.0E-1	2.3E-1	6.7E-2	9.5E-1	1.2E+0	6.5E+0	6.7E+0



Integral Fission Rate Ratio (Gen ON/OFF) Uncertainties (%) in the MUSE3 Pb Configuration - JEF2.2

The MUSE Experiment

Isotope	σ_{cap}	σ_{fiss}	ν	σ_{el}	σ_{inel}	$\sigma_{n,2n}$	Total
Pu239	1.8E-2	7.2E-2	2.9E-2	1.4E-2	2.1E-2	8.8E-3i	8.3E-2
Pu240	9.7E-3	2.3E-2	6.8E-3	8.0E-3	7.3E-3	6.0E-3i	2.7E-2
Pu241	2.5E-3i	7.8E-3	1.5E-3i	7.2E-4	5.3E-4	3.5E-4	7.3E-3
Pu242	1.5E-3	6.4E-4	3.1E-4	2.6E-4	2.6E-4	0.0E+0	1.7E-3
U235	7.0E-4i	7.8E-3	1.9E-3	7.0E-4	2.6E-4	1.7E-3i	7.8E-3
U238	9.2E-3	8.3E-2	3.5E-2	6.6E-3i	1.4E-2	5.5E-2	1.1E-1
Am241	0.0E+0	1.1E-2	0.0E+0	0.0E+0	0.0E+0	0.0E+0	1.1E-2
Np237	3.8E-8	7.2E-9	2.8E-9	4.3E-11	3.8E-10	0.0E+0	3.9E-8
Fe56	1.5E-1	0.0E+0	0.0E+0	3.1E-2	4.0E-2	0.0E+0	1.6E-1
Fe57	2.6E-3	0.0E+0	0.0E+0	5.8E-3	2.9E-2	0.0E+0	3.0E-2
Cr52	2.8E-2	0.0E+0	0.0E+0	2.7E-2	1.6E-1	0.0E+0	1.6E-1
Ni58	3.7E-2	0.0E+0	0.0E+0	2.5E-2	1.8E-2	0.0E+0	4.8E-2
Pb	8.8E-2	0.0E+0	0.0E+0	2.5E-1	1.2E+0	6.5E+0	6.6E+0
Na	4.7E-2	0.0E+0	0.0E+0	2.8E-2	4.1E-2	0.0E+0	6.8E-2
H	3.5E-2	0.0E+0	0.0E+0	4.6E-2	0.0E+0	0.0E+0	5.8E-2
Total	1.9E-1	1.1E-1	4.6E-2	2.6E-1	1.2E+0	6.5E+0	6.6E+0



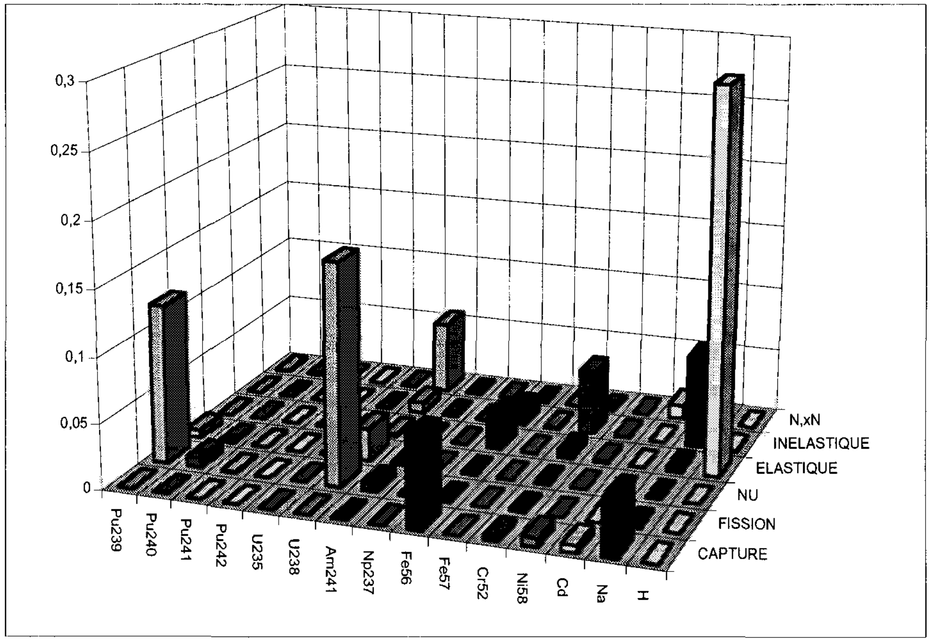
Integral Fission Rate Ratio (Gen ON/OFF) Uncertainties (%) in the MUSE3 Pb Configuration - ERALIB1

MUSE Experiment

- Uncertainty on the fission rate ratio $<\Sigma_f\Phi_S>_{ON}/<\Sigma_f\Phi_S>_{OFF}$ have been calculated also for the MUSE3 + Cd and MUSE3 SC3 configurations, using both the JEF2.2 and ERALIB1 dispersion matrices. In these configurations, because the buffer is not present, the lead reaction *(n,2n)* does not give any significant contribution

The MUSE Experiment

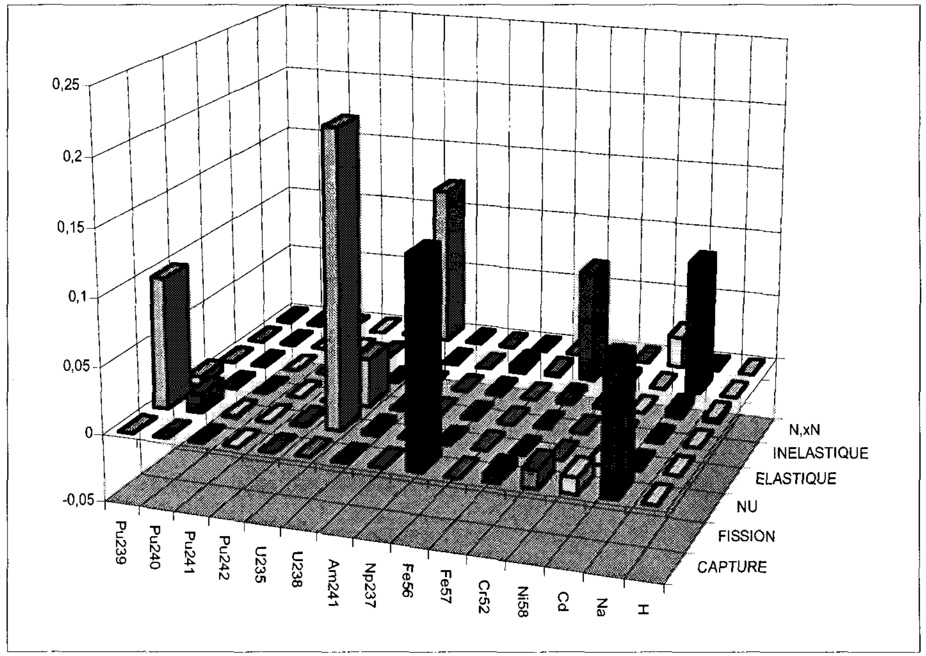
Isotope	σ_{cap}	σ_{fiss}	ν	σ_{el}	σ_{inel}	$\sigma_{n,2n}$	Total
Pu239	2.2E-2	3.7E-1	8.5E-2	1.4E-2	1.9E-2	3.2E-2	3.9E-1
Pu240	1.1E-2	9.2E-2	2.8E-2	8.4E-3	7.0E-3	1.7E-2	9.9E-2
Pu241	1.8E-3	2.2E-2	2.5E-3	6.9E-4	5.3E-4	1.6E-3	2.2E-2
Pu242	5.0E-4	3.0E-3	9.2E-4	3.2E-4	2.4E-4	1.5E-3	3.6E-3
U235	3.4E-4	1.5E-2	7.2E-4	2.5E-4	1.8E-4	3.4E-4	1.5E-2
U238	8.7E-3	4.4E-1	1.7E-1	3.6E-2	9.6E-2	2.5E-1	5.4E-1
Am241	1.6E-2	8.0E-2	2.6E-2	2.8E-4	2.3E-3	0.0E+0	8.5E-2
Np237	7.8E-9	2.8E-9	9.9E-10	6.0E-11	1.2E-10	0.0E+0	8.4E-9
Fe56	2.8E-1	0.0E+0	0.0E+0	1.7E-1	1.2E-1	0.0E+0	3.5E-1
Fe57	5.5E-3	0.0E+0	0.0E+0	8.7E-3	3.6E-2	0.0E+0	3.7E-2
Cr52	5.3E-2	0.0E+0	0.0E+0	7.7E-2	2.4E-1	0.0E+0	2.6E-1
Ni58	8.7E-2	0.0E+0	0.0E+0	3.4E-2	3.5E-2	0.0E+0	9.9E-2
Cd	7.7E-2	0.0E+0	0.0E+0	1.4E-2	9.6E-3	1.1E-1	1.3E-1
Na	2.2E-1	0.0E+0	0.0E+0	5.3E-2	2.8E-1	0.0E+0	3.6E-1
H	8.4E-3	0.0E+0	0.0E+0	5.8E-1	0.0E+0	0.0E+0	5.8E-1
Total	3.8E-1	5.9E-1	1.9E-1	6.1E-1	4.0E-1	2.8E-1	1.1E+0



Integral Fission Rate Ratio (Gen ON/OFF) Uncertainties (%) in the MUSE3 Cd Configuration - JEF2.2

The MUSE Experiment

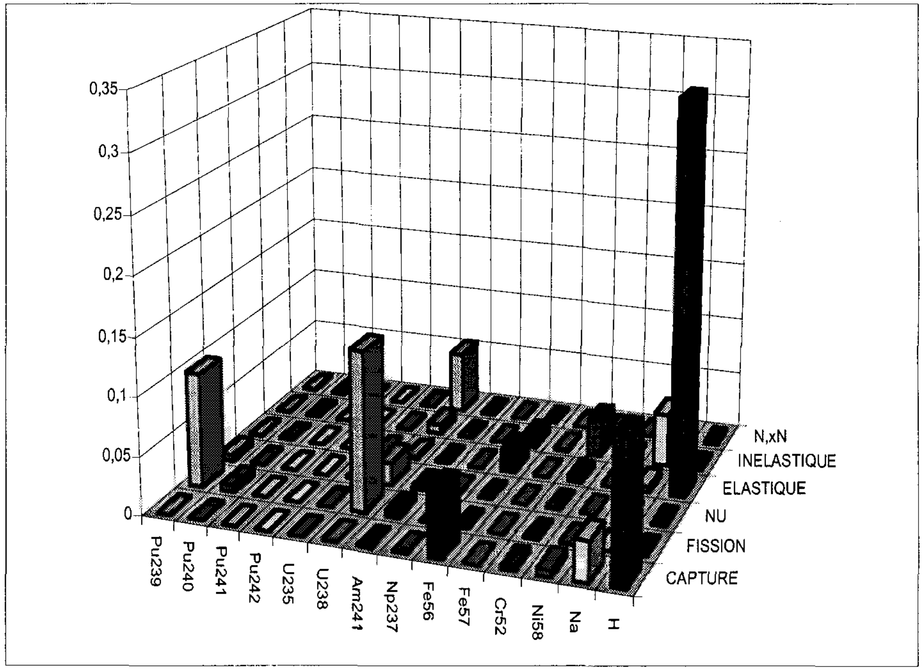
Isotope	σ_{cap}	σ_{fiss}	ν	σ_{el}	σ_{inel}	$\sigma_{n,2n}$	Total
Pu239	1.0E-2	2.2E-1	5.8E-2	1.0E-2	9.7E-3	1.9E-2i	2.3E-1
Pu240	4.0E-3	8.4E-2	2.3E-2	3.3E-3	5.7E-3	1.6E-2i	8.6E-2
Pu241	1.7E-3i	1.8E-2	2.5E-3i	6.4E-4	4.9E-4	1.5E-3	1.8E-2
Pu242	5.7E-4	7.1E-4i	9.7E-4	3.2E-4	2.4E-4	0.0E+0	9.6E-4
U235	1.6E-3	2.7E-2	2.3E-3i	1.5E-3	1.7E-3	4.6E-3i	2.7E-2
U238	6.8E-3	3.3E-1	1.3E-1	1.4E-2i	2.9E-2	2.5E-1	4.4E-1
Am241	0.0E+0	2.8E-2	0.0E+0	0.0E+0	0.0E+0	0.0E+0	2.8E-2
Np237	7.8E-9	2.8E-9	9.9E-10	6.0E-11	1.2E-10	0.0E+0	8.4E-9
Fe56	2.8E-1	0.0E+0	0.0E+0	2.3E-2	5.2E-2	0.0E+0	2.8E-1
Fe57	5.5E-3	0.0E+0	0.0E+0	8.7E-3	3.6E-2	0.0E+0	3.7E-2
Cr52	5.2E-2	0.0E+0	0.0E+0	3.5E-2	2.0E-1	0.0E+0	2.1E-1
Ni58	8.1E-2	0.0E+0	0.0E+0	2.4E-2	2.5E-2	0.0E+0	8.8E-2
Cd	7.7E-2	0.0E+0	0.0E+0	1.4E-2	9.6E-3	1.1E-1	1.3E-1
Na	2.2E-1	0.0E+0	0.0E+0	4.6E-2	2.2E-1	0.0E+0	3.1E-1
H	7.6E-4i	0.0E+0	0.0E+0	3.4E-2	0.0E+0	0.0E+0	3.4E-2
Total	3.7E-1	4.1E-1	1.5E-1	7.7E-2	3.1E-1	2.7E-1	7.1E-1



Integral Fission Rate Ratio (Gen ON/OFF) Uncertainties (%) in the MUSE3 Cd Configuration - ERALIB1

The MUSE Experiment

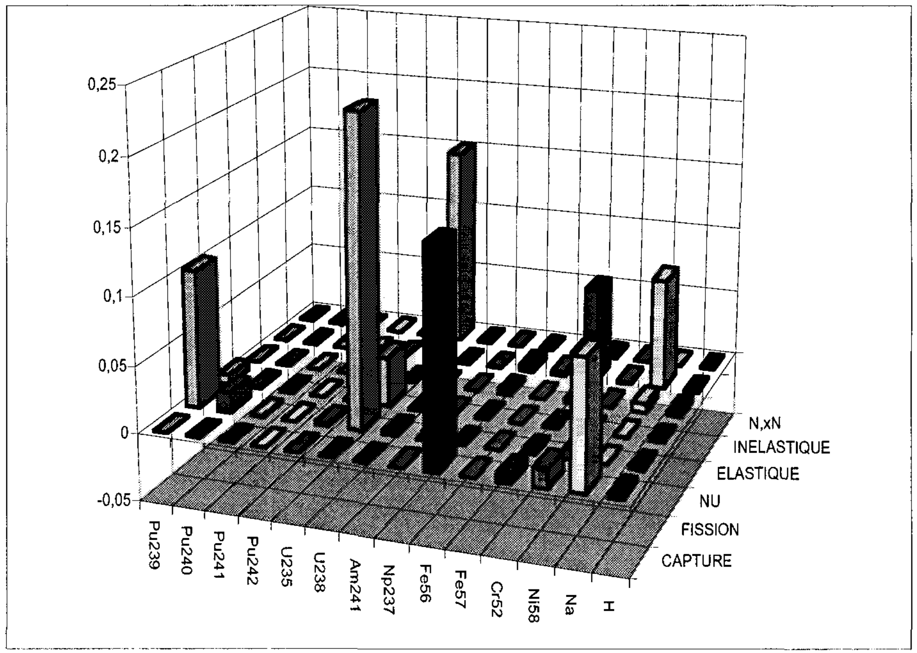
Isotope	σ_{cap}	σ_{fiss}	ν	σ_{el}	σ_{inel}	$\sigma_{n,2n}$	Total
Pu239	2.9E-2	4.3E-1	9.5E-2	2.0E-2	2.9E-2	4.1E-2	4.5E-1
Pu240	1.6E-2	1.1E-1	3.2E-2	1.2E-2	1.0E-2	2.2E-2	1.2E-1
Pu241	2.3E-3	2.6E-2	2.8E-3	9.4E-4	7.7E-4	2.0E-3	2.6E-2
Pu242	8.1E-4	3.5E-3	1.1E-3	4.4E-4	3.5E-4	1.9E-3	4.3E-3
U235	4.4E-4	1.8E-2	8.1E-4	3.5E-4	2.8E-4	4.3E-4	1.8E-2
U238	1.1E-2	5.1E-1	1.9E-1	5.0E-2	1.3E-1	3.2E-1	6.5E-1
Am241	2.4E-2	9.2E-2	3.0E-2	3.8E-4	3.3E-3	0.0E+0	1.0E-1
Np237	8.7E-9	3.4E-9	1.2E-9	7.0E-11	1.4E-10	0.0E+0	9.4E-9
Fe56	3.3E-1	0.0E+0	0.0E+0	1.9E-1	1.3E-1	0.0E+0	4.0E-1
Fe57	6.4E-3	0.0E+0	0.0E+0	9.2E-3	4.3E-2	0.0E+0	4.4E-2
Cr52	6.2E-2	0.0E+0	0.0E+0	8.4E-2	2.5E-1	0.0E+0	2.7E-1
Ni58	1.0E-1	0.0E+0	0.0E+0	3.9E-2	3.5E-2	0.0E+0	1.1E-1
Na	2.5E-1	0.0E+0	0.0E+0	9.2E-2	2.9E-1	0.0E+0	4.0E-1
H	4.8E-1	0.0E+0	0.0E+0	8.0E-1	0.0E+0	0.0E+0	9.3E-1
Total	6.5E-1	6.9E-1	2.2E-1	8.3E-1	4.3E-1	3.2E-1	1.4E+0



Integral Fission Rate Ratio (Gen ON/OFF) Uncertainties (%) in the MUSE3 SC3 Configuration - JEF2.2

The MUSE Experiment

Isotope	σ_{cap}	σ_{fiss}	ν	σ_{el}	σ_{inel}	$\sigma_{n,2n}$	Total
Pu239	1.3E-2	2.6E-1	6.7E-2	1.5E-2	1.7E-2	1.7E-2i	2.7E-1
Pu240	7.4E-3	9.8E-2	2.5E-2	6.0E-3	8.8E-3	1.6E-2i	1.0E-1
Pu241	2.2E-3i	2.1E-2	2.9E-3i	8.8E-4	7.2E-4	1.9E-3	2.1E-2
Pu242	1.4E-3	7.6E-4	1.1E-3	4.4E-4	3.5E-4	0.0E+0	2.1E-3
U235	1.7E-3	3.2E-2	2.5E-3i	2.0E-3	2.2E-3	5.2E-3i	3.1E-2
U238	3.3E-3i	3.9E-1	1.5E-1	1.2E-2i	3.9E-2	3.1E-1	5.2E-1
Am241	0.0E+0	3.2E-2	0.0E+0	0.0E+0	0.0E+0	0.0E+0	3.2E-2
Np237	8.7E-9	3.4E-9	1.2E-9	7.0E-11	1.4E-10	0.0E+0	9.4E-9
Fe56	3.2E-1	0.0E+0	0.0E+0	3.7E-2	5.4E-2	0.0E+0	3.3E-1
Fe57	6.4E-3	0.0E+0	0.0E+0	9.2E-3	4.3E-2	0.0E+0	4.4E-2
Cr52	6.1E-2	0.0E+0	0.0E+0	3.8E-2	2.1E-1	0.0E+0	2.2E-1
Ni58	9.3E-2	0.0E+0	0.0E+0	2.8E-2	2.5E-2	0.0E+0	1.0E-1
Na	2.5E-1	0.0E+0	0.0E+0	6.6E-2	2.3E-1	0.0E+0	3.5E-1
H	3.8E-2	0.0E+0	0.0E+0	4.2E-2	0.0E+0	0.0E+0	5.7E-2
Total	4.2E-1	4.8E-1	1.7E-1	1.0E-1	3.3E-1	3.1E-1	8.1E-1



Integral Fission Rate Ratio (Gen ON/OFF) Uncertainties (%) in the MUSE3 SC3 Configuration - ERALIB1

MUSE Experiment

- Physically one would expect to correlate the external source importance to a fission rate (integral or at a given point near to the external source) in the presence of the external source and to correlate the fission source importance to a fission rate without the external source. To this purpose, the variation of power when switching on the generator has been also measured. This indicates the relative amount of power created by the generator compared to the inherent source.
- From the Table we note that the subcriticality level does not affect the importance of the total source (inherent + fusion source) in the MUSE3 REF, SC1, SC2 and SC3 configurations, since the large change in reactivity from one configuration to another is obtained by modifying the outer boundary of the core, and not the vicinity of the source.

MUSE Experiment

Relative Power Measurements

Configuration	Relative Power generator OFF	Power variation with generator ON (measured)	Power variation with generator ON (calculated)		φ^* (calculated)	
MUSE3 REF	1.	5.82	4.62		1.58	
MUSE3 SC1	0.0878	5.68	4.55		1.58	
MUSE3 SC2	0.03376	5.50	4.69		1.58	
MUSE3 SC3	0.02541	5.70	4.87		1.58	
MUSE3 Pb	0.00916	4.30	3.70	3.27**	1.37	1.22**
MUSE3 Na	0.00861	3.64	3.15		1.18	

(with forcing the *(n,2n)* cross section in lead to be zero in the code)**

MUSE Experiment

- The relative amount of power due to the generator is therefore independent of the reactivity for these configurations. The introduction of a sodium or lead buffer zone has a dramatic effect on φ^* : indeed, the spectrum of the neutrons produced by the external source is modified by scattering reactions in the buffer, and they are less likely to produce fissions when they reach the core. This effect is very important in the case of the sodium buffer, whereas it is partially compensated by the *(n,2n)* reactions taking place in the lead buffer. The *(n,2n)* reactions in the lead buffer have an effect on the fission rate and on the source importance but they don't have any effect on the K_{eff}.

MUSE Experiment

- At this point we will study the correlation factor between the parameter φ^* and a fission rate ratio between situations where the neutron generator is successively switched on and off. In Table V the results obtained using the two sets of cross sections: JEF2.2 and ERALIB1.
- We can observe that the correlation factor is strong. For the MUSE3 Pb configuration the uncertainty profiles of the two parameters are dominated by the contribution due to the lead cross sections, particularly by the *(n,2n)* reaction. Further, because the lead cross sections are unadjusted, the passage from JEF2.2 library to the ERALIB1 library does not cause any change in the results.

MUSE Experiment

Correlation factor between φ^* and $(<\Sigma_f \Phi_S>_{ON} / <\Sigma_f \Phi_S>_{OFF})$

MUSE3 Pb Configuration	$\varphi^* \cap (<\Sigma_f \Phi_S>_{ON} / <\Sigma_f \Phi_S>_{OFF})$	
	JEF2.2	ERALIB1
Total Uncertainty [%] on the φ^*	6.48	6.42
Total Uncertainty [%] on the $(<\Sigma_f \Phi_S>_{ON} / <\Sigma_f \Phi_S>_{OFF})$	6.73	6.65
Correlation Factor	.99975	.99996
Reduced Uncertainty [%] on the φ^*	0.14	0.06
ABSOLUTE CALCULATED VALUES : $\varphi^* = 1.42$ $(<\Sigma_f \Phi_S>_{ON} / <\Sigma_f \Phi_S>_{OFF}) = 3.47$ $K_{eff} = 0.956333$		

MUSE Experiment

- We are also interested in the application of the same correlation factor analysis to the configuration MUSE + Cd and MUSE3 SC3 without buffer.
- The results (high correlation factors) confirm that the power change when the generator is switched on is directly linked to the importance of the source φ^{*}, . Therefore, the measurement of the ratio of fission rate with generator on and off will allow to reduce the uncertainty on the φ^{*} parameter.

MUSE Experiment

Correlation factor between φ^* and $(<\Sigma_f\Phi_S>_{ON}/<\Sigma_f\Phi_S>_{OFF})$

MUSE3 + Cd Configuration	$\varphi^* \cap (<\Sigma_f\Phi_S>_{ON}/<\Sigma_f\Phi_S>_{OFF})$	
	JEF2.2	ERALIB1
Total Uncertainty [%] on the φ^*	0.98	0.66
Total Uncertainty [%] on the $(<\Sigma_f\Phi_S>_{ON}/<\Sigma_f\Phi_S>_{OFF})$	1.07	0.71
Correlation Factor	.96010	.99648
Reduced Uncertainty [%] on the φ^*	0.28	0.06
Absolute calculated values: $\varphi^* = 1.53$ $(<\Sigma_f\Phi_S>_{ON}/<\Sigma_f\Phi_S>_{OFF}) = 3.96$ $K_{eff} = 0.985951$		

MUSE Experiment

Correlation factor between φ^* and $(<\Sigma_f\Phi_S>_{ON}/<\Sigma_f\Phi_S>_{OFF})$

MUSE3 SC3 Configuration	$\varphi^* \cap (<\Sigma_f\Phi_S>_{ON}/<\Sigma_f\Phi_S>_{OFF})$	
	JEF2.2	ERALIB1
Total Uncertainty [%] on the φ^*	1.02	0.65
Total Uncertainty [%] on the $(<\Sigma_f\Phi_S>_{ON}/<\Sigma_f\Phi_S>_{OFF})$	1.39	0.81
Correlation Factor	.85860	.99580
Reduced Uncertainty [%] on the φ^*	0.52	0.06
Absolute calculated values: : $\varphi^* = 1.56$ $(<\Sigma_f\Phi_S>_{ON}/<\Sigma_f\Phi_S>_{OFF})=4.26$ $K_{eff}=0.996090$		

Representativeness of MUSE

- Accelerator Driven Systems differ from the MUSE3 experiments essentially by three factors: the external source: (spallation for the first one, fusion source for the second}; coolant and fuel compositions; size.
- We will use the correlation methodology in order to quantify how relevant the MUSE3 experiments are with respect to actual ADS designs. A 100 MWth and 1500 MWth concepts will be considered in these calculations.

Representativeness of MUSE

- The 100 MWth option is designed with a liquid metal coolant (lead-bismuth) and is representative of a demonstration plant where, at first, the fuel will be UO_2-PuO_2 and where gradually more and more actinides with advanced fuel will be introduced . The UO_2-PuO_2 fuel has a Pu fuel fraction of less than 40% and gives a K_{eff} of about 0.97. The spallation source is produced by a 600 MeV proton beam on a lead-bismuth target.

Representativeness of MUSE

Representativity between MUSE-3 and a 100 MWth Pb-Bi ADS

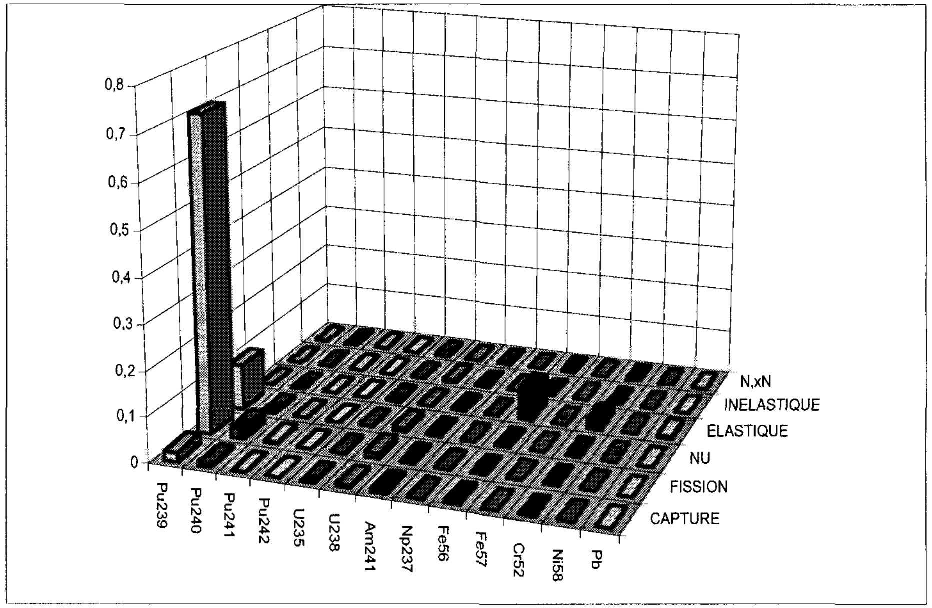
	k_{eff}		φ^*	
	JEF2.2	ERALIB1	JEF2.2	ERALIB1
Total Uncertainty [%] on the Reactor : MUSE3 Pb	1.64	0.22	6.42	6.42
Total Uncertainty [%] on the Experiment : Hybrid System	1.64	0.47	0.78	0.65
Representativity Factor	0.95161	0.74529	0.89830	0.97818
Reduced Uncertainty [%] on the Reactor	0.05	0.15	2.82	1.33
CALCULATED VALUES FOR THE HYBRID SYSTEM : $\varphi^*= 0.815$ $K_{eff}=0.96363$				

Representativeness of MUSE

The calculated uncertainties for k_{eff} and φ^* of the Hybrid System using the JEF2.2 and ERALIB1 dispersion matrix show that for the k_{eff} parameter using the unadjusted library JEF2.2 the uncertainty profiles are dominated by the contribution due to the Pu239 cross sections so that in this case the representativity of the MUSE3 experiment is important. When using the ERALIB1 adjusted library, the absolute value of the uncertainty is dominated by the contribution due to the unadjusted lead cross sections, and the uncertainty profiles of the two parameters change: the representativity between the two systems decreases sharply. For the φ^*, in both cases, JEF2.2 and ERALIB1, the Pu239 does not play any role. The two uncertainty profiles are dominated by the contribution due to the lead cross sections increasing the representativity factor.

Representativeness of MUSE

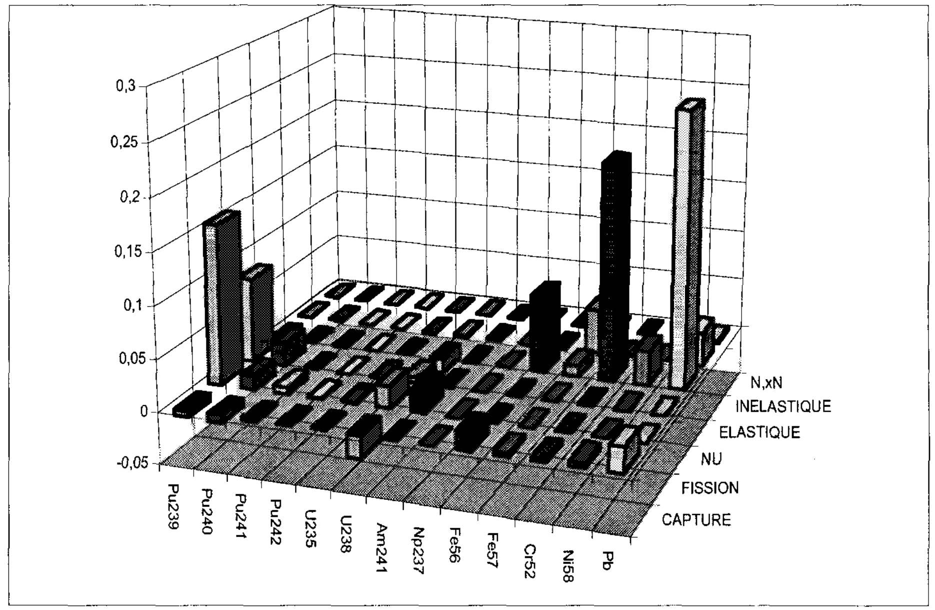
Isotope	σ_{cap}	σ_{fiss}	ν	σ_{el}	σ_{inel}	$\sigma_{n,2n}$	Total
Pu239	1.8E-1	1.2E+0	4.4E-1	7.2E-3	2.0E-2	4.0E-4	1.3E+0
Pu240	1.9E-1	4.4E-1	1.4E-1	8.0E-3	1.3E-2	3.3E-4	5.0E-1
Pu241	1.1E-1	5.6E-1	9.7E-2	2.7E-3	4.6E-3	9.4E-4	5.8E-1
Pu242	4.8E-2	9.7E-2	3.2E-2	2.6E-3	4.1E-3	2.7E-4	1.1E-1
U235	2.2E-3	2.7E-2	2.2E-3	1.2E-4	1.9E-4	8.1E-6	2.7E-2
U238	1.2E-1	1.2E-1	1.0E-1	2.2E-2	8.8E-2	3.5E-3	2.2E-1
Am241	9.9E-2	4.4E-2	1.5E-2	1.4E-4	2.2E-3	0.0E+0	1.1E-1
Np237	8.7E-17	4.5E-17	1.7E-17	2.1E-19	3.3E-18	0.0E+0	9.9E-17
Fe56	9.6E-2	0.0E+0	0.0E+0	3.8E-1	9.5E-2	0.0E+0	4.0E-1
Fe57	1.4E-2	0.0E+0	0.0E+0	1.7E-2	9.2E-2	0.0E+0	9.5E-2
Cr52	1.3E-2	0.0E+0	0.0E+0	1.1E-1	6.0E-3	0.0E+0	1.1E-1
Ni58	9.1E-4	0.0E+0	0.0E+0	1.1E-3	1.8E-4	0.0E+0	1.5E-3
Pb	3.2E-2	0.0E+0	0.0E+0	3.7E-1	1.4E-1	3.8E-2	4.0E-1
Total	3.4E-1	1.4E+0	4.8E-1	5.4E-1	2.1E-1	3.8E-2	1.6E+0



Keff Uncertainties (%) in the 100 MWth Hybrid System - JEF2

Representativeness of MUSE

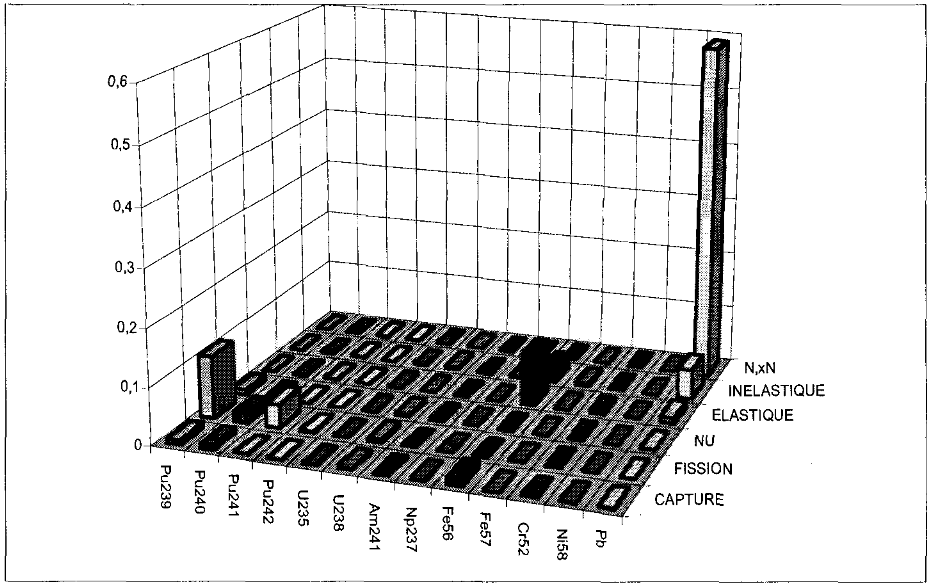
Isotope	σ_{cap}	σ_{fiss}	ν	σ_{el}	σ_{inel}	$\sigma_{n,2n}$	Total
Pu239	3.5E-2i	1.4E-1	2.7E-2	7.0E-3i	1.3E-2i	1.0E-3	1.4E-1
Pu240	1.8E-2i	5.9E-2	6.5E-2	9.8E-3i	7.9E-3	6.6E-4	8.6E-2
Pu241	2.9E-2	1.3E-1	7.9E-2	1.3E-3i	4.5E-3	9.2E-4	1.6E-1
Pu242	1.0E-2	2.5E-2	3.0E-2	2.6E-3	4.1E-3	0.0E+0	4.1E-2
U235	3.0E-3i	1.2E-2	3.2E-3	1.0E-3i	1.5E-3	2.5E-4	1.2E-2
U238	5.2E-2i	2.7E-2	3.9E-2i	2.7E-2i	3.0E-2i	3.0E-3	7.2E-2i
Am241	0.0E+0	2.5E-2	0.0E+0	0.0E+0	0.0E+0	0.0E+0	2.5E-2
Np237	8.7E-17	4.5E-17	1.7E-17	2.1E-19	3.3E-18	0.0E+0	9.9E-17
Fe56	5.7E-2	0.0E+0	0.0E+0	5.4E-2	3.0E-2	0.0E+0	8.4E-2
Fe57	1.4E-2	0.0E+0	0.0E+0	1.7E-2	9.2E-2	0.0E+0	9.5E-2
Cr52	7.0E-3	0.0E+0	0.0E+0	2.9E-2i	2.3E-3i	0.0E+0	2.9E-2i
Ni58	3.3E-3i	0.0E+0	0.0E+0	5.2E-3i	1.1E-3i	0.0E+0	6.2E-3i
Pb	3.2E-2	0.0E+0	0.0E+0	3.7E-1	1.4E-1	3.8E-2	4.0E-1
Total	3.5E-2	2.1E-1	1.0E-1	3.7E-1	1.6E-1	3.8E-2	4.7E-1



Keff Uncertainties (%) in the 100 MWth Hybrid System - ERALIB1

Representativeness of MUSE

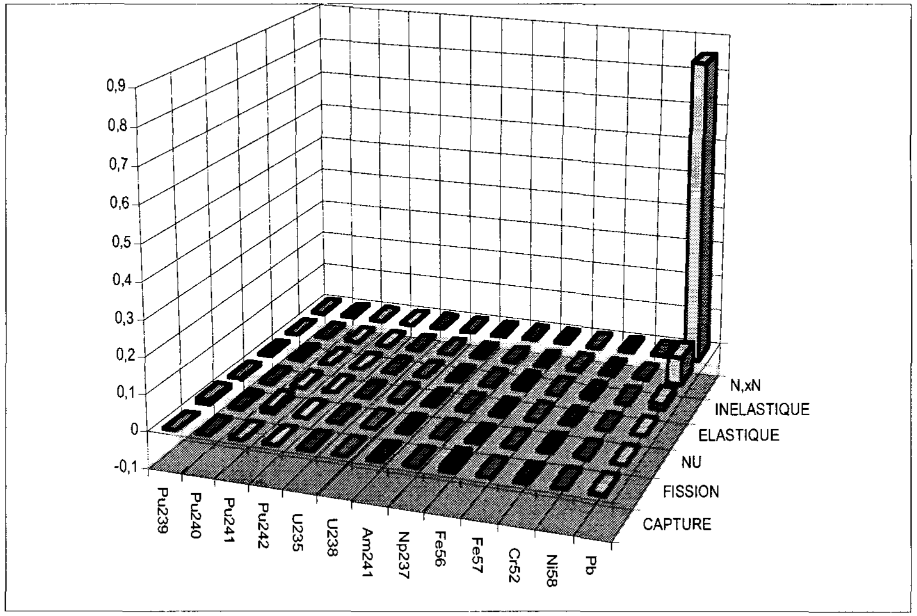
Isotope	σ_{cap}	σ_{fiss}	ν	σ_{el}	σ_{inel}	$\sigma_{n,2n}$	Total
Pu239	7.3E-2	2.6E-1	7.2E-2	3.9E-3	6.3E-3	4.1E-4	2.8E-1
Pu240	6.4E-2	1.0E-1	2.6E-2	4.5E-3	5.5E-3	5.8E-4	1.2E-1
Pu241	2.6E-2	1.6E-1	1.6E-2	1.6E-3	2.0E-3	2.3E-4	1.6E-1
Pu242	1.6E-2	2.6E-2	8.3E-3	1.5E-3	2.0E-3	4.5E-4	3.2E-2
U235	8.4E-4	6.8E-3	3.6E-4	6.5E-5	5.7E-5	6.2E-6	6.9E-3
U238	4.4E-2	5.7E-2	4.6E-2	1.2E-2	4.2E-2	4.0E-3	9.6E-2
Am241	3.5E-2	1.8E-2	6.0E-3	7.3E-5	1.0E-3	0.0E+0	3.9E-2
Np237	3.5E-17	1.3E-17	5.0E-18	1.2E-19	1.5E-18	0.0E+0	3.8E-17
Fe56	8.0E-2	0.0E+0	0.0E+0	2.4E-1	1.3E-1	0.0E+0	2.8E-1
Fe57	1.1E-2	0.0E+0	0.0E+0	7.5E-3	4.0E-2	0.0E+0	4.2E-2
Cr52	1.0E-2	0.0E+0	0.0E+0	4.1E-2	2.6E-2	0.0E+0	4.9E-2
Ni58	7.1E-4	0.0E+0	0.0E+0	7.5E-4	2.3E-4	0.0E+0	1.1E-3
Pb	3.2E-2	0.0E+0	0.0E+0	7.7E-2	1.8E-1	6.0E-1	6.3E-1
Total	1.5E-1	3.3E-1	9.2E-2	2.5E-1	2.3E-1	6.0E-1	7.9E-1



φ^* Uncertainties (%) in the 100 MWth Hybrid System - JEF2

Representativeness of MUSE

Isotope	σ_{cap}	σ_{fiss}	ν	σ_{el}	σ_{inel}	$\sigma_{n,2n}$	Total
Pu239	4.2E-3	6.7E-2	3.3E-2	5.2E-3i	7.7E-3	1.2E-3i	7.5E-2
Pu240	2.4E-2	3.3E-2	1.2E-2	7.2E-3i	6.2E-3	1.2E-3i	4.2E-2
Pu241	2.0E-2	7.6E-2	1.5E-2	5.1E-4	1.9E-3	2.2E-4	8.0E-2
Pu242	8.2E-3	6.9E-3	8.0E-3	1.5E-3	1.9E-3	0.0E+0	1.4E-2
U235	7.5E-4i	4.5E-3	2.5E-3	1.7E-4i	4.4E-4i	2.0E-4i	5.1E-3
U238	9.6E-3	1.1E-2	4.4E-2	9.1E-3	1.1E-2	4.2E-3	4.9E-2
Am241	0.0E+0	8.6E-3	0.0E+0	0.0E+0	0.0E+0	0.0E+0	8.6E-3
Np237	3.5E-17	1.3E-17	5.0E-18	1.2E-19	1.5E-18	0.0E+0	3.8E-17
Fe56	5.8E-2	0.0E+0	0.0E+0	5.1E-2	2.3E-2i	0.0E+0	7.4E-2
Fe57	1.1E-2	0.0E+0	0.0E+0	7.5E-3	4.0E-2	0.0E+0	4.2E-2
Cr52	8.3E-3	0.0E+0	0.0E+0	3.9E-2	2.2E-2	0.0E+0	4.6E-2
Ni58	1.1E-3i	0.0E+0	0.0E+0	4.6E-4i	4.5E-4	0.0E+0	1.1E-3i
Pb	3.2E-2	0.0E+0	0.0E+0	7.7E-2	1.8E-1	6.0E-1	6.3E-1
Total	7.6E-2	1.1E-1	5.9E-2	1.0E-1	1.8E-1	6.0E-1	6.5E-1



φ^* Uncertainties (%) in the 100 MWth Hybrid System - ERALIB1

Representativeness of MUSE

- The 1500 MWth ADS has a gas (helium) coolant and is representative of a typical ADS to be introduced in the existing nuclear park in order to reduce waste. The fuel is a “Pu + MA double strata”, that is coming from a Fast Reactor where it has been recycled several times. In the double strata approach, ADS are associated with PWR’s and FR’s, in order to reduce the amount of waste requiring disposal (in fact some residual losses exist in the reprocessing plants). The target and buffer are both made of liquid lead-bismuth.

Representativeness of MUSE

Representativity between MUSE-3 and a 1500 MWth Gas-Cooled ADS

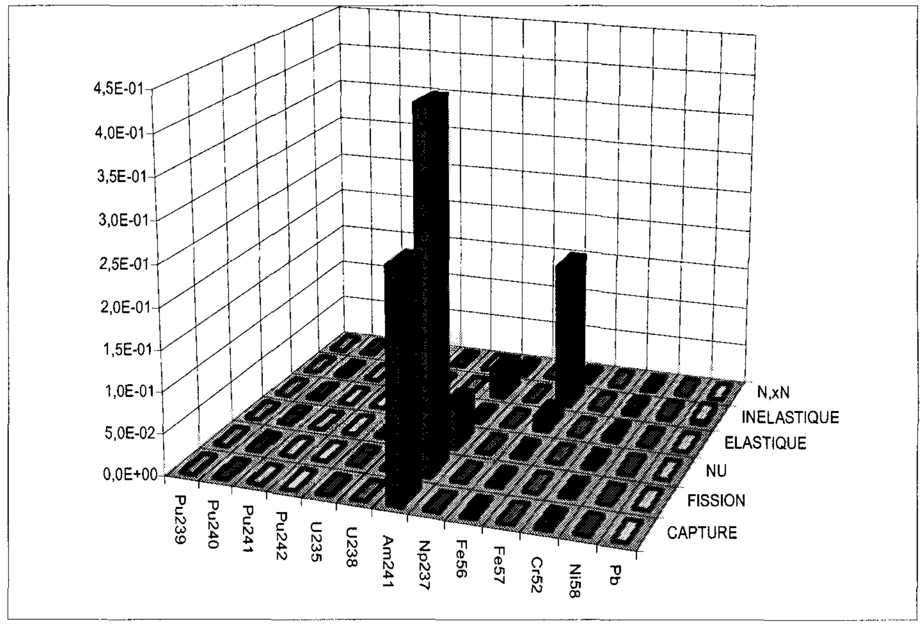
	k_{eff}		φ^*	
	JEF2.2	ERALIB1	JEF2.2	ERALIB1
Total Uncertainty [%] on the Reactor : MUSE3 Pb	1.64	0.22	6.42	6.42
Total Uncertainty [%] on the Experiment : Hybrid System	1.73	0.70	172	1.57
Representativity Factor	0.10927	0.22208	0.63409	0.16870
Reduced Uncertainty [%] on the Reactor	1.63	0.21	6.34	6.32
CALCULATED VALUES FOR THE HYBRID SYSTEM : φ^*= 1.01 K_{eff}=0.95408				

Representativeness of MUSE

For the φ^* parameter, one can observe that using the unadjusted library JEF2.2 the uncertainty profiles are dominated by the contribution due to the Pu239 cross sections so that in this case the correlation between the parameters analysed remains relatively high. When using the ERALIB1 adjusted library, the uncertainties profiles of the two parameters change: the correlation between the two systems decreases sharply. For the parameter K_{eff} in the two cases the uncertainty profiles make the correlation factor quite small (the 1500 MWth system is dominated by the uncertainty on Am241). One can conclude that MUSE3 is not representative of a commercial ADS of this type.This conclusion shows that although MUSE experiment brings a large contribution to the understanding of ADS systems, caution should be given to the different aspects of the measured values for transferring to the ADS neutronic characteristics.

Representativeness of MUSE

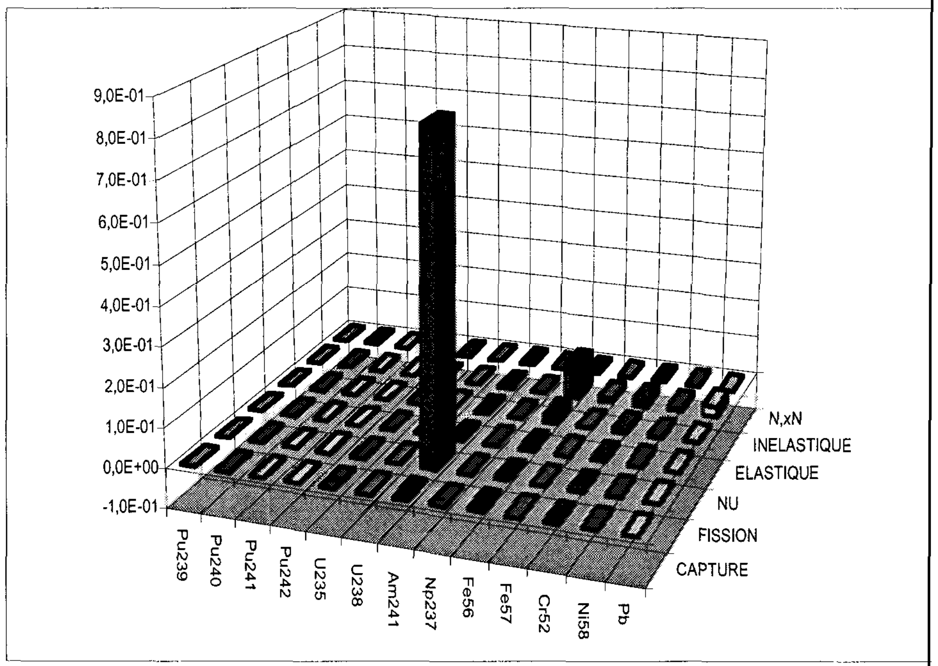
Isotope	σ_{cap}	σ_{fiss}	ν	σ_{el}	σ_{inel}	$\sigma_{n,2n}$	Total
Pu239	1,6E-17	2,6E-16	8,0E-17	1,2E-18	2,7E-17	2,1E-20	2,8E-16
Pu240	1,5E-17	9,8E-17	3,1E-17	1,6E-18	1,7E-17	1,0E-20	1,0E-16
Pu241	1,0E-17	1,1E-16	1,8E-17	5,2E-19	5,6E-18	5,3E-20	1,1E-16
Pu242	4,1E-18	2,1E-17	6,8E-18	5,1E-19	4,8E-18	8,5E-21	2,3E-17
U235	3,5E-20	2,5E-18	7,4E-20	3,7E-21	4,9E-20	0,0E+0	2,5E-18
U238	5,4E-21	5,0E-19	1,2E-20	1,7E-21	4,6E-20	5,3E-23	5,0E-19
Am241	9,1E-3	1,1E-2	3,9E-3	2,4E-5	3,2E-3	0,0E+0	1,5E-2
Np237	3,2E-19	4,6E-19	1,7E-19	1,7E-21	1,9E-19	0,0E+0	6,2E-19
Fe56	3,7E-4	0,0E+0	0,0E+0	2,1E-3	7,3E-3	0,0E+0	7,6E-3
Fe57	4,5E-5	0,0E+0	0,0E+0	1,1E-4	6,8E-4	0,0E+0	6,9E-4
Cr52	1,1E-4	0,0E+0	0,0E+0	8,6E-4	9,0E-4	0,0E+0	1,2E-3
Ni58	3,8E-4	0,0E+0	0,0E+0	1,5E-4	8,5E-4	0,0E+0	9,5E-4
Pb	4,7E-5	0,0E+0	0,0E+0	2,2E-4	1,1E-3	9,0E-6	1,1E-3
Total	9,1E-3	1,1E-2	3,9E-3	2,3E-3	8,2E-3	9,0E-6	1,7E-2



Keff Uncertainties (%) in the 1500 MWth Hybrid System – JEF2

Representativeness of MUSE

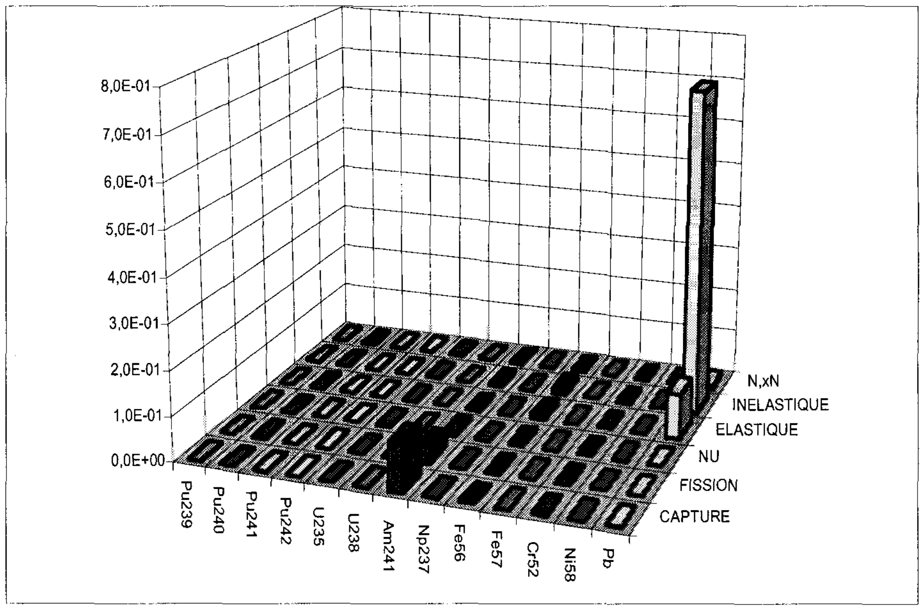
Isotope	σ_{cap}	σ_{fiss}	ν	σ_{el}	σ_{inel}	$\sigma_{n,2n}$	Total
Pu239	1,3E-11i	1,3E-10i	5,9E-11i	4,1E-12	1,2E-11	8,0E-13i	1,5E-10i
Pu240	1,0E-11i	4,6E-11i	3,4E-11i	3,6E-12	1,4E-11i	5,3E-13i	6,0E-11i
Pu241	3,0E-18	3,3E-11i	1,4E-17	3,7E-19i	5,4E-18	5,2E-20	3,3E-11i
Pu242	5,1E-16	2,6E-11i	6,5E-18	5,0E-19	4,7E-18	0,0E+0	2,6E-11i
U235	3,3E-13i	4,3E-12i	2,1E-12i	3,9E-13	1,7E-12i	6,7E-14i	5,0E-12i
U238	4,7E-13	1,1E-12i	1,1E-12	3,7E-13	6,3E-13	3,6E-16i	9,2E-13
Am241	0,0E+0	6,4E-3	0,0E+0	0,0E+0	0,0E+0	0,0E+0	6,4E-3
Np237	3,2E-19	4,6E-19	1,7E-19	1,7E-21	1,9E-19	0,0E+0	6,2E-19
Fe56	2,6E-4	0,0E+0	0,0E+0	8,4E-4	2,0E-3	0,0E+0	2,2E-3
Fe57	4,5E-5	0,0E+0	0,0E+0	1,1E-4	6,8E-4	0,0E+0	6,9E-4
Cr52	8,1E-5	0,0E+0	0,0E+0	5,3E-4	8,2E-4	0,0E+0	9,8E-4
Ni58	2,7E-4	0,0E+0	0,0E+0	1,6E-4	5,8E-4	0,0E+0	6,7E-4
Pb	4,7E-5	0,0E+0	0,0E+0	2,2E-4	1,1E-3	9,0E-6	1,1E-3
Total	3,9E-4	6,4E-3	6,8E-11i	1,0E-3	2,6E-3	9,0E-6	7,0E-3



Keff Uncertainties (%) in the 1500 MWth Hybrid System – ERALIB1

Representativeness of MUSE

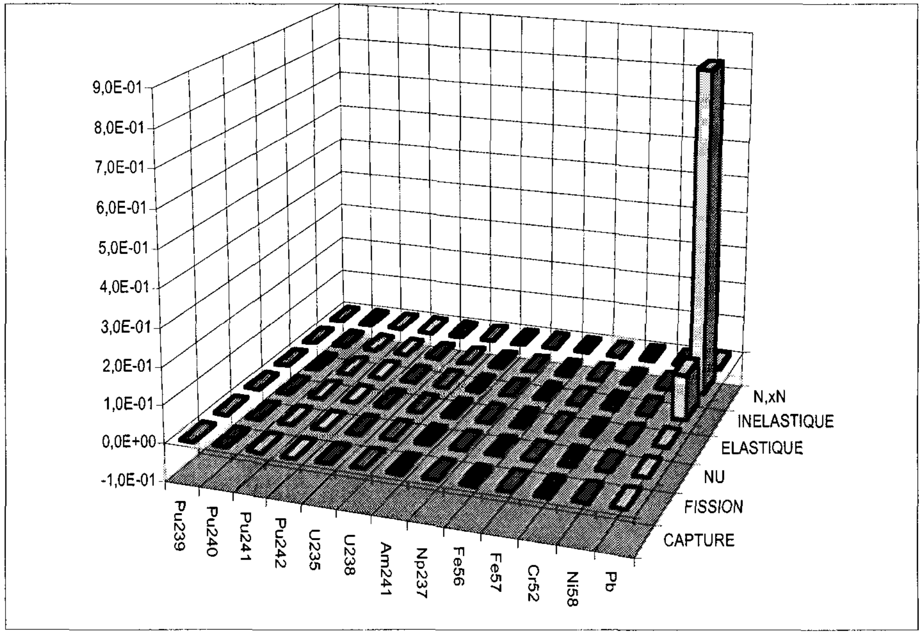
Isotope	σ_{cap}	σ_{fiss}	ν	σ_{el}	σ_{inel}	$\sigma_{n,2n}$	Total
Pu239	9,3E-18	1,3E-16	3,7E-17	2,7E-18	4,6E-18	5,3E-20	1,4E-16
Pu240	8,5E-18	3,4E-17	7,9E-18	3,0E-18	2,6E-18	6,0E-20	3,7E-17
Pu241	4,6E-18	6,4E-17	8,3E-18	1,0E-18	9,9E-19	5,5E-20	6,4E-17
Pu242	2,1E-18	6,1E-18	1,4E-18	9,6E-19	8,6E-19	4,6E-20	6,8E-18
U235	2,0E-20	1,4E-18	3,5E-20	8,1E-21	1,0E-20	1,8E-22	1,4E-18
U238	2,9E-21	1,4E-19	1,6E-21	4,2E-21	1,2E-20	1,9E-22	1,4E-19
Am241	5,6E-3	3,2E-3	1,1E-3	6,4E-5	9,3E-4	0,0E+0	6,6E-3
Np237	1,9E-19	1,7E-19	6,0E-20	3,7E-21	5,4E-20	0,0E+0	2,7E-19
Fe56	2,6E-4	0,0E+0	0,0E+0	1,6E-3	1,8E-3	0,0E+0	2,4E-3
Fe57	2,2E-5	0,0E+0	0,0E+0	5,3E-5	3,9E-4	0,0E+0	4,0E-4
Cr52	4,9E-5	0,0E+0	0,0E+0	4,2E-4	3,4E-4	0,0E+0	5,4E-4
Ni58	8,3E-5	0,0E+0	0,0E+0	1,8E-4	1,4E-4	0,0E+0	2,5E-4
Pb	3,4E-4	0,0E+0	0,0E+0	5,4E-3	1,5E-2	1,4E-3	1,6E-2
Total	5,6E-3	3,2E-3	1,1E-3	5,7E-3	1,5E-2	1,4E-3	1,7E-2



_* Uncertainties (%) in the 1500 MWth Hybrid System – JEF2

Representativeness of MUSE

Isotope	σ_{cap}	σ_{fiss}	ν	σ_{el}	σ_{inel}	$\sigma_{n,2n}$	Total
Pu239	5,2E-12i	4,5E-11i	2,6E-11i	4,1E-12	3,6E-12i	1,0E-12i	5,2E-11i
Pu240	4,5E-12i	1,5E-11i	1,1E-11i	2,8E-12	1,3E-12i	1,0E-12i	1,8E-11i
Pu241	5,3E-19i	1,6E-11i	7,2E-18	1,0E-18	9,5E-19	5,4E-20	1,6E-11i
Pu242	2,8E-16	3,9E-12i	1,3E-18	9,5E-19	8,5E-19	0,0E+0	3,9E-12i
U235	2,1E-13i	1,6E-12i	9,8E-13i	3,2E-13	1,9E-13i	9,7E-14i	1,9E-12i
U238	2,3E-13	1,0E-13i	1,2E-13i	2,8E-13	1,6E-13	5,8E-16i	3,6E-13
Am241	0,0E+0	9,1E-4	0,0E+0	0,0E+0	0,0E+0	0,0E+0	9,1E-4
Np237	1,9E-19	1,7E-19	6,0E-20	3,7E-21	5,4E-20	0,0E+0	2,7E-19
Fe56	2,3E-4	0,0E+0	0,0E+0	5,4E-4	1,9E-4	0,0E+0	6,2E-4
Fe57	2,2E-5	0,0E+0	0,0E+0	5,3E-5	3,9E-4	0,0E+0	4,0E-4
Cr52	4,3E-5	0,0E+0	0,0E+0	3,4E-4	3,2E-4	0,0E+0	4,7E-4
Ni58	7,4E-5	0,0E+0	0,0E+0	1,4E-4	9,5E-5	0,0E+0	1,8E-4
Pb	3,4E-4	0,0E+0	0,0E+0	5,4E-3	1,5E-2	1,4E-3	1,6E-2
Total	4,2E-4	9,1E-4	2,8E-11i	5,5E-3	1,5E-2	1,4E-3	1,6E-2



_* Uncertainties (%) in the 1500 MWth Hybrid System –ERALIB1

Conclusions

- A methodology based on sensitivity profiles and use of dispersion matrix allows to quantify in terms of uncertainties the impact of data on the main neutronic integral design parameters of an ADS
- Application to an ATW model show that uncertainty larger (about a factor two) than that typical of a large size reactor are found. These types of uncertainties will be unacceptable even at a preconceptual design stage.
- Application to the MUSE experimental program has highlighted the critical role of the lead cross sections. The use of adjusted cross section sets can reduce drastically the total uncertainty. Representativity of the experiments is somewhat limited.