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# **A NEW APPROACH FOR ANALYSING THE IMPACT OF NUCLEAR DATA UNCERTAINTIES ON THE ASTRID SODIUM VOID REACTIVITY EFFECT**

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## **ABSTRACT**

For ensuring sustainable nuclear energy, France has chosen to develop sodium cooled fast reactors. The ASTRID project is a demonstrator of such technology exhibiting innovative features such as the CFV core which has a negative sodium void reactivity effect. In order to study in details the uncertainty associated to this parameter, we split it into two components : the central component (CC) which is a positive reactivity effect due to spectrum changes and the leakage component (LC) which is a negative reactivity effect due to the increase of the neutron mean free path. This paper presents the development of an innovative GPT procedure for computing sensitivities of the CC and the LC. With such sensitivities and the use of the COMAC-V2 covariance matrix, we are able to calculate the uncertainties due to nuclear data on each component using JEFF-3.2 nuclear data. The application of the method to the ASTRID CFV core shows a 2.44% uncertainty on the CC, a 2.98% uncertainty on the LC and a 14.8% on the total sodium void reactivity effect. There is a correlation factor of -0.5776 between the LC and CC uncertainties. This approach gives perspectives in studying experimental programmes performed in zero power facilities such as MASURCA.

**KEYWORDS:** Sodium Void Reactivity Effect, GPT, ASTRID, nuclear data sensitivities and uncertainties.

## **1 INTRODUCTION**

The future of nuclear energy involves the development of the 4<sup>th</sup> generation of nuclear reactors such as Sodium cooled Fast Reactors (SFR). These reactors have to implement an enhanced safety but they also have to burn radioactive waste like Plutonium, one of the main contributors to radiotoxicity. Furthermore using the whole uranium ore as a fuel ensures the sustainability of this energy which is one of the main concerns of this century. France has chosen to build an advanced demonstrator of SFR technology, the so-called ASTRID reactor (which stands for Advanced Sodium Technological Reactor for Industrial Demonstration). This design is built on the “CFV core” which is designed to get a negative sodium void reactivity effect. In case of loss of coolant the number of neutrons leaking out of the core increases and the energy spectrum becomes harder; these two antagonistic effects are part of the sodium void reactivity effect. Each effect is affected by nuclear data uncertainties and needs to be calculated precisely. In this paper, we present a way to get the sensitivity of each component to nuclear data and hence uncertainties on each of these components.

## 2 The ASTRID CFV core

### 2.1 The ASTRID CFV core lay out

The Advanced Sodium Technological Reactor for Industrial Demonstration (ASTRID)[1] project aims at building a sodium fast demonstrator in the next ten years. An innovative core design has been selected by CEA: the so-called “CFV core”. These innovations, concerning the geometry, have been conceived to ensure the natural shutdown of the chain reaction in case of loss of coolant. In this accidental situation the energy spectrum of neutrons is harder because they are not anymore scattered on sodium nuclei. Furthermore a harder spectrum means that neutrons production by fission is increased. The associated reactivity effect is positive and is defined as the central component. However the total cross section is decreased allowing more neutrons to leak out of the core, this negative reactivity effect is the leakage component and it has to be greater than the central component for safety reasons. The CFV core has four major innovations to get the highest leakage component in case of sodium void: an outer core higher than the inner core, a fertile slab in the inner core, a plenum sodium on the core and neutronic absorber on the plenum sodium (see figure 2.1).

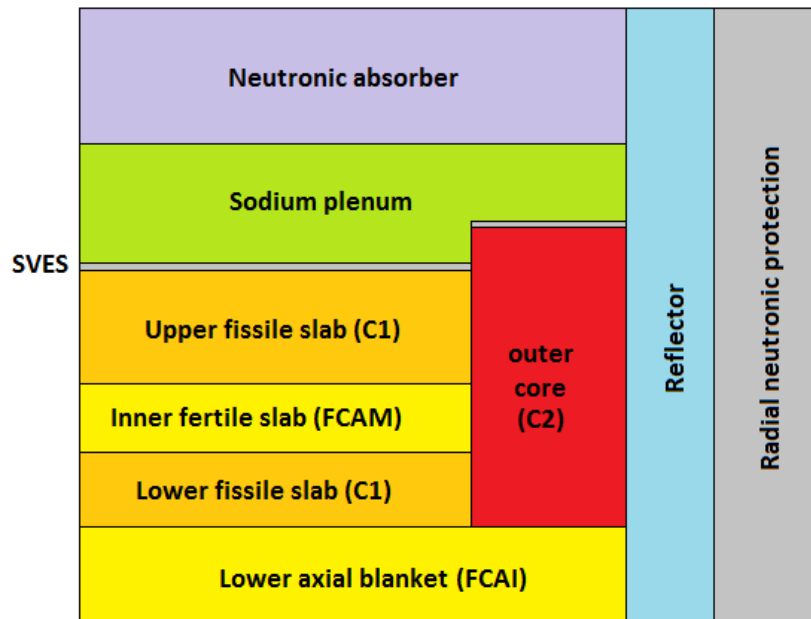


Figure 2.1: RZ geometry of the CFV core

### 2.2 The sodium void reactivity effect in ASTRID CFV core

The sodium void reactivity effect is breakdown into a central component and a leakage component.

$$\Delta\rho_{Na} = CC + LC$$

ASTRID core design exhibits very innovative features compared to past reactors (such as Super-Phénix). The ASTRID core is very heterogeneous [2] and achieves negative sodium void reactivity effect through the existence of a large leakage component (Table 2.1). Sodium void reactivity effect are measured in  $\$$  which is the reactivity difference normalised by the effective delayed neutron fraction.

**Table 2.1: Break down of sodium void reactivity effect in the ASTRID CFV core with JEFF-3.2**

	Void Effect	Central Component	Leakage component
$\Delta\rho_{Na}$ (pcm, \$)	-550 (-1.4\$)	2773 (7.1\$)	-3323 (-8.5\$)

The ERANOS code system makes use of the effective cross sections produced by the ECCO cell code (P1 consistent order 1 approximation) to perform full reactor calculations. To determine these two components, perturbation calculations were performed using the ERANOS code system with transport theory (S8 P1 approximation). The separation of the leakage and the non-leakage components of the reactivity worth in transport theory is performed in the following way :

$$LC = \sum_g \delta\Sigma_t^g \left( \frac{1}{(4\pi^2)} \int_{4\pi} \Psi_g d\vec{\Omega} \int_{4\pi} \Psi_g^+ d\vec{\Omega} - \frac{1}{4\pi} \int_{4\pi} \Psi_g \Psi_g^+ d\vec{\Omega} \right) + \text{high order scattering terms.} \quad 2.1$$

where  $\Psi_g$  and  $\Psi_g^+$  are respectively the direct and adjoint angular fluxes. The leakage component is negative and takes into account the increase of the mean free path of neutrons when the core is voided.

The central component is the sum of physical variations: capture, fission, spectrum, elastic removal, inelastic removal and n,xn removal which are globally positive. It can be calculated directly using the scalar direct and adjoint fluxes.

**Table 2.2: Breakdown of sodium void reactivity effect by reaction and by domain in the ASTRID CFV core with JEFF-3.2 (in pcm)**

Domain	Capture	Fission	Spectrum	Leakage	Elastic	Inelastic	N,XN	Sum
C1	135.5	3.9	6.7	-358.7	535.4	416.6	-0.3	739.1
C2	129.2	-0.2	4.4	-367.3	350.8	270.8	-0.2	387.5
FCAM	39.3	-0.5	-0.2	-40.0	282.7	86.2	0.0	367.4
FCAI	0.0	0.0	0.0	-0.1	1.6	0.2	0.0	1.6
FCALE	1.6	0.0	0.0	-33.9	6.6	3.5	0.0	-22.1
SVES	4.0	0.0	0.0	-224.0	32.2	14.9	0.0	-172.9
PLENUM	20.4	0.0	0.0	-2299.4	325.4	103.3	0.0	-1850.2
Sum	330.0	3.2	10.9	-3323.5	1534.8	895.6	-0.5	-549.6

### 3 Sensitivity of the sodium void reactivity effect to nuclear data

In the following parts the notations used are for integrals on space, energy and angle:

$$\langle f \rangle = \int_V d^3r \int_{4\pi} d^2\Omega \int_0^\infty dE f(\vec{r}, \vec{\Omega}, E) \quad 3.1$$

$$\langle f | g \rangle = \int_V d^3r \int_{4\pi} d^2\Omega \int_0^\infty dE f(\vec{r}, \vec{\Omega}, E) g(\vec{r}, \vec{\Omega}, E) \quad 3.2$$

We define also two operators: **A** the transport, removal and scattering operator and **F** the fission source operator. In a critical system we get the neutron flux and his adjoint flux with the forward and adjoint Boltzmann equations 3.3.

$$\left( \mathbf{A} - \frac{\mathbf{F}}{k} \right) \Phi = 0 \quad \text{and} \quad \left( \mathbf{A}^+ - \frac{\mathbf{F}^+}{k^+} \right) \Phi^+ \quad 3.3$$

### 3.1 Sensitivities to nuclear data

The sensitivity of a given parameter  $P$  to a nuclear data  $\sigma$ , such as a microscopic section or an energy spectrum, is:

$$S(P, \sigma) = \frac{dP}{P} / \frac{d\sigma}{\sigma} \quad 3.4$$

The sensitivity of the reactivity to nuclear data  $S(\rho, \sigma)$  can be obtained with the exact Standard Perturbation Theory (SPT) formula (see 3.5) which gives the reactivity variation between the nominal state (noted “n”) and the perturbed state (noted “p”):

$$d\rho = \frac{dk}{k^2} = - \frac{\langle \Phi_n^+ | \left( d\mathbf{A}_n - \frac{d\mathbf{F}_n}{k_n} \right) \Phi_n^p \rangle}{\langle \Phi_n^+ | \mathbf{F} \Phi_n^p \rangle} \quad 3.5$$

The reactivity variation is related to the multiplication factor  $k$  with:  $\rho = 1 - \frac{k}{k}$  meaning that :  $\frac{d\rho}{\rho} = \frac{dk}{k(k-1)}$ . Furthermore the operators ( $\mathbf{A}$  and  $\mathbf{F}$ ) of the Boltzmann equation vary linearly with nuclear data so the derivation of the operators is restricted to the considered nuclear data  $\sigma$ .

$$S(\rho, \sigma) = \frac{d\rho}{\rho} / \frac{d\sigma}{\sigma} = - \frac{k}{k-1} \frac{\langle \Phi_n^+ | \left( d\mathbf{A}_n - \frac{d\mathbf{F}_n}{k_n} \right) \Phi_n^p \rangle_{\sigma}}{\langle \Phi_n^+ | \mathbf{F} \Phi_n^p \rangle} \quad 3.6$$

### 3.2 The EGPT method to calculate the sensitivity of the total sodium void reactivity effect

The sodium void reactivity effect is the difference between the nominal reactivity (n) and the voided (v) configuration reactivity  $\Delta\rho = \rho_v - \rho_n$ . In order to vary this reactivity effect we can use twice the exact SPT formula which perturbs the two configurations as follow:

$$d(\Delta\rho) = d\rho_v - d\rho_n = - \frac{\langle \Phi_v^+ | \left( d\mathbf{A}_v - \frac{d\mathbf{F}_v}{k_v} \right) \Phi_v^p \rangle}{\langle \Phi_v^+ | \mathbf{F} \Phi_v^p \rangle} + \frac{\langle \Phi_n^+ | \left( d\mathbf{A}_n - \frac{d\mathbf{F}_n}{k_n} \right) \Phi_n^p \rangle}{\langle \Phi_n^+ | \mathbf{F} \Phi_n^p \rangle} \quad 3.7$$

With :  $d\mathbf{A}_i = \mathbf{A}_i^p - \mathbf{A}_i$  and  $d\mathbf{F}_i = \mathbf{F}_i^p - \mathbf{F}_i$ ,  $i \in \{n, v\}$ .

This formula is called the first order Equivalent Generalised Perturbation Theory (EGPT). Using twice the SPT is much easier to implement in neutronic code than applying the Generalised Perturbation Theory (GPT) on the sodium void reactivity effect (which would have been exact) that is why it is called “equivalent”. The results of the EGPT applied to sodium void reactivity effect in the ASTRID core are given in the following table 3.1.

**Table 3.1 : Sensitivities (%/%) of the total sodium void reactivity effect to nuclear data with JEFF-3.2**

Isotope	Fission	Capture	Elastic	Inelastic	N,xN	Nu	Spectrum	Sum
B10	0.00E+0	-4.91E-1	-3.85E-3	-1.64E-4	0.00E+0	0.00E+0	0.00E+0	-4.95E-1
B11	0.00E+0	-7.74E-6	1.68E-2	-1.65E-4	-9.88E-8	0.00E+0	0.00E+0	1.67E-2
Na23	0.00E+0	-2.38E-1	1.30E+0	-1.02E+0	3.86E-5	0.00E+0	0.00E+0	4.05E-2
O16	0.00E+0	4.39E-2	3.30E-1	5.87E-3	-1.94E-8	0.00E+0	0.00E+0	3.79E-1
Fe56	0.00E+0	-2.28E-1	-2.29E-1	1.75E-1	-1.14E-4	0.00E+0	0.00E+0	-2.82E-1
U238	-9.30E-1	-1.49E+0	-2.44E-1	6.85E-1	3.34E-3	-1.47E+0	-1.62E+0	-5.06E+0
Pu238	-1.95E-2	-7.22E-2	-2.61E-3	1.92E-3	-2.16E-5	-1.69E-2	-2.13E-2	-1.31E-1
Pu239	6.74E-1	-8.10E-1	-2.03E-2	2.56E-2	2.67E-5	1.14E+0	1.28E+0	2.28E+0
Pu240	-8.25E-1	-5.52E-1	-1.88E-2	2.47E-2	5.04E-4	-1.15E+0	-1.25E+0	-3.77E+0
Pu241	5.71E-1	-1.01E-1	-4.62E-3	5.78E-3	-2.79E-4	8.45E-1	9.53E-1	2.27E+0
Pu242	-2.58E-1	-1.62E-1	-8.21E-3	9.14E-3	-1.31E-4	-3.57E-1	-3.78E-1	-1.15E+0
SUM	-7.85E-1	-4.24E+0	8.75E-1	-1.12E-2	8.77E-3	-1.00E+0	-1.00E+0	-6.15E+0

The mains contributors to the sensitivity of the total sodium void reactivity effect are the capture, fission, spectrum and nu contribution of U238, Pu240 and Pu239 which are the main isotopes of the ASTRID fuel (with low quality Plutonium) then the spectrum effect have an important impact on these isotopes cross sections. Obviously elastic and inelastic cross sections of Na23 are also big contributors to the sensitivity.

### 3.3 The GPT method to calculate the sensitivity of the central component

The GPT allows to calculate exactly the sensitivity of others parameters than reactivity or multiplication factor to nuclear data, for instance using GPT [3], we can compute the sensitivity of reaction rate, reaction rate ratio, etc. The central component is the sum of the variation between the nominal and the voided configuration of different physical components: the capture, the fission, the production, the spectrum, the scattering removal (elastic plus inelastic plus “n,xn” removal). In ERANOS [4] [5] the energy range is breakdown into 33 groups of energy, for each group “g” the physical components are weighed by the adjoint flux as follow:

$$\text{Capture} \quad C_c^g = -\delta\Sigma_c^g \cdot \int_V \Phi_g^+ \cdot \Phi_g dV \quad 3.8$$

$$\text{Fission} \quad C_f^g = -\delta\Sigma_f^g \cdot \int_V \Phi_g^+ \cdot \Phi_g dV + \delta(\nu\Sigma_f^g) \cdot \int_V \Phi_g \sum_{g'} \chi_g \Phi_{g'}^+ dV \quad 3.9$$

$$\text{Production} \quad C_v^g = \delta(\nu\Sigma_f^g) \cdot \int_V \Phi_g \sum_{g'} \chi_g \Phi_{g'}^+ dV \quad 3.10$$

$$\text{Spectrum} \quad C_{\text{spec}}^g = \delta\chi^g \int_V \Phi_g^+ \cdot \sum_{g'} \nu\Sigma_f^{g'} \Phi_{g'} dV \quad 3.11$$

$$\text{Scattering} \quad C_{\text{scatt}}^g = \sum_{g'} \delta\Sigma_{\text{scatt}}^{g \rightarrow g'} \left( \int_V \Phi_{g'}^+ \cdot \Phi_g dV - \int_V \Phi_g^+ \cdot \Phi_{g'} dV \right) \quad 3.12$$

This sum of physical component is a reactivity variation and GPT can be applied in this case to compute the sensitivity of the CC to nuclear data :  $S(\text{CC}) = \frac{d\text{CC}}{\text{CC}} / \frac{d\sigma}{\sigma}$ . The derivation of the CC (function of nuclear data  $\sigma$ , the flux  $\Phi$  and adjoint flux  $\Phi^+$ ) is done using two Lagrange multipliers  $\Psi$  et  $\Psi^+$  (called generalised importances functions), we get the variation of the functional T defined as follow :

$$T = \ln(\langle CC(\sigma, \Phi, \Phi^+) \rangle) - \left\langle \Psi^+ \left| \left( \mathbf{A} - \frac{\mathbf{F}}{k} \right) \Phi \right. \right\rangle - \left\langle \Psi \left| \left( \mathbf{A}^+ - \frac{\mathbf{F}^+}{k^+} \right) \Phi^+ \right. \right\rangle \quad 3.13$$

$$dT = \frac{dCC}{CC} - \left\langle \Psi^+ \left| \left( d\mathbf{A} - \frac{d\mathbf{F}}{k} \right) \Phi \right. \right\rangle - \left\langle \Psi \left| \left( d\mathbf{A}^+ - \frac{d\mathbf{F}^+}{k^+} \right) \Phi^+ \right. \right\rangle - \left\langle \Psi^+ \left| \left( \mathbf{A} - \frac{\mathbf{F}}{k} \right) d\Phi \right. \right\rangle - \left\langle \Psi \left| \left( \mathbf{A}^+ - \frac{\mathbf{F}^+}{k^+} \right) d\Phi^+ \right. \right\rangle - \frac{dk}{k^2} (\langle \Psi^+ | \mathbf{F} \Phi \rangle + \langle \Psi | \mathbf{F}^+ \Phi^+ \rangle) \quad 3.14$$

With :  $\frac{dCC}{CC} = \left\langle \frac{\partial CC}{\partial \sigma} \frac{d\sigma}{CC} + \frac{\partial CC}{\partial \Phi} \frac{d\Phi}{CC} + \frac{\partial CC}{\partial \Phi^+} \frac{d\Phi^+}{CC} \right\rangle$ , we can group the terms in  $d\Phi$  and  $d\Phi^+$ :

$$dT = \left\langle \frac{\partial CC}{\partial \sigma} \frac{d\sigma}{CC} \right\rangle - \left\langle \Psi^+ \left| \left( d\mathbf{A} - \frac{d\mathbf{F}}{k} \right) \Phi \right. \right\rangle - \left\langle \Psi \left| \left( d\mathbf{A}^+ - \frac{d\mathbf{F}^+}{k^+} \right) \Phi^+ \right. \right\rangle + \left\langle \frac{\partial CC}{\partial \Phi} \frac{d\Phi}{CC} - \left( \mathbf{A}^+ - \frac{\mathbf{F}^+}{k^+} \right) \Psi^+ \left| d\Phi \right. \right\rangle + \left\langle \frac{\partial CC}{\partial \Phi^+} \frac{d\Phi^+}{CC} - \left( \mathbf{A} - \frac{\mathbf{F}}{k} \right) \Psi \left| d\Phi^+ \right. \right\rangle - \frac{dk}{k^2} (\langle \Psi^+ | \mathbf{F} \Phi \rangle + \langle \Psi | \mathbf{F}^+ \Phi^+ \rangle) \quad 3.15$$

The terms in  $d\Phi$  and  $d\Phi^+$  vanish because we compute  $\Psi$  and  $\Psi^+$  such as:

$$\left( \mathbf{A}^+ - \frac{\mathbf{F}^+}{k^+} \right) \Psi^+ = \frac{\partial CC}{\partial \Phi} \frac{d\Phi}{CC} \quad \text{and} \quad \left( \mathbf{A} - \frac{\mathbf{F}}{k} \right) \Psi = \frac{\partial CC}{\partial \Phi^+} \frac{d\Phi^+}{CC} \quad 3.16$$

$S_1$   $S_2$

The exact expression of the source  $S_1$  and  $S_2$  are given by :

$$S_1^g = \frac{-\delta \Sigma_c^g \Phi_g^+ - \delta \Sigma_f^g \Phi_g^+ + \delta (\nu \Sigma_f)_g \sum_{g'} \chi_{g'} \Phi_{g'}^+ + (\nu \Sigma_f)_g \sum_{g'} \delta \chi_{g'} \Phi_{g'}^+ + \sum_{g'} \delta \Sigma_s^{g \rightarrow g'} (\Phi_{g'}^+ - \Phi_g^+)}{\langle CC \rangle} \quad 3.17$$

$$S_2^g = \frac{-\delta \Sigma_c^g \Phi_g - \delta \Sigma_f^g \Phi_g + \chi_g \sum_{g'} \delta (\nu \Sigma_f)_{g'} \Phi_{g'} + \delta \chi_g \sum_{g'} (\nu \Sigma_f)_{g'} \Phi_{g'} + \sum_{g'} \delta \Sigma_s^{g' \rightarrow g} (\Phi_{g'} - \Phi_g)}{\langle CC \rangle} \quad 3.18$$

Furthermore terms in  $dk$  vanish too since  $\Psi$  and  $\Psi^+$  are not exactly defined for any scalar  $\lambda$  and  $\lambda^+$ ,  $(\Psi - \lambda \Phi)$  and  $(\Psi^+ - \lambda^+ \Phi^+)$  are also solutions of the equations 3.16,  $\lambda$  and  $\lambda^+$  are usually chosen to make the terms  $\langle \Psi^+ | \mathbf{F} \Phi \rangle$  and  $\langle \Psi | \mathbf{F}^+ \Phi^+ \rangle$  vanish. In the end we can breakdown the sensitivity into two terms: direct and indirect.

$$S_{CC} = \frac{dCC}{d\sigma} \frac{\sigma}{CC} = \frac{\sigma}{CC} \left( \underbrace{\left\langle \frac{\partial CC}{\partial \sigma} \right\rangle}_{\text{Direct term}} - \underbrace{\left\langle \Psi^+ \left| \left( \frac{d\mathbf{A}}{d\sigma} - \frac{1}{k} \frac{d\mathbf{F}}{d\sigma} \right) \Phi \right. \right\rangle - \left\langle \Psi \left| \left( \frac{d\mathbf{A}^+}{d\sigma} - \frac{1}{k} \frac{d\mathbf{F}^+}{d\sigma} \right) \Phi^+ \right. \right\rangle}_{\text{Indirect term}} \right) \quad 3.19$$

### 3.4 Sensitivity of the LC to nuclear data for ASTRID CFV core

Once we get the sensitivity of the CC and of the total sodium void reactivity effect (using EGPT) to nuclear data we can calculate the sensitivity of the LC to nuclear data as follow:

$$S_{\Delta \rho_{Na}} = \frac{d(\Delta \rho_{Na})}{d\sigma} \frac{\sigma}{\Delta \rho_{Na}} = \frac{d(CC + LC)}{d\sigma} \frac{\sigma}{\Delta \rho_{Na}} = \frac{dCC}{d\sigma} \frac{\sigma}{\Delta \rho_{Na}} + \frac{dLC}{d\sigma} \frac{\sigma}{\Delta \rho_{Na}} = S_{CC} \frac{CC}{\Delta \rho_{Na}} + S_{LC} \frac{LC}{\Delta \rho_{Na}} \quad 3.20$$

$$S_{LC} = S_{\Delta \rho_{Na}} \frac{\Delta \rho_{Na}}{LC} - S_{CC} \frac{CC}{LC} \quad 3.21$$

These sensitivities ( $S_{\Delta \rho_{Na}}$ ,  $S_{LC}$ ,  $S_{CC}$ ) calculated with JEFF-3.2 are given in **appendix A**.

## 4 Uncertainty of the sodium void effect due to nuclear data

Once sensitivities are calculated we use the Sandwich formula:

$$I^2 = S^t \cdot B \cdot S \quad 4.1$$

Where: B is the dispersion matrix which is based on the covariance matrix (such as COMAC developed at CEA [6]). The covariance matrix depends on the nuclear data library used: COMAC-V0.1 for JEFF-3.1

and COMAC-V2 for JEFF3.2 [6]. This covariance matrix takes into account the covariance between all neutronic parameters for each isotope. It was established with experimental results.

#### 4.1 The uncertainty of the total sodium void reactivity effect

Using the formula 4.1 with the sensitivities given by the EGPT method (see section 3.2) for the total sodium void reactivity we get the uncertainty due to nuclear data on the  $\Delta\rho_{Na}$  of 14.8% meaning 81.41 pcm.

Table 4.1: Uncertainties (in %) of the total sodium void reactivity effect with JEFF3-2 and COMAC-V2

Isotope	Fission	Capture	Elastic	Inelastic	N,xN	Nu	Spectrum	Sum
Na23	0.00	3.10	3.05	2.29	0.01	0.00	0.00	4.92
O16	0.00	1.01	0.38	0.04	0.00	0.00	0.00	1.08
Fe56	0.00	2.40	1.14	0.41	0.00	0.00	0.00	2.68
U235	0.12	0.08	0.00	0.01	0.00	0.04	0.02	0.15
U238	1.80	4.71	0.34	3.18	0.29	0.72	0.74	6.06
Pu238	0.14	0.65	0.02	0.02	0.00	0.34	0.16	0.76
Pu239	8.94	3.47	0.10	0.10	0.01	1.37	0.68	9.71
Pu240	5.50	3.63	0.15	0.55	0.01	0.19	1.52	6.74
Pu241	1.72	1.14	0.03	0.06	0.01	0.66	0.76	2.29
Pu242	0.46	1.80	0.06	0.08	0.00	0.24	0.10	1.87
TOTAL	10.80	8.32	3.31	3.90	0.29	1.74	1.98	14.80

As expected the main contributors to the uncertainty are the fuel isotopes (Pu239 and Pu240) and fertile isotopes (U238) but also the structure material (Fe56) and coolant isotope (Na23) of course.

#### 4.2 The uncertainty of the central component of the sodium void reactivity effect

As seen in section 3.3 and using the 3.19 equation to calculate the sensitivity of the CC to nuclear data we get an uncertainty of 2.44% on the CC of the ASTRID core when using JEFF-3.2 and COMAC-V2 i.e. an uncertainty of 67.6 pcm of the 2773 pcm CC. The main contributors to these uncertainties (Table 4.2) are the fission cross sections of Pu239, the capture, elastic and inelastic cross sections of Na23 and the inelastic cross sections of U238.

Table 4.2: Uncertainties (in %) of the CC due to nuclear data with JEFF-3.2 and COMAC-V2

Isotope	Fission	Capture	Elastic	Inelastic	N,xN	Nu	Spectrum	Sum
Na23	0.00	0.71	1.55	0.80	0.00	0.00	0.00	1.89
O16	0.00	0.12	0.28	0.00	0.00	0.00	0.00	0.31
Fe56	0.00	0.14	0.14	0.08	0.00	0.00	0.00	0.21
U235	0.01	0.03	0.00	0.00	0.00	0.00	0.01	0.04
U238	0.28	0.15	0.03	0.90	0.04	0.13	0.02	0.97
Pu238	0.02	0.04	0.00	0.01	0.00	0.15	0.14	0.21
Pu239	0.49	0.20	0.02	0.09	0.00	0.15	0.21	0.60
Pu240	0.95	0.47	0.01	0.10	0.00	0.03	0.24	0.85
Pu241	0.14	0.15	0.00	0.04	0.00	0.13	0.31	0.40
Pu242	0.05	0.10	0.00	0.03	0.00	0.03	0.03	0.12
TOTAL	1.11	0.65	1.59	1.21	0.04	0.28	0.47	2.44

The main contributors (apart from nu and spectrum) to the sensitivity of the CC are the elastic and inelastic of Na23 and O16 isotopes at high energy (see figure 4.1).

Sensitivities of the CC

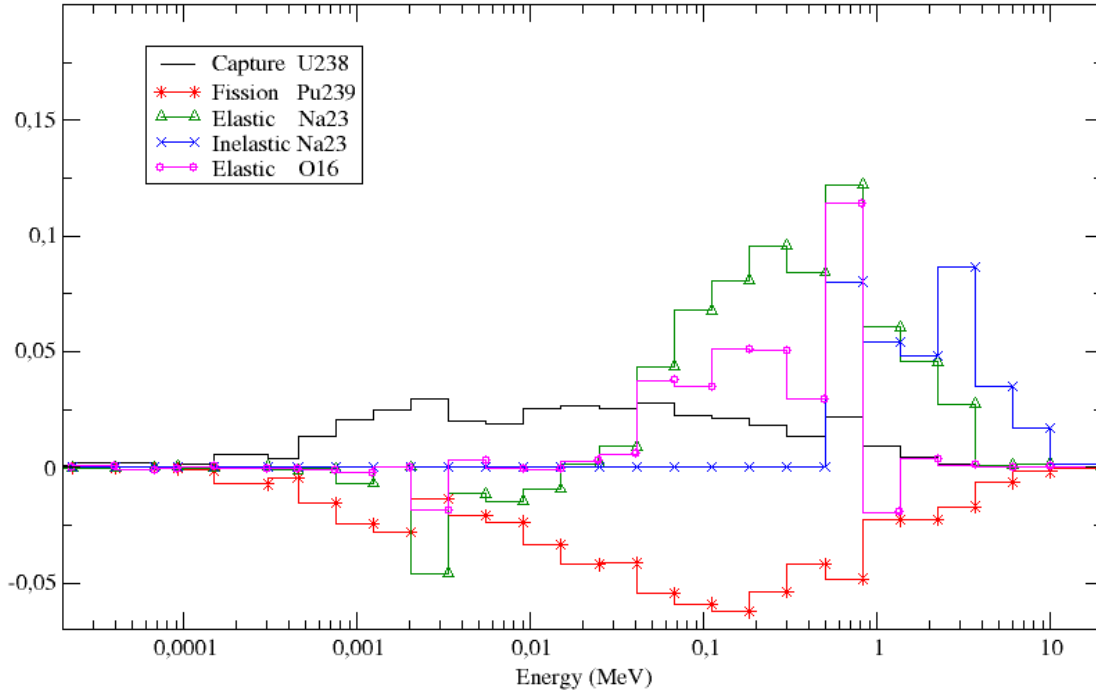


Figure 4.1: Sensitivity comparison between main contributors to CC sensitivity

### 4.3 The uncertainty of the leakage component of the void sodium reactivity effect

As seen in section 3.4 and using the 3.22 equation to calculate the sensitivity of the LC to nuclear data we get an uncertainty of 2.98% on the LC for the ASTRID core with JEFF-3.2 and COMAC-V2 i.e. an uncertainty of 98.9 pcm of the -3323 pcm LC. The main contributors to these uncertainties are the fission cross section of Pu239 and capture and inelastic cross sections of Na23.

Table 4.3: Uncertainties(in %) of the LC due to nuclear data with JEFF-3.2 and COMAC-V2

Isotope	Fission	Capture	Elastic	Inelastic	N,xN	Nu	Spectrum	Sum
Na23	0.00	1.11	0.78	1.05	0.00	0.00	0.00	1.71
O16	0.00	0.07	0.20	0.00	0.00	0.00	0.00	0.21
Fe56	0.00	0.49	0.27	0.05	0.00	0.00	0.00	0.56
U235	0.02	0.03	0.00	0.00	0.00	0.01	0.01	0.04
U238	0.12	0.81	0.04	0.26	0.01	0.02	0.14	0.87
Pu238	0.02	0.14	0.00	0.01	0.00	0.17	0.15	0.26
Pu239	1.72	0.65	0.04	0.06	0.00	0.29	0.29	1.89
Pu240	0.20	0.63	0.03	0.09	0.00	0.01	0.45	0.81
Pu241	0.34	0.21	0.01	0.03	0.00	0.22	0.38	0.60
Pu242	0.05	0.37	0.01	0.02	0.00	0.01	0.03	0.37
TOTAL	1.77	1.78	0.86	1.09	0.01	0.41	0.69	2.98

The fission cross section of Pu239 has high sensitivities at high energy (around 200keV-1MeV) but also at lower energies (around 1keV) see figure 4.2.

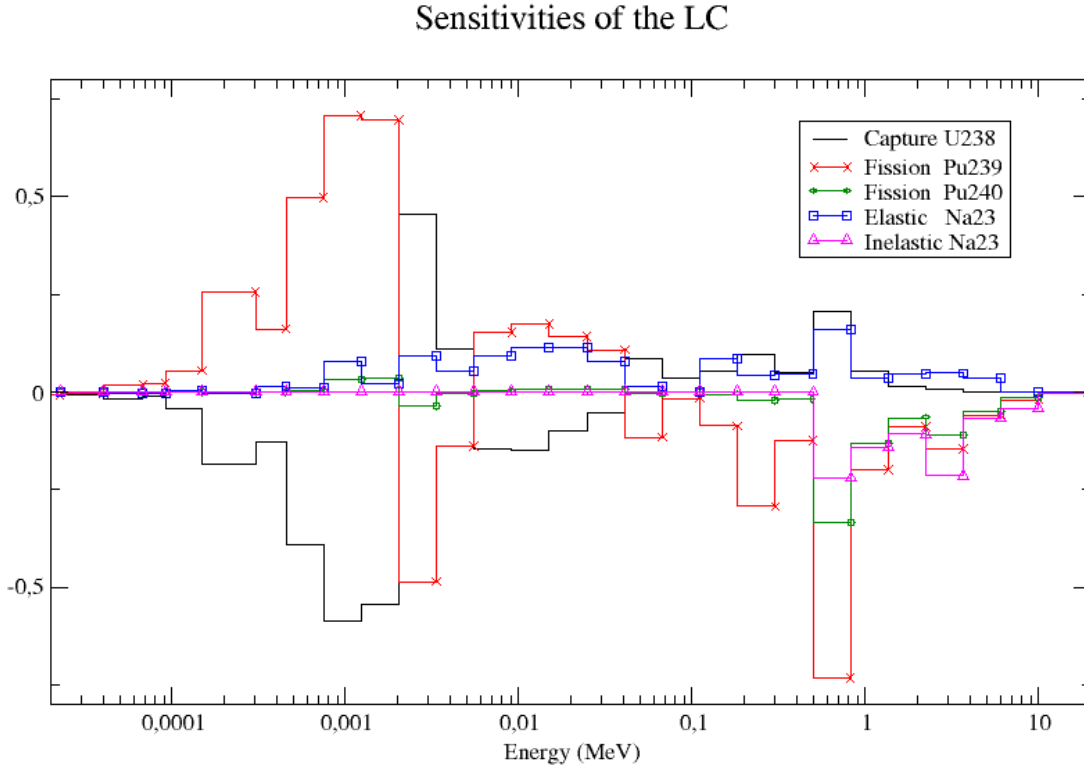


Figure 4.2: Sensitivity comparison between main contributors to LC sensitivity.

#### 4.4 The correlation between the sensitivities of each components of the sodium void reactivity effect

The correlation between the uncertainty on one hand the CC and on the other hand the LC is calculated as follow :

$$I_{\Delta\rho_{Na}}^2 (\text{in}\%) = S_{\Delta\rho_{Na}}^t \cdot B \cdot S_{\Delta\rho_{Na}} = \left( S_{CC}^t \frac{CC}{\Delta\rho_{Na}} + S_{LC}^t \frac{LC}{\Delta\rho_{Na}} \right) \cdot B \cdot \left( S_{CC} \frac{CC}{\Delta\rho_{Na}} + S_{LC} \frac{LC}{\Delta\rho_{Na}} \right) \quad 4.2$$

$$I_{\Delta\rho_{Na}}^2 (\text{in}\%) = I_{CC}^2 (\text{in}\%) \frac{CC^2}{\Delta\rho_{Na}^2} + I_{LC}^2 (\text{in}\%) \frac{LC^2}{\Delta\rho_{Na}^2} + 2 S_{CC}^t \cdot B \cdot S_{LC} \frac{LC \times CC}{\Delta\rho_{Na}^2} \quad 4.3$$

$$I_{\Delta\rho_{Na}}^2 = I_{CC}^2 + I_{LC}^2 + 2 S_{CC}^t \cdot B \cdot S_{LC} \cdot LC \cdot CC \quad 4.4$$

This expression gives us the correlation between these uncertainties comparing to this one :

$$I_{\Delta\rho_{Na}}^2 = I_{CC}^2 + I_{LC}^2 + 2 r_{CC,LC} I_{CC} I_{LC} \quad 4.5$$

$$r_{CC,LC} = \frac{S_{CC}^t \cdot B \cdot S_{LC} \cdot LC \cdot CC}{I_{CC} I_{LC}} \quad 4.6$$

This parameter  $r_{CC,LC}$  vary between -1 to +1 and the closer to |1| the more correlated it is. Using the sensitivity calculated by GPT for the CC and the ones calculated for the LC we got : **-0.5776** (with JEFF-3.2 and COMAC-V2) as correlation between the CC and the LC. Meaning that CC and LC for ASTRID core are not correlated and it justifies the historical choice to study independently the impact of CC and

LC in sodium void reactivity measurement. It will be very interesting to apply this work to past experiments where sodium void reactivity measurements were conducted (such as PRE-RACINE [7] and CIRANO [8] programmes in the MASURCA zero power facility at CEA Cadarache). This method will offer a new perspective for analysing the experimental SVRE where CC and LC have different relative contributions.

## **5 Conclusion**

The development of an innovative procedure in ERANOS allows getting the sensitivities of each component of the total sodium void reactivity effect. For the ASTRID program this work has predicted an uncertainty of 81.4 pcm on the sodium void reactivity effect with a breakdown into an uncertainty of 67.6 pcm on the CC and 98.9 pcm on the LC. The correlation between these uncertainties is calculated as -0.5776 meaning that the independent study of each component in an experimental program is justified. Finally the same work has to be done with integral experiments where sodium void reactivity were measured such as PRE-RACINE and CIRANO program lead in the MASURCA facility at CEA Cadarache. Furthermore the high value of uncertainties due to nuclear data for ASTRID CFV core gives credit to lead a new experimental program in MASURCA with a core configuration more representative than last experiments. For instance PRE-RACINE and CIRANO programs have no plenum sodium which is an important feature of the CFV core.

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APPENDIX A

Table A.1: Sensitivities of the total sodium void reactivity effect with JEFF-3.2

ISOTOPE	FISSION	CAPTURE	ELASTIC	INELASTIC	N.XN	NU	SPEC	SUM
B10	0.00E+0	-4.91E-1	-3.85E-3	-1.64E-4	0.00E+0	0.00E+0	0.00E+0	-4.95E-1
B11	0.00E+0	-7.74E-6	1.68E-2	-1.65E-4	-9.88E-8	0.00E+0	0.00E+0	1.67E-2
Na23	0.00E+0	-2.38E-1	1.30E+0	-1.02E+0	3.86E-5	0.00E+0	0.00E+0	4.05E-2
O16	0.00E+0	4.39E-2	3.30E-1	5.87E-3	-1.94E-8	0.00E+0	0.00E+0	3.79E-1
Cr52	0.00E+0	-3.09E-2	-9.58E-2	3.20E-2	-1.05E-5	0.00E+0	0.00E+0	-9.47E-2
Fe56	0.00E+0	-2.28E-1	-2.29E-1	1.75E-1	-1.14E-4	0.00E+0	0.00E+0	-2.82E-1
U235	1.83E-2	-1.20E-2	-3.88E-4	1.69E-3	-1.60E-5	3.11E-2	5.53E-2	9.41E-2
U238	-9.30E-1	-1.49E+0	-2.44E-1	6.85E-1	3.34E-3	-1.47E+0	-1.62E+0	-5.06E+0
Pu238	-1.95E-2	-7.22E-2	-2.61E-3	1.92E-3	-2.16E-5	-1.69E-2	-2.13E-2	-1.31E-1
Pu239	6.74E-1	-8.10E-1	-2.03E-2	2.56E-2	2.67E-5	1.14E+0	1.28E+0	2.28E+0
Pu240	-8.25E-1	-5.52E-1	-1.88E-2	2.47E-2	5.04E-4	-1.15E+0	-1.25E+0	-3.77E+0
Pu241	5.71E-1	-1.01E-1	-4.62E-3	5.78E-3	-2.79E-4	8.45E-1	9.53E-1	2.27E+0
Pu242	-2.58E-1	-1.62E-1	-8.21E-3	9.14E-3	-1.31E-4	-3.57E-1	-3.78E-1	-1.15E+0
Am241	-1.48E-2	-3.67E-2	-4.57E-4	8.57E-4	1.72E-5	-2.00E-2	-2.27E-2	-9.38E-2
PART	1.26E+0	7.77E-2	1.65E+0	1.01E+0	9.36E-3	2.01E+0	2.29E+0	8.31E+0
PART	-2.05E+0	-4.32E+0	-7.78E-1	-1.02E+0	-5.90E-4	-3.01E+0	-3.29E+0	-1.45E+1
SUM	-7.85E-1	-4.24E+0	8.75E-1	-1.12E-2	8.77E-3	-1.00E+0	-1.00E+0	-6.15E+0

**TableA.2: Sensitivities of the LC with JEFF-3.2**

ISOTOPE	FISSION	CAPTURE	ELASTIC	INELASTIC	N.XN	NU	SPEC	SUM
B10	0.00E+0	-4.08E-1	-3.17E-3	-1.38E-4	0.00E+0	0.00E+0	0.00E+0	-4.12E-1
B11	0.00E+0	-6.43E-6	1.42E-2	-1.39E-4	-8.30E-8	0.00E+0	0.00E+0	1.41E-2
Na23	0.00E+0	-1.90E-1	1.17E+0	-7.98E-1	3.84E-5	0.00E+0	0.00E+0	1.87E-1
O16	0.00E+0	3.74E-2	3.23E-1	4.96E-3	-1.75E-8	0.00E+0	0.00E+0	3.65E-1
Cr52	0.00E+0	-2.53E-2	-7.93E-2	2.71E-2	-9.15E-6	0.00E+0	0.00E+0	-7.76E-2
Fe56	0.00E+0	-1.88E-1	-1.85E-1	1.49E-1	-9.93E-5	0.00E+0	0.00E+0	-2.24E-1
U235	1.25E-2	-9.73E-3	-3.19E-4	1.48E-3	-1.37E-5	2.24E-2	3.96E-2	6.60E-2
U238	-7.96E-1	-1.18E+0	-2.01E-1	5.95E-1	2.94E-3	-1.26E+0	-1.36E+0	-4.20E+0
Pu238	-2.31E-2	-5.93E-2	-2.17E-3	1.69E-3	-1.86E-5	-2.33E-2	-2.62E-2	-1.32E-1
Pu239	4.55E-1	-6.67E-1	-1.68E-2	2.23E-2	2.40E-5	8.11E-1	8.86E-1	1.49E+0
Pu240	-7.06E-1	-4.53E-1	-1.56E-2	2.16E-2	4.38E-4	-9.85E-1	-1.03E+0	-3.17E+0
Pu241	4.44E-1	-8.23E-2	-3.84E-3	4.99E-3	-2.40E-4	6.65E-1	7.30E-1	1.76E+0
Pu242	-2.20E-1	-1.33E-1	-6.81E-3	8.11E-3	-1.12E-4	-3.04E-1	-3.12E-1	-9.68E-1
Am241	-1.27E-2	-3.00E-2	-3.79E-4	7.56E-4	1.50E-5	-1.72E-2	-1.88E-2	-7.83E-2
PART	9.12E-1	6.72E-2	1.52E+0	8.73E-1	8.07E-3	1.50E+0	1.66E+0	6.53E+0
PART	-1.76E+0	-3.51E+0	-6.38E-1	-7.98E-1	-5.08E-4	-2.59E+0	-2.75E+0	-1.20E+1
SUM	-8.46E-1	-3.44E+0	8.80E-1	7.47E-2	7.56E-3	-1.09E+0	-1.09E+0	-5.51E+0

**Table A.3: Sensitivities of the CC with JEFF-3.2**

ISOTOPE	FISSION	CAPTURE	ELASTIC	INELASTIC	N.XN	NU	SPEC	SUM
Na23	0.00E+0	5.28E-2	5.50E-1	3.23E-1	3.74E-5	0.00E+0	0.00E+0	9.26E-1
O16	0.00E+0	4.51E-3	2.88E-1	4.11E-4	-7.78E-9	0.00E+0	0.00E+0	2.93E-1
Fe56	0.00E+0	1.62E-2	3.43E-2	1.66E-2	-2.51E-5	0.00E+0	0.00E+0	6.72E-2
U235	-1.67E-2	1.53E-3	2.51E-5	4.07E-4	-1.96E-6	-2.16E-2	-3.96E-2	-7.59E-2
U238	-1.22E-1	3.60E-1	1.50E-2	1.45E-1	9.18E-4	-2.08E-1	-5.05E-2	1.41E-1
Pu238	-4.12E-2	5.34E-3	6.15E-5	5.08E-4	-3.21E-6	-5.54E-2	-5.09E-2	-1.42E-1
Pu239	-6.46E-1	5.47E-2	7.76E-4	5.61E-3	1.04E-5	-8.38E-1	-1.08E+0	-2.51E+0
Pu240	-1.04E-1	4.87E-2	6.38E-4	6.15E-3	1.04E-4	-1.49E-1	3.93E-2	-1.58E-1
Pu241	-1.95E-1	9.47E-3	1.22E-4	1.02E-3	-4.12E-5	-2.46E-1	-3.93E-1	-8.23E-1
Pu242	-2.69E-2	1.65E-2	2.40E-4	2.91E-3	-1.74E-5	-3.95E-2	1.98E-2	-2.69E-2
Am241	-1.78E-3	3.60E-3	1.46E-5	2.51E-4	3.90E-6	-2.58E-3	6.19E-4	1.33E-4
PART	0.00E+0	6.01E-1	9.11E-1	5.08E-1	1.58E-3	0.00E+0	5.98E-2	2.08E+0
PART	-1.15E+0	0.00E+0	-3.65E-3	-1.59E-5	-9.47E-5	-1.56E+0	-1.62E+0	-4.33E+0
SUM	-1.15E+0	6.01E-1	9.07E-1	5.08E-1	1.49E-3	-1.56E+0	-1.56E+0	-2.25E+0