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Implementation of the CLUTCH method in the MORET code

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Abstract - *A continuous energy sensitivity coefficients calculation to nuclear data capability has been developed in the version 5.D.1 of the MORET Monte Carlo code developed at IRSN (Institut de Radioprotection et de Sûreté nucléaire). It relies on the differential operator method and the simulation of "dummy" neutrons in order to estimate the adjoint flux with the Iterated Fission Probability (IFP). However, as implemented in the MORET code, the IFP method may lead to an increase in computation time and provide a high standard deviation in some configurations. In order to mitigate these effects, an alternate approach to the simulation of "dummy" neutrons has been recently implemented in the MORET code based on the CLUTCH approach for the estimation of the adjoint source. It consists of estimating the average progeny for a geometrical mesh during inactive cycles and then use this approximation instead of simulating "dummy" neutrons. This approach allows reducing the computation time and the variance associated to the estimation of sensitivity coefficients. The verification of the implementation has been performed on three benchmarks and compared to the IFP, which is considered as a reference calculation.*

I. INTRODUCTION

Identifying which parameters are responsible for the largest changes in the response (for example, the k_{eff} value in criticality applications) per unit change is an important issue when performing criticality safety studies. On the one hand, it is paramount to estimate the reactivity effect due to the material composition or geometry modelling changes to determine the overall uncertainty in the eigenvalue for systems. On the other hand, evaluating the impact of uncertainties due to nuclear data is required when trying to quantify biases and uncertainties for an application case. Both issues are of particularly importance in the code validation process to identify sources of computational bias and highlight the most important parameters. All these applications are based on sensitivity and perturbation theories, which estimate the impact on the response due to a modification on the input data.

A continuous-energy sensitivity coefficients calculation capability has been recently implemented in the Monte Carlo code MORET [1, 2], which uses ACE formatted files as nuclear data files. This implementation relies on the differential operator method [3] and the estimation of the adjoint source using the Iterated Fission Probability (IFP) [4]. As a "dummy neutron" and its progeny are simulated at every absorption point of a neutron, this method can be time consuming and display a high variance but its implementation does not strongly increase memory requirements [1].

An alternate approach to the IFP adjoint source estimation has been developed by C. Perfetti et al. [5] for the CLUTCH method used in the SCALE package. This method is based on the ability of calculating a reliable adjoint source (denoted F^* in [5]) on a spatial mesh. This function is estimated during inactive cycles and then is used when calculating sensitivity coefficients.

This paper presents the adaptation of this approach into the MORET code for the calculation of sensitivity coefficients.

II. THEORY

Denoting α a cross section, the sensitivity coefficient of k_{eff} with respect to α is defined as equation (1).

$$S_\alpha = \frac{\alpha}{k_{eff}} \frac{\partial k_{eff}}{\partial \alpha} \tag{1}$$

The sensitivity coefficient S_α to the cross section α can be written as equation (2).

$$S_\alpha = \frac{\alpha}{k_{eff}} \frac{\partial k_{eff}}{\partial \alpha} = \frac{\sum_j p_j \alpha \mu_0 \xi_j Q^+(\mathbf{r}_N)}{\sum_j p_j \xi_j Q^+(\mathbf{r}_N)} \tag{2}$$

Where j is the neutron index in the current cycle, ξ_j is the random contribution of neutron j for the absorption estimator of k_{eff}, p_j is the probability of realization of history j, which can be explicitly written in terms of probabilities describing elementary events of neutron history. Finally, $Q^+(\mathbf{r}_N)$ is the adjoint source at the location $\mathbf{r}_N$ and μ_0 is a random contribution term fully described for the different reactions in [1].

The adjoint source can be linked to the adjoint flux $\phi^+(x)$ using the relation (3), where the brackets denotes integration over its subscripts.

$$Q^+(r) = \left\langle \frac{1}{4\pi} \chi(x) \phi^+(x) \right\rangle_{E,\mathbf{\Omega}} \tag{3}$$

Where $\chi(x)$ is the fission spectrum. Two different methods can be used to estimate the adjoint source: the Iterated Fission Probability [3] and the approach used in the CLUTCH method, which is an estimation on a spatial mesh [5].

1. Iterated Fission Probability

A quantity proportional to the adjoint flux can be accessed by simulating L independent random super-histories (neutrons and their progeny), each of them consisting of simulating M generations. Here, L is the number of realization for the

Monte Carlo estimation of the adjoint flux at location x. For practical and implementation reasons, L is set to one in our implementation. In the following of this paper, we will denote "dummy" the neutrons that are simulated to estimate the adjoint source only and "active" the neutrons that may contribute to tallies.

The simulation of a dummy neutron and its progeny over M generations will yield

$$\frac{1}{k_0^M}\prod_{m=1}^{M}\frac{\nu^i\sigma_f^i(z_m)}{\sigma_a^i(z_m)} \tag{4}$$

neutrons where z_m is the absorption site of progeny m. In this model a single dummy neutron is simulated in each generation m and the production rate is accumulated over generations, meaning that the simulated neutron carries all the weight of the progeny. The index i represents the nuclide in which the neutron undergoes an absorption, which may be different for the M generations. In this case, k_0^M is a preset constant (for this cycle) and will be eliminated by the normalization factor. Thus, there is no need to take it into account in equations and tallies. So, the estimation of the adjoint flux is

$$\phi^+(x) \sim \prod_{m=1}^{M}\frac{\nu^i\sigma_f^i(z_{l,m})}{\sigma_a^i(z_{l,m})} \tag{5}$$

Now the adjoint source has to be estimated, i.e. estimates equation 3. It can be done by emitting fission neutron at $\mathbf{r}_N$ with random energy, according to the fission spectrum, and angle, which is Monte Carlo integration. The algorithm implemented in the MORET code for estimating the adjoint source is depicted in figure 1.

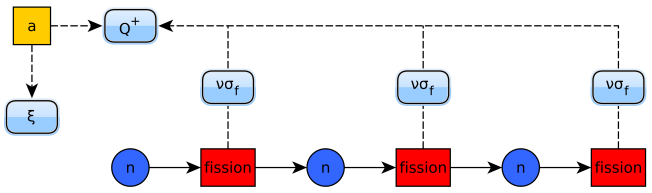

Fig. 1. Algorithm for the estimation of the adjoint source

In this figure, a represents the absorption of an active neutron, n represents the simulation of a dummy neutron. It should be noted that if a dummy neutron is absorbed by a non-fissile nuclide or leaks out of the system, the estimation of $Q^+(\mathbf{r}_N)$ is null.

2. CLUTCH approach

The CLUTCH approach consists of estimating the adjoint source on a spatial mesh. The adjoint source will be considered as constant over each single mesh interval and represents the average progeny (or importance) for a neutron born in this mesh. The estimation can be achieved by identifying the mesh where a neutron is born and by transmitting this information to the progeny through several generations. Once the number of generation specified by the user is reached, the ancestor birth mesh is used to accumulate progeny for that mesh.

This quantity can be estimated during the inactive cycles. Indeed, as Q^+ describes the average progeny, its estimation does not require a converged fission source [5]. The procedure below has been implemented in the MORET code to estimate the neutron contribution to Q^+ for the mesh k.

1. Store the particle weight (ω_j) at mesh k,
2. Add the integer k to the list of ancestors birth location,
3. Transmit the list to the progeny,
4. After the required number of generations, accumulate the production rates for the last generation of each neutron progeny.

Then, all neutron contributions to the mesh k are added and normalized by the sum of weights of neutrons born in this mesh. This leads to the estimation of Q^+ for the mesh k.

Convergence of the tally and the refinement of the mesh are the two parameters of importance in the estimation of Q^+. Preliminary studies performed by C. Perfetti et al. [5] showed that mesh intervals between 1 and 2 cm allow sufficient resolution and that 50 to 100 inactive histories per mesh will generate sufficiently converged tally. As in the MORET model, the adjoint source weights tallies at the absorption point on a fissile isotope, this mesh have to encompass all fissile volumes of the geometry.

For now, the only implemented mesh is a Cartesian regular mesh in each x,y,z-direction based on the outer limits of the simulated system. However, it is completely independent of the geometry description and is superimposed to it. As a future work on the mesh, it is planned to allow modifying the limits of the mesh. Indeed, as the importance map has non-zero values only for mesh that contains a part of fissile material, we may limit the mesh to parts of the geometry containing fissile material and thus reduce memory requirements.

III. VERIFICATION

The verification of the CLUTCH approach has been performed comparing to the Iterated Fission Probability method implemented in the MORET code which has been validated mainly with comparisons to MCNP6.1 and SCALE6.1 [1, 2]. Three different benchmarks were used for the verification: the Jezebel experiment and the Pu-Sol-Therm-001 configuration from the ICSBEP Handbook and the detailed benchmark of the phase III of the Expert Group on Uncertainty Analyses for Criticality Safety Assessment (EG UACSA) from the ICSBEP.

For each configuration, energy-integrated sensitivity coefficients (mean and relative σ) and energy resolved sensitivity profiles are compared. Profiles are provided per unit lethargy on the 238 SCALE energy binning and plotted through step functions with Monte Carlo uncertainties added to each value, where plus and minus one standard deviation is displayed.

1. Jezebel

The first configuration used for verification of the implementation is the Jezebel benchmark. The Jezebel benchmark, issued from the ICSBEP handbook [6], consists of a bare sphere of plutonium metal with a ^{239}Pu content higher than 90 wt. % and with 4.5 wt. % of ^{240}Pu. The experiment was

performed in the mid-1950s at Los Alamos Scientific Laboratory (LASL). It consists of the "assembly" of two hemispheres to reach criticality. Some devices, which are of low worth on keff, are removed from the description of the experiment in order to simplify the benchmark model. Various levels of simplifications are proposed in the last revision of the benchmark. Only the description of the simplified model is used in this study, thus, the Jezebel configuration is a single sphere with a radius of 6.3849 cm.

For the CLUTCH approach, space has been divided with a 10x10x10 mesh. Calculations were performed using 100 000 neutrons per cycle and 200 inactive cycles with the ENDF/B-VII.1 nuclear data library.

Figure 2 displays the adjoint source function obtained for the Jezebel calculation. The figure is obtained for the mesh located at the z-altitude comprised between -0.6349 cm and 0 cm. The spherical shape of Jezebel clearly appears on this adjoint source map. The most important mesh intervals being the ones in the center of the sphere and the less important at the edges of the sphere. The zero values at the corners correspond to the meshes where there is no fissile material, which by the way are outside of the simulated system.

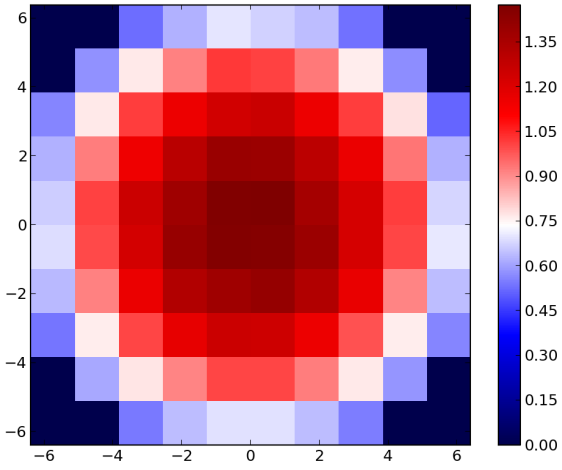

Fig. 2. Adjoint Source Map for the Jezebel benchmark

Table I represents the energy integrated sensitivity coefficients for ^{239}Pu to major nuclear data with IFP and CLUTCH calculations performed with the 5.D.1 version of the MORET code. This table also displays the absolute relative difference (ratio minus one) between the CLUTCH approach and the IFP (denoted R1), and the ratio between R1 and the combined standard deviation (denoted R2).

Results show a very good agreement between the IFP and the CLUTCH approach, the relative difference being below 1.5%. Futhermore, the ratio R2 is below 3 which means that estimations are consistent. The only exception is for the sensitivity to the fission cross section, however, in this case the relative difference is below 0.1% and standard deviations are below 0.02%. So, we can consider that these results are consistent. It may also be noticed that standard deviations are on average divided by a factor of 2 for the CLUTCH method compared to the IFP one.

nuclear data	IFP mean	IFP σ (%)	CLUTCH approach mean	CLUTCH σ(%)	CLUTCH R1(%)	CLUTCH R2
σ_f	0.72728	0.02	0.72661	0.01	0.09	4.2
$\bar{\nu}$	0.96571	0.01	0.96570	0.00	0.00	0.1
σ_{el}	0.06323	0.68	0.06231	0.23	1.45	2.0
σ_{in}	0.03875	0.65	0.03821	0.22	1.40	2.0
$\sigma_{n,\gamma}$	-0.00753	0.14	-0.00754	0.05	0.21	1.4

TABLE I. ^{239}Pu integrated sensitivity coefficients for the Jezebel configuration

Figure 3 displays the energy resolved sensitivity profile to the fission cross section of ^{239}Pu. This figure suggests a very good agreement between the two methods as profiles seem to match.

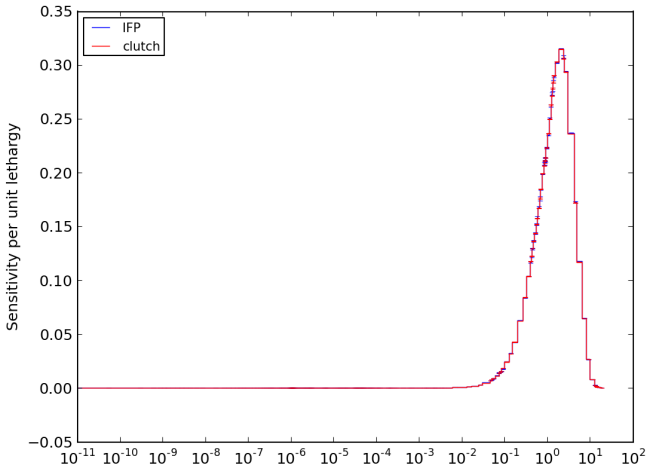

Fig. 3. Sensitivity profile to ^{239}Pu fission cross section with both methods implemented in the MORET code for the Jezebel benchmark

This is enhanced by figure 4, which displays the relative difference of sensitivity profiles of ^{239}Pu fission on the 0.1 to 10 MeV energy range. In this figure, the highest group-wise relative difference is about 5% and is about 1-2% on average, which suggest a good consistency between the two methods.

These preliminary results suggest that the implementation of the estimation of $\dot{Q}^+$ has been successfully performed.

2. UACSA phase III

Under the guidance of the OECD/NEA Working Party on Nuclear Criticality Safety (WPNCS), the Expert Group on Uncertainty Analyses for Criticality Safety Assessment (EG UACSA) proposed a benchmark [7] which aims at providing common models for the comparison of sensitivity calculation capabilities from several software packages. Although the benchmark is made of three test cases, this paper presents the results obtained for the detailed model of the Phase III.1 only. This case consists of a square lattice of Mixed Plutonium-Uranium Oxide Pins containing 19.7 wt. % of plutonium out of which 11.5 wt. % was ^{240}Pu. This configuration represents a reprocessed fast reactor fuel element in a shipping cask for an accidental scenario where water fills the cask. It is based

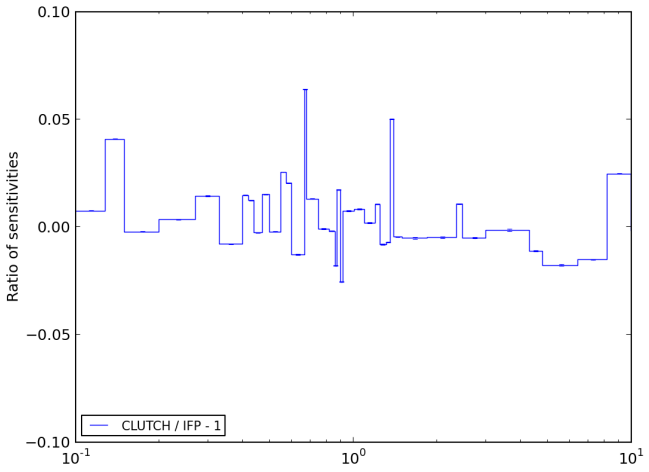

Fig. 4. Ratios of sensitivity to ^{239}Pu fission for the Jezebel benchmark

on the benchmark model that can be found in the International Handbook of Evaluated Criticality Safety Benchmark Experiments (referred to as ICSBEP Handbook) under identifier MIX-COMP-THERM-001-001 [6].

The fuel pins model consists of a clad of diameter 0.5842 cm, a gap of diameter 0.508 cm and the MOX fuel of diameter 0.49403 cm and the pin's height is 91.44 cm. The array of pins consists of 28 (17 only for the upper row) × 22 identical pins for a total of 605 pins with a pitch of 0.9525 cm. The top and bottom of the pins are modeled by a homogenized material.

Figure 5 provides a radial view of the detailed configuration. Missing pins can easily be identified at the top of the figure.

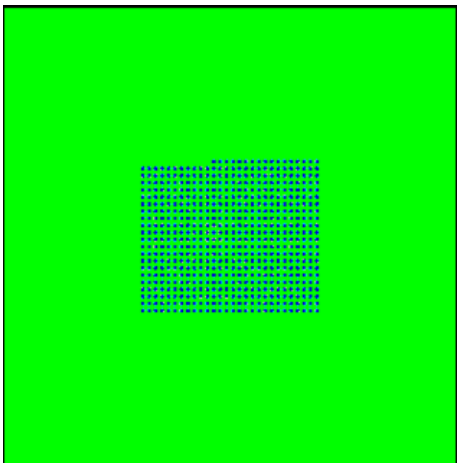

Fig. 5. Radial view of the detailed UACSA phase III configuration

The calculation was performed with a 40×40×10 mesh for the calculation using the importance map. 36300 neutrons per cycle were used together with 200 inactive cycles and 500 active ones. Figure 6 exhibits the importance map for the UACSA phase III detailed model between -12.446 cm and 0 cm. The shape of the assembly with the missing pins appears as non-zero values since only fissile material contributes to the importance map.

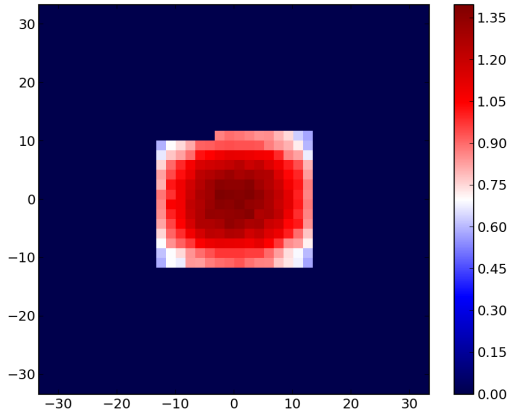

Fig. 6. Importance Map between z-level -12.446 cm and 0 cm for the UACSA phase III configuration

Table II shows the top ten integrated sensitivity coefficients calculated with the Iterated Fission Probability and the CLUTCH method developed in the MORET 5 code. This table also displays the absolute relative difference (ratio minus one) between IFP and CLUTCH (denoted R1) and the ratio between R1 and the combined standard deviation (denoted R2).

Isotope reaction	IFP mean	IFP σ(%)	CLUTCH mean	CLUTCH σ(%)	R1(%)	R2
$^{239}Pu\ \bar{\nu}$	0.92445	0.02	0.92468	0.01	0.03	1.1
$^{1}H\ \sigma_{el}$	0.40834	0.82	0.40642	0.40	0.47	0.5
$^{239}Pu\ \sigma_{f}$	0.37735	0.11	0.37774	0.06	0.10	0.8
$^{239}Pu\ \sigma_{n,\gamma}$	-0.26190	0.08	-0.26185	0.04	0.02	0.2
$^{16}O\ \sigma_{el}$	0.08639	1.24	0.08449	0.66	2.21	1.6
$^{1}H\ \sigma_{n,\gamma}$	-0.08131	0.22	-0.08223	0.10	1.13	4.7
$^{240}Pu\ \sigma_{n,\gamma}$	-0.05778	0.17	-0.05776	0.09	0.03	0.2
$^{238}U\ \sigma_{n,\gamma}$	-0.05015	0.17	-0.05024	0.09	0.18	0.9
$^{241}Pu\ \bar{\nu}$	0.02821	0.40	0.02790	0.21	1.11	2.5
$^{238}U\ \bar{\nu}$	0.02559	0.46	0.02518	0.22	1.59	3.1

TABLE II. Top ten integrated sensitivity coefficients for the UACSA phase III configuration

From this table, we may remark that relative differences between the IFP and the CLUTCH method are below ∼2% with an average of ∼0.7% highlighting a very good agreement between the two methods. Furthermore, the ratio R2 is below 3 for all coefficients (except for ^{1}H radiative capture) meaning that the relative difference is within the 3 combined standard deviation. Regarding the radiative capture of ^{1}H, even though 3-σ confidence intervals do not overlap as shown by the ratio R2 of 4.7, the relative difference is ∼1%, which is acceptable.

In addition, as already identified in the Jezebel configuration, we may notice that using the CLUTCH method provide a lower standard deviation, a factor of ∼2, compared to the IFP method.

Figure 7 shows the energy resolved sensitivity profiles to

elastic scattering cross section of ^{1}H. It can be highlighted that sensitivity profiles agree very well and 3-σ confidence interval generally overlap over the whole energy domain. The lower standard deviation obtained with the CLUTCH method compared to the IFP clearly appears on this profile.

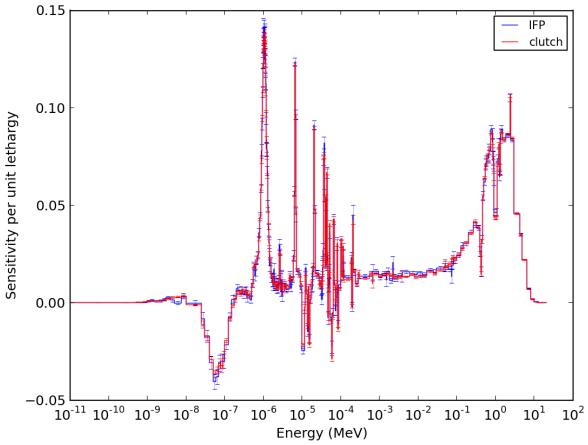

Fig. 7. ^{1}H elastic scattering sensitivity profile for the UACSA phase III configuration

Figure 8 and figure 9 display the sensitivity profiles respectively to the fission cross section of ^{239}Pu and to the capture cross section of ^{238}U. A very good agreement is observed between the two methods.

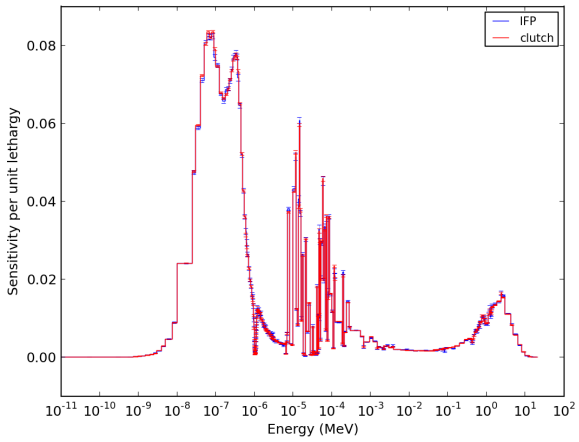

Fig. 8. ^{239}Pu fission sensitivity profile for the UACSA phase III configuration

Finally, these results suggest that the implementation of the CLUTCH approach for estimating the importance map and its use in sensitivity coefficients calculation has been performed correctly.

3. Pu-Sol-Therm-001

The simplified benchmark model of the PU-SOL-THERM-001 benchmark is composed of concentric spheres.

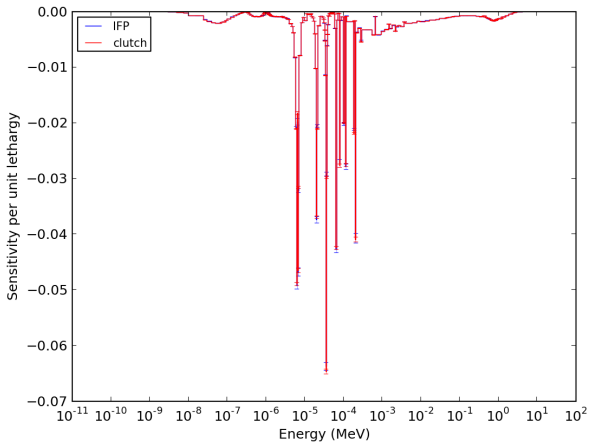

Fig. 9. ^{238}U capture sensitivity profile for the UACSA phase III configuration

The center sphere contains a Plutonium nitrate solution (which does not fill the entire sphere) surrounded by steel. This sphere is reflected by water. The fuel sphere have a radius of 14.5603 cm, the stainless steel sphere has an outer radius of 14.6848 cm, the surrounding sphere of water has an outer radius of 44.6848 cm.

Calculations have been performed using 50 000 neutrons per cycle, 200 inactive cycles and 500 active cycles. Two mesh were used for these calculations. The first one is a 40×40×40 mesh providing the results displayed in table III. This table also displays the absolute relative difference (ratio minus one) between IFP and CLUTCH (denoted R1) and the ratio between R1 and the combined standard deviation (denoted R2).

Isotope reaction	IFP mean	IFP σ(%)	CLUTCH mean	CLUTCH σ(%)	R1(%)	R2
$^{239}Pu\ \bar{\nu}$	0.99582	0.00	0.99582	0.00	0.00	0.0
$^{1}H\ \sigma_{el}$	0.56649	0.57	0.56682	0.27	0.06	0.1
$^{239}Pu\ \sigma_{f}$	0.40251	0.09	0.40371	0.04	0.30	3.1
$^{239}Pu\ \sigma_{n,\gamma}$	-0.28180	0.05	-0.28120	0.03	0.21	3.5
$^{1}H\ \sigma_{n,\gamma}$	-0.11892	0.11	-0.12028	0.05	1.14	9.3
$^{16}O\ \sigma_{el}$	0.11849	0.86	0.11709	0.41	1.18	1.2
$^{240}Pu\ \sigma_{n,\gamma}$	-0.03608	0.16	-0.03600	0.08	0.22	1.2
$^{56}Fe\ \sigma_{n,\gamma}$	-0.00748	0.26	-0.00773	0.11	3.32	11.9
$^{241}Pu\ \bar{\nu}$	0.00391	0.95	0.00390	0.49	0.27	0.2
$^{56}Fe\ \sigma_{el}$	0.00247	6.24	0.00247	2.95	0.04	0.0
$^{14}N\ \sigma_{el}$	0.00228	8.03	0.00190	5.24	16.53	1.7
$^{241}Pu\ \sigma_{f}$	0.00164	2.28	0.00163	1.18	0.35	0.1
$^{53}Cr\ \sigma_{n,\gamma}$	-0.00159	0.26	-0.00164	0.11	3.31	11.9
$^{58}Ni\ \sigma_{n,\gamma}$	-0.00129	0.26	-0.00134	0.10	3.29	11.9
$^{55}Mn\ \sigma_{n,\gamma}$	-0.00127	0.25	-0.00131	0.10	3.30	12.1

TABLE III. Top fifteen integrated sensitivity coefficients for the PST-001 configuration using a 40×40×40 mesh

These results show a quite good agreement between the IFP and the CLUTCH method except for the sensitivity to (n,γ) reactions in steel where they display a R2 ratio of ~11 which indicates that confidence intervals does not overlap. From this observation, a second calculation was performed changing the mesh for the CLUTCH method to a 90×90×90

mesh and keeping all other calculation parameters.

Figure 10 displays the importance map used for the calculation using the CLUTCH method with the 90×90×90 mesh.

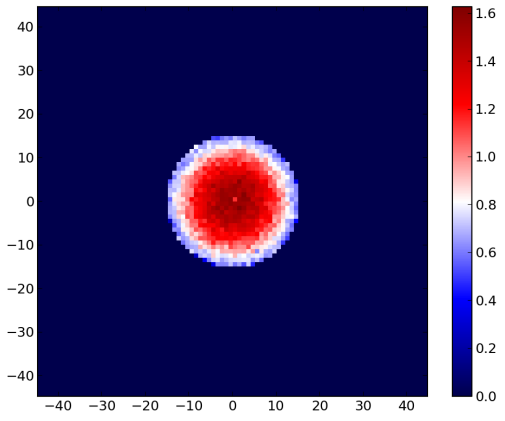

Fig. 10. Importance Map between z-level -0.99 cm and 0 cm for the PST-001 configuration

Table IV displays the integrated sensitivity coefficients calculated with a 90×90×90 mesh. This table also displays the absolute relative difference (ratio minus one) between IFP and CLUTCH (denoted R1) and the ratio between R1 and the combined standard deviation (denoted R2).

Isotope reaction	IFP mean	IFP σ(%)	CLUTCH mean	CLUTCH σ(%)	R1(%)	R2
$^{239}Pu\ \bar{\nu}$	0.99582	0.00	0.99582	0.00	0.00	0.0
$^{1}H\ \sigma_{el}$	0.56649	0.57	0.56870	0.27	0.39	0.6
$^{239}Pu\ \sigma_{f}$	0.40251	0.09	0.40302	0.04	0.13	1.3
$^{239}Pu\ \sigma_{n,\gamma}$	-0.28180	0.05	-0.28158	0.03	0.08	1.3
$^{1}H\ \sigma_{n,\gamma}$	-0.11892	0.11	-0.11929	0.05	0.31	2.5
$^{16}O\ \sigma_{el}$	0.11849	0.86	0.11745	0.41	0.88	0.9
$^{240}Pu\ \sigma_{n,\gamma}$	-0.03608	0.16	-0.03607	0.08	0.03	0.2
$^{56}Fe\ \sigma_{n,\gamma}$	-0.00748	0.26	-0.00754	0.10	0.83	3.0
$^{241}Pu\ \bar{\nu}$	0.00391	0.95	0.00390	0.49	0.29	0.3
$^{56}Fe\ \sigma_{el}$	0.00247	6.24	0.00250	2.88	1.08	0.2
$^{14}N\ \sigma_{el}$	0.00228	8.03	0.00193	5.16	15.31	1.6
$^{241}Pu\ \sigma_{f}$	0.00164	2.28	0.00163	1.18	0.56	0.2
$^{53}Cr\ \sigma_{n,\gamma}$	-0.00159	0.26	-0.00160	0.10	0.81	2.9
$^{58}Ni\ \sigma_{n,\gamma}$	-0.00129	0.26	-0.00130	0.10	0.80	2.9
$^{55}Mn\ \sigma_{n,\gamma}$	-0.00127	0.25	-0.00128	0.10	0.84	3.1

TABLE IV. Top fifteen integrated sensitivity coefficients for the PST-001 configuration using a 90×90×90 mesh

These results show a very good agreement between the IFP and the CLUTCH calculations, the R2 ratios being all lower than 3.1. This demonstrate that the discrepancies observed in the previous calculation were only due to an insufficient mesh resolution. Furthermore, relative difference (R1) are below ∼1% except for the elastic scattering of ^{14}N which is ∼15%. However, for this quantity, the relative uncertainty is too high to draw any conclusion.

Figure 11 displays the energy resolved sensitivity profile for elastic scattering cross section of ^{1}H. This figure shows a very good agreement between the profiles computed with the two methods, confidence intervals overlapping in most energy groups.

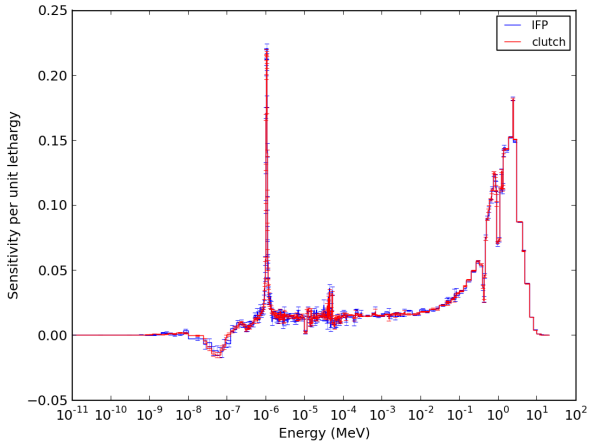

Fig. 11. ^{1}H elastic scattering sensitivity profile for the PST-001 configuration

Figure 12 and figure 13 exhibit respectively the energy resolved sensitivity profile for fission cross section of ^{239}Pu and for radiative capture cross section of ^{240}Pu. A very good agreement is observed between the two methods as all confidence intervals overlap throughout the energy domain.

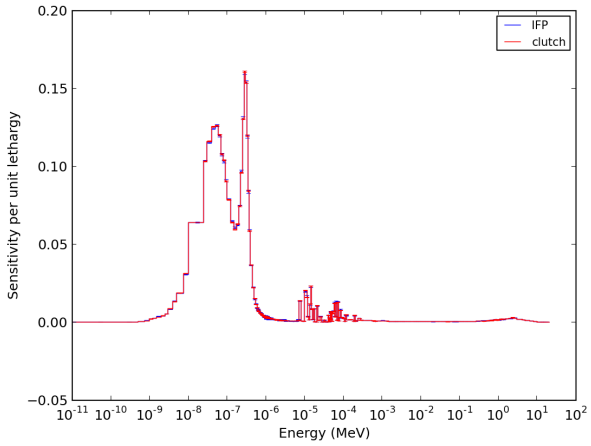

Fig. 12. ^{239}Pu fission sensitivity profile for the PST-001 configuration

Results presented here suggest that the CLUTCH method as implemented in the MORET code is consistent with the IFP for the calculation of sensitivity coefficients. Furthermore, the geometric resolution of the importance map is of importance in order to correctly compute sensitivity coefficients. As already foreseen on previous cases, standard deviations for coefficients computed with the CLUTCH method are significantly lower than coefficients computed with the IFP, on average a factor 2.

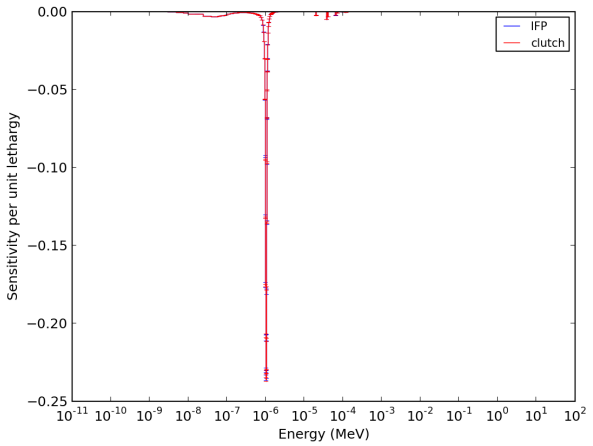

Fig. 13. ^{240}Pu capture sensitivity profile for the PST-001 configuration

This case highlighted the importance of having a sufficiently high resolution for the spatial mesh of the CLUTCH method in order to obtain sensitivity coefficients consistent with the Iterated Fission Probability. A study on spatial resolution and tally convergence for Q^+ is foreseen in order to determine recommendations for users.

IV. PERFORMANCE

In order to compare performance of the CLUTCH approach to the Iterated Fission Probability method, standard deviations computed for several energy integrated coefficients and the computation time required for each calculation were compared. From these quantities, the increase of the figure of merit (FOM), which is a metric commonly used to compare computational efficiency of Monte Carlo calculations, has been computed as the ratio of the CLUTCH and IFP figures of merits. Its definition is provided in equation 6 where σ denotes the standard deviation and T is the computation time.

$$FOM = \frac{1}{\sigma^2 T} \tag{6}$$

Table V displays for the three previous case the computation time, the relative standard deviation and the ratio of figure of merits for each configuration.

Case	Isotope reaction	IFP T(min)	IFP σ(%)	CLUTCH T(min)	CLUTCH σ(%)	ratios of FOM
Jezebel	$^{239}Pu\ \sigma_f$	88	0.02	86	0.01	4.1
UACSA	$^{239}Pu\ \sigma_f$	766	0.11	625	0.06	4.1
	$^{1}H\ \sigma_{el}$		0.82		0.40	5.2
	$^{16}O\ \sigma_{el}$		1.24		0.66	4.3
PST-001	$^{1}H\ \sigma_{el}$	537	0.57	483	0.27	5.0
	$^{239}Pu\ \sigma_f$		0.09		0.04	5.6
	$^{56}Fe\ \sigma_{n,\gamma}$		0.26		0.10	7.5

TABLE V. Comparison of the CLUTCH and IFP figures of merit for calculation of integrated sensitivity coefficients for several nuclides

This table highlights a reduction of the Monte Carlo uncertainty by a factor of ~2 when using the CLUTCH approach for the adjoint weighting. This reduction appears because all active neutrons that are absorbed by fissile nuclide will provide non-zero tallies for sensitivity coefficient. On the contrary, when using the Iterated Fission Probability as implemented in the MORET code, "dummy" neutrons will be simulated over several generations and may provide a zero value for the adjoint weighting if a history ends as non-fissile absorption or leakage whereas some other neutron chains will produce large values for the importance. These discrepancies in adjoint weighting will introduce variance for sensitivity coefficients.

In addition to variance reduction, the computation time is reduced for the thermal systems (UACSA and PST-001) by 10% to 20% when using the CLUTCH approach. However it did not reduce the computation time for the Jezebel configuration, which is in fast spectrum. Combining these effects, the figure of merit is increased by a factor comprised between 4 and 7.5 according to the observed sensitivity coefficient.

Finally, based on the studied configurations, the CLUTCH approach displays a better computational efficiency than the Iterated Fission Probability both in terms of computation time and in terms of standard deviation. In addition, the increase of memory usage has been observed to be less than 1 MB for the studied configurations.

V. CONCLUSION

An alternate approach to the IFP method for weighting sensitivity coefficients has been successfully implemented in the MORET code. Based on the CLUTCH method used in SCALE to treat the adjoint weighting, this alternate approach consists of constructing an adjoint source function on a spatial mesh during inactive cycles. The importance is considered as fixed in each single mesh interval and represents the average progeny for a fission neutron in that mesh. Once this map is constructed, it is used at every absorption point instead of simulating "dummy" neutrons, which allows saving computation time and reducing the variance of sensitivity coefficients.

The preliminary verification has been performed using comparison to the Iterated Fission Probability method already implemented in the MORET code. The verification has been performed on three different benchmarks and show a very good agreement between the Iterated Fission Probability and CLUTCH methods. Results exhibit a relative difference generally lower than 2% for energy integrated sensitivity coefficients and confidence intervals generally overlap. Furthermore, sensitivity coefficients profiles display a very good agreement for all nuclides and reactions observed in these configurations. On average a reduction of a factor 2 is observed on standard deviations when using the CLUTCH method compared to the IFP.

Performance between the IFP and the CLUTCH methods have been compared demonstrating for the studied cases a better computational efficiency of the CLUTCH approach. However, the Iterated Fission Probability may be considered as a reference calculation as there is no approximation on the adjoint weighting whereas the CLUTCH results may depend on the spatial mesh resolution and the number of neutrons sim-

ulated to estimate the average progeny in each mesh interval, as showed in the calculations for the PST-001 configuration.

Future work will consist of increasing the verification database, improving the user interface and optimizing performance. In addition, it is foreseen to extend the CLUTCH method to the calculation of kinetic parameters and perturbations to isotopic concentration and density using Taylor expansion. A study is planned on the mesh spatial resolution and tally convergence for Q^+ in order to provide default values and recommendations for the users. Furthermore, it is foreseen to work on the development of indicators of the reliability of the importance map.

For now, this method has only been tested on sensitivity coefficients to cross sections and not on distribution (fission spectrum or cosine scattering laws) yet. The adaptation of the CLUTCH method to the calculation of sensitivity profiles to distributions is also foreseen.

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