

Sensitivity of Pressurized Water Reactors Vessels Aging to Fuel Composition

02/12/2021

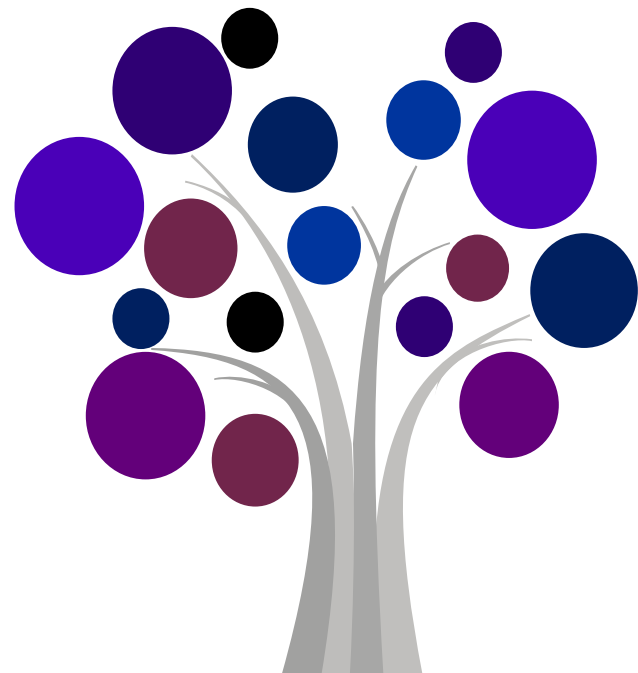
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 **ANS** Winter Meeting & Expo

Content

- Introduction
- Calculation Scheme
- Results
- Conclusion and Prospects





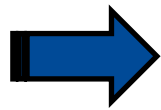
Introduction

Study context

- Extension of PWRs operation duration
 - Vessel = 2nd confinement barrier → essential to accurately characterize its structural integrity
 - Neutron irradiation → embrittlement of the vessel material
- Monitoring of embrittlement : Surveillance Programs
 - Accelerated irradiation of vessel material samples → mechanical strength tests

➤ *Embrittlement = f(vessel composition, $\varphi_{>1\text{ MeV}}$)*

fast neutron fluence



Limit not to exceed

$$\varphi_{>1\text{ MeV}} = \int_0^T \int_{E>1\text{ MeV}} \phi(t, E) \cdot dE \cdot dt$$

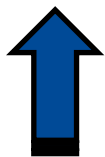
- $\sigma_{\varphi_{>1\text{ MeV}}} \sim 10\% - 20\%$

Reactors are getting closer to the limit → need to better analyse the global bias and uncertainty on $\varphi_{>1\text{ MeV}}$ assessments

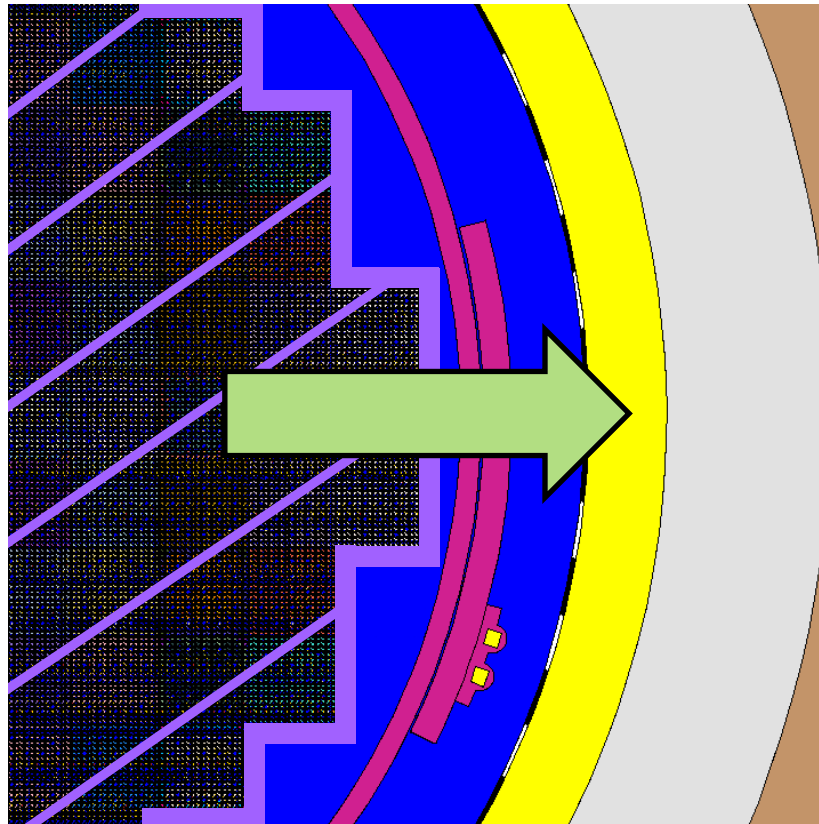
Usual calculation scheme for vessel fluence assessments

First step:
fission neutron
source term
evaluation

Where are the
fission neutrons
emitted and what
is their energy ?



Sensitivity to fuel
composition
perturbations ?



+ time integration

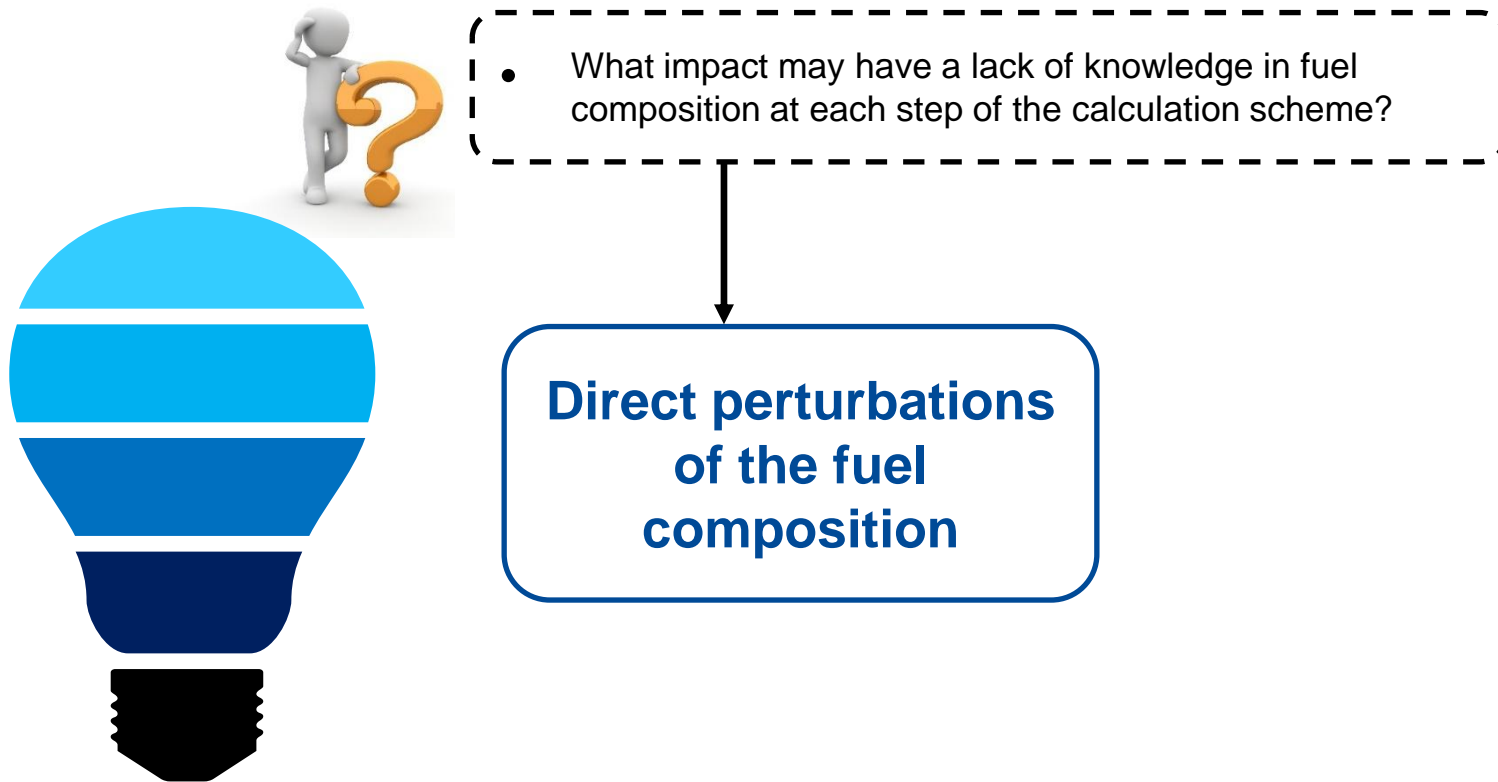
Second step:
modeling of neutron
attenuation from the core
to the sites of interest
(vessel, capsules)

For a quantity of
emitted neutrons, how
many reach the vessel
and what is their
energy ?

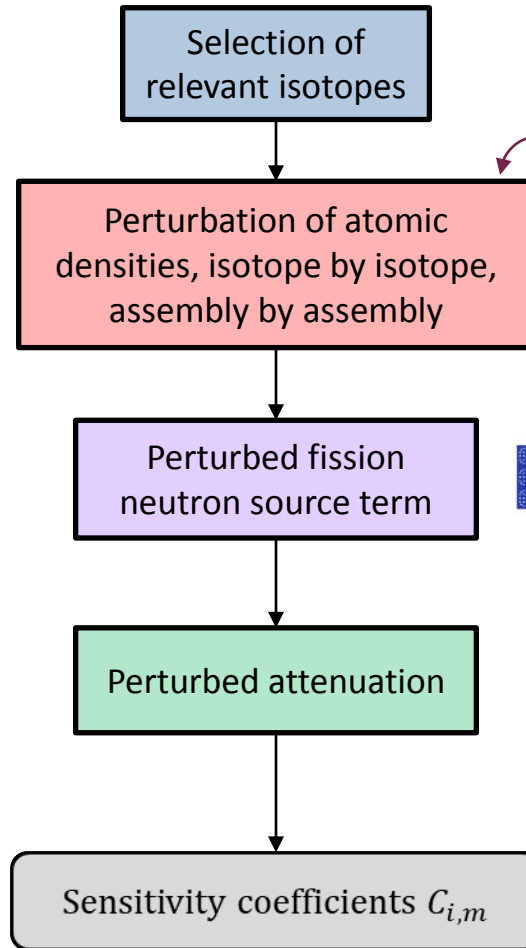
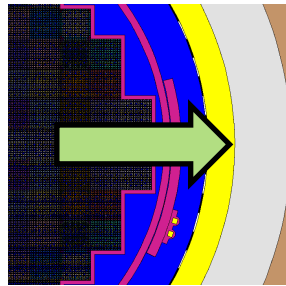
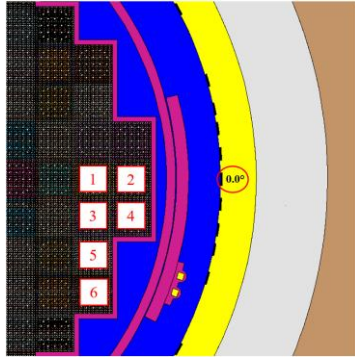


Sensitivity to fuel
composition
perturbations ?

Questioning and objectives

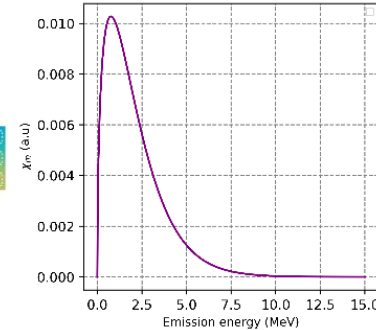
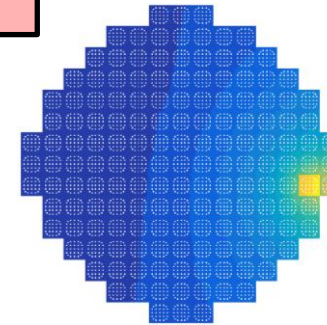


Study methodology



several perturbations $\in [0\% ; +30\%]$

hypothesis of independence between the atomic densities of the isotopes



$$C_{i,m} = \frac{\delta \phi_{>1\text{MeV}} / \phi_{>1\text{MeV}}}{\delta N_{i,m} / N_{i,m}}$$

Fast neutron flux

Atomic density

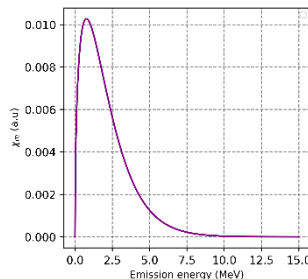
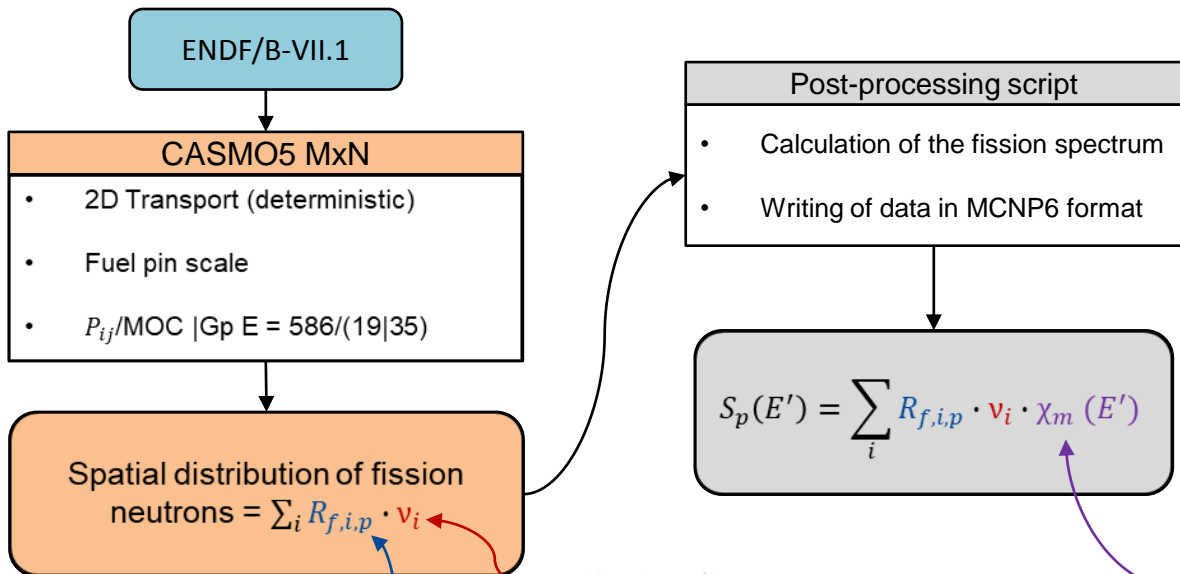
$m = \text{assembly}$
 $i = \text{isotope}$



Calculation Scheme

Calculation scheme – first step

Study case : French 900 MW_e PWR ; UOX/MOX



Average fission spectrum at an assembly scale

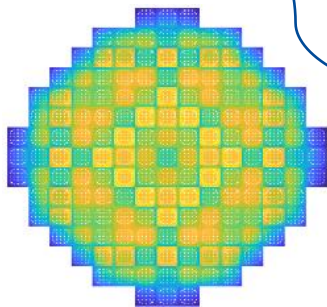
Probability that the neutron emission comes from isotope i

$$\chi_m(E') = \frac{\sum_i R_{f,i,m} \cdot v_i \cdot \chi_i(E')}{\sum_i R_{f,i,m} \cdot v_i}$$

Spatial distribution of fission neutrons = $\sum_i R_{f,i,p} \cdot v_i$

Number of neutrons emitted per fission

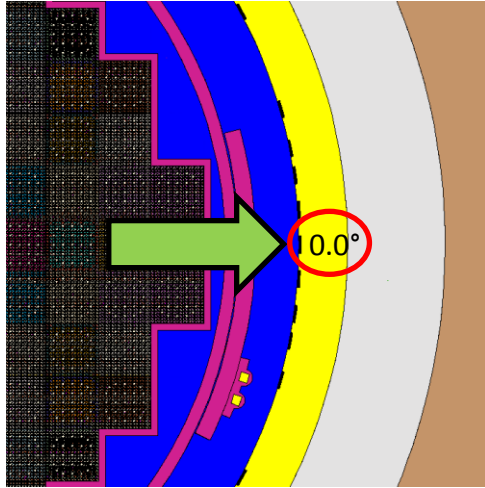
Fission rate



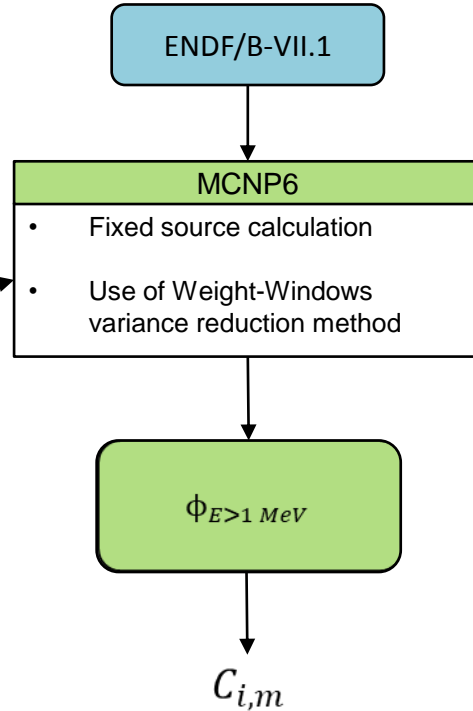
p = fuel pin
 i = isotope
 m = assembly
 E' = energy of emitted neutron

Calculation scheme – second step

Study case : French 900 MW_e PWR ; UOX/MOX



$$S_p(E') = \sum_i R_{f,i,p} \cdot v_i \cdot \chi_m(E')$$



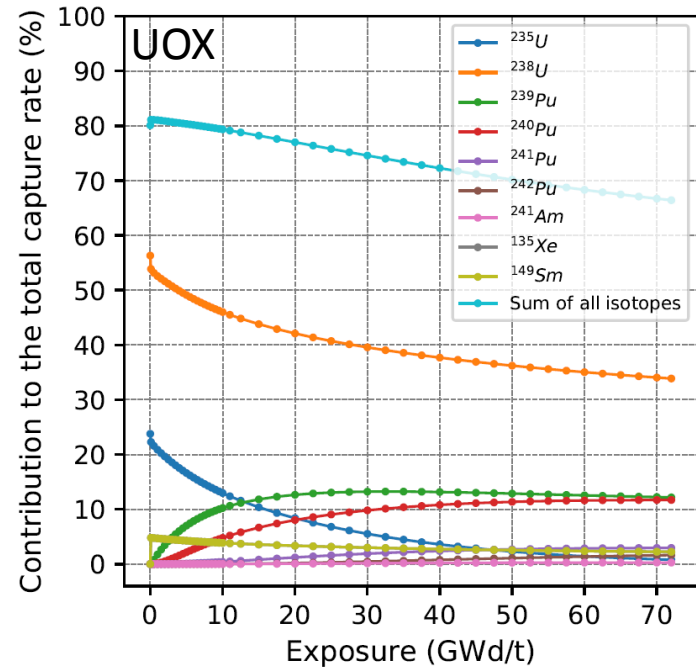
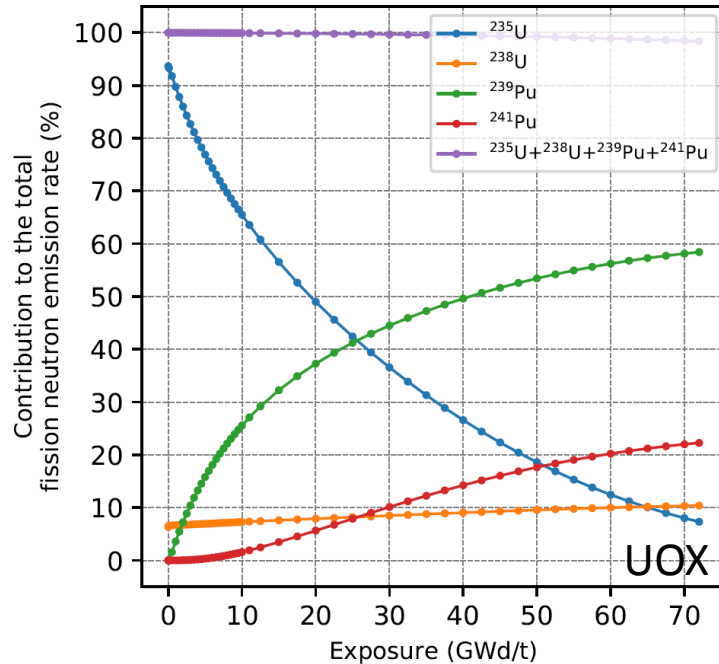
$\sigma_{\Phi} \sim 0,7\%$



Results

Isotopes selection

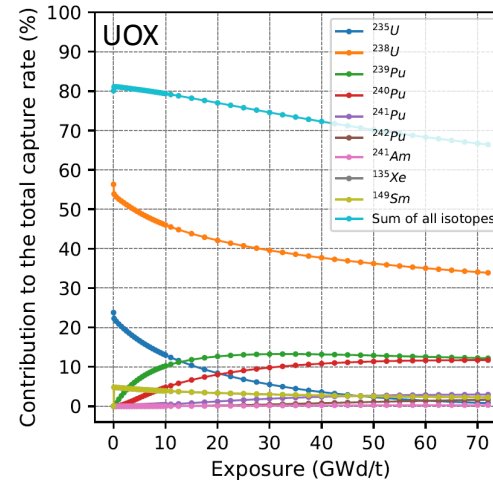
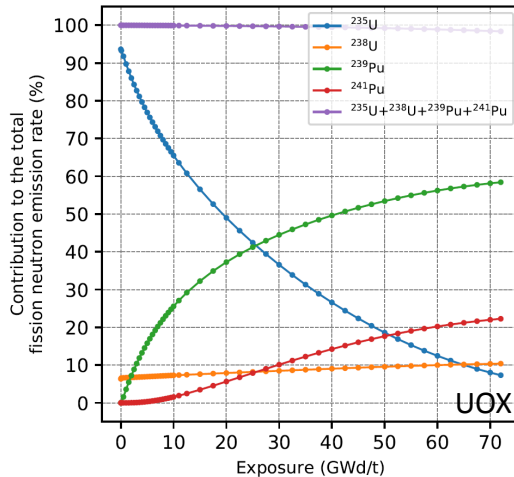
- CASMO5 – depletion calculation on assemblies in an infinite medium
- Criterion: contribution $\geq 1\%$ of the total emission or capture rate (for a UOX or a MOX assembly)



Isotopes selection

■ CASMO5 – assemblies in an infinite medium

■ Criterion: contribution $\geq 1\%$ of the total emission or capture rate (for a UOX or a MOX assembly)



The rest comes from +100 isotopes with low contribution (<1%)



Emissions
~99% for UOX and MOX assemblies

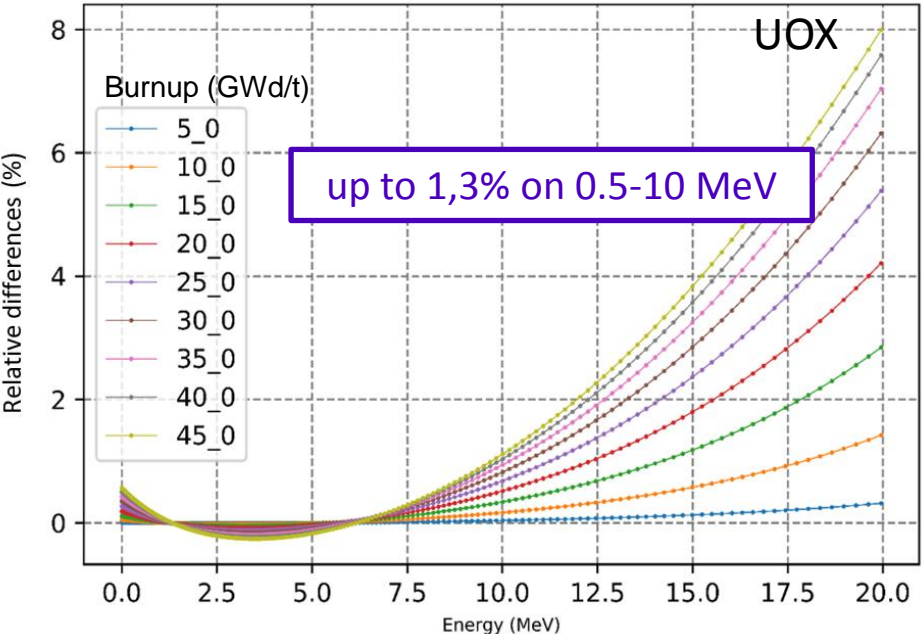
^{235}U , ^{238}U , ^{239}Pu , ^{241}Pu , ^{240}Pu , ^{242}Pu , ^{149}Sm , ^{135}Xe and ^{241}Am

Capture
UOX \in [65% - 80%]
MOX \in [72% - 93%]

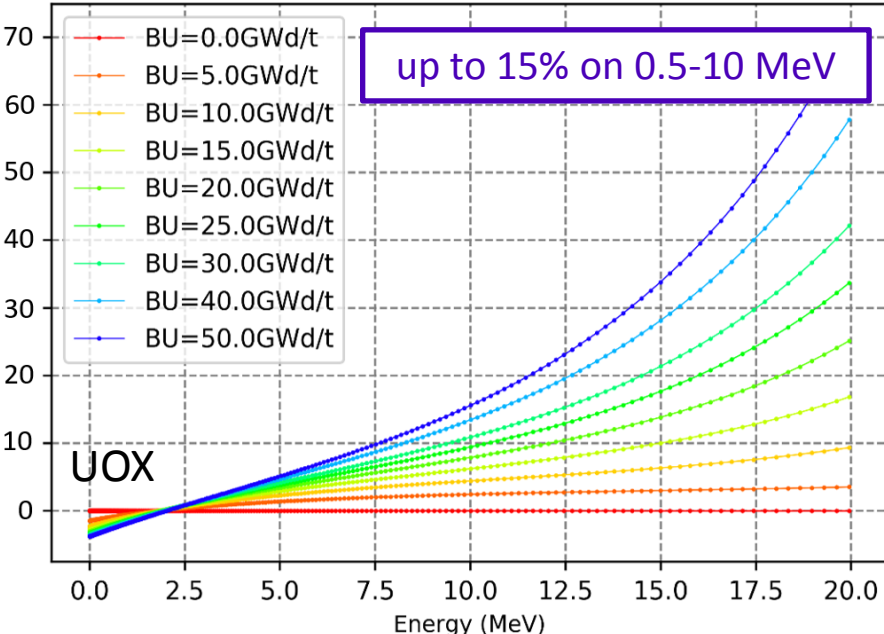
Impact of fuel composition perturbation on the fission spectrum

UOX assembly (equivalent results for MOX assemblies)

Impact of a +30% ²⁴¹Pu perturbation for several fuel exposure level



Evolution of the fission spectrum with fuel exposure



Negligible effect of composition perturbations on the fission spectrum

Sensitivity coefficients

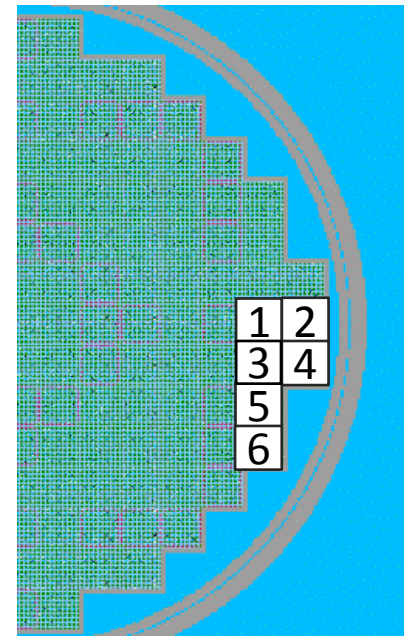
- Propagation of perturbed fission neutron source terms to the fast neutron flux incident on the vessel (azimuthal position 0°)

Isotope – Assembly position	$C_{i,m}$ (%flux / %density)
U ²³⁵ - N°1	0.42 ± 0.04
Pu ²³⁹ - N°1	0.33 ± 0.04
U ²³⁸ - N°1	-0.42 ± 0.03
U ²³⁸ - N°2	-0.12 ± 0.03
Pu ²³⁹ - N°2	0.35 ± 0.04
Pu ²⁴⁰ - N°2	-0.15 ± 0.03
Pu ²⁴¹ - N°2	0.24 ± 0.04
U ²³⁵ - N°3	0.78 ± 0.04
U ²³⁸ - N°3	-0.40 ± 0.03
Xe ¹³⁵ - N°3	-0.13 ± 0.03
U ²³⁵ - N°4	0.10 ± 0.04
Pu ²³⁹ - N°4	0.15 ± 0.04
U ²³⁵ - N°5	0.53 ± 0.04
U ²³⁸ - N°5	-0.24 ± 0.03
U ²³⁵ - N°6	0.20 ± 0.04
U ²³⁸ - N°6	-0.09 ± 0.03

$$C_{i,m} = \frac{\delta\phi_{>1MeV}/\phi_{>1MeV}}{\delta N_{i,m}/N_{i,m}}$$

$C_{i,m}$ depends on

- Assembly position
- Assembly type
- Assembly exposure



Assembly number (cf. Fig. 1)	Fuel Type	Number of irradiation cycles	Contribution to the fast neutron flux at 0° (%)
1	UOX	3	6
2	MOX	4	43
3	UOX	1	6
4	UOX	4	17
5	UOX	1	1
6	UOX	1	1



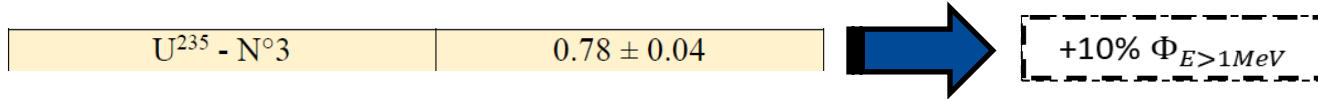
Conclusion and Prospects

Conclusion

- $C_{i,m}$ were evaluated for 9 isotopes in 6 assemblies (azimuthal position 0°)
 - Linearity on the range [0% ; +30%]
 - Hypothesis of independence between the atomic densities of the isotopes
- [GEORGIEVA et al., 2018]
 - CASMO5 ^{235}U density predictions deviates up to +13% from experimental data

$$C_{i,m} = \frac{\delta\phi_{>1\text{MeV}}/\phi_{>1\text{MeV}}}{\delta N_{i,m}/N_{i,m}}$$

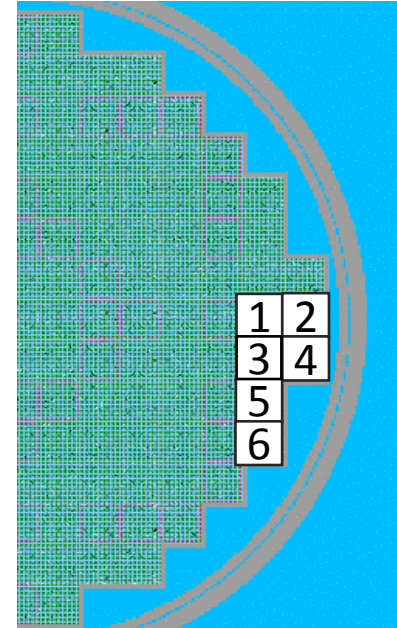
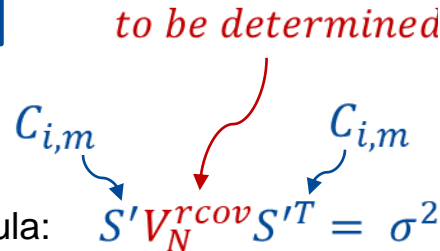
^{235}U , ^{238}U , ^{239}Pu , ^{241}Pu ,
 ^{240}Pu , ^{242}Pu , ^{149}Sm , ^{135}Xe
 and ^{241}Am



Lack of knowledge of fuel composition may induce significant bias/uncertainty on vessel aging assessments

Prospects

- Uncertainty propagation, using the sandwich formula: $S' V_N^{rcov} S'^T = \sigma^2$





Thank you for your attention

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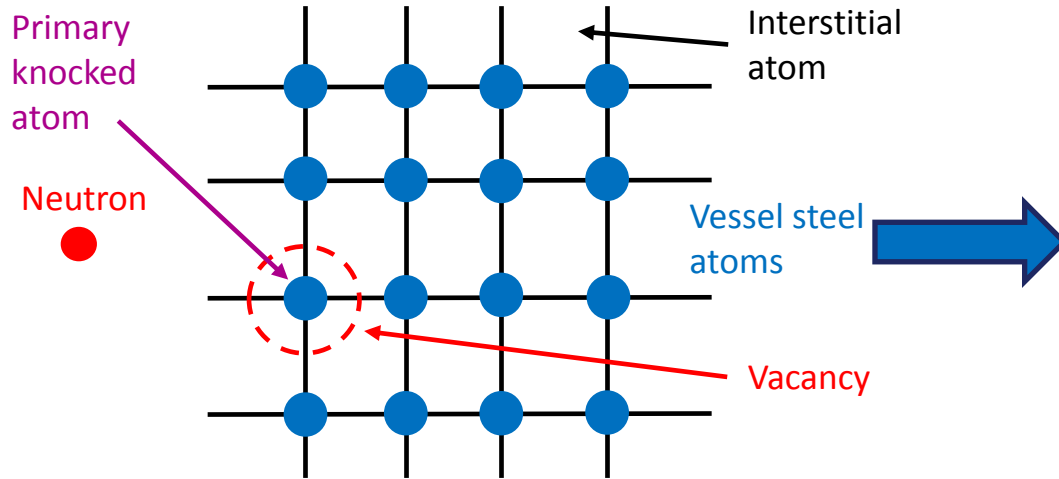
Romain VUIART



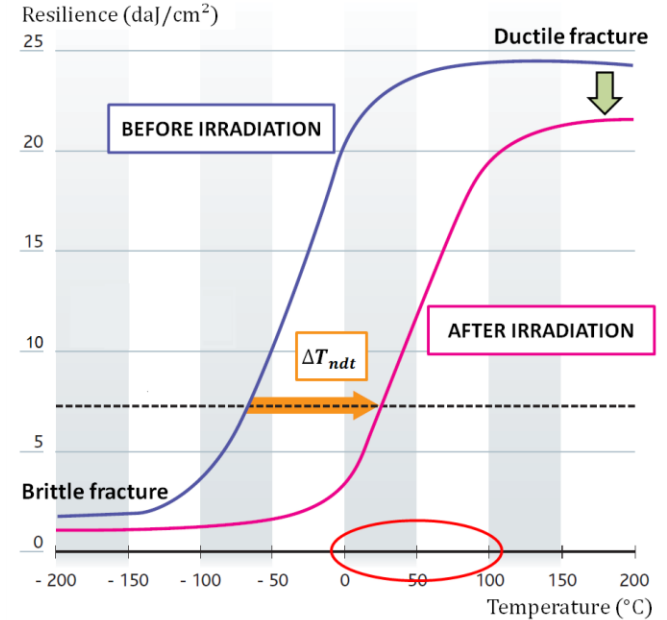
BACK-UP

Effect of neutron irradiation of the RPV material

Neutron irradiation → material embrittlement

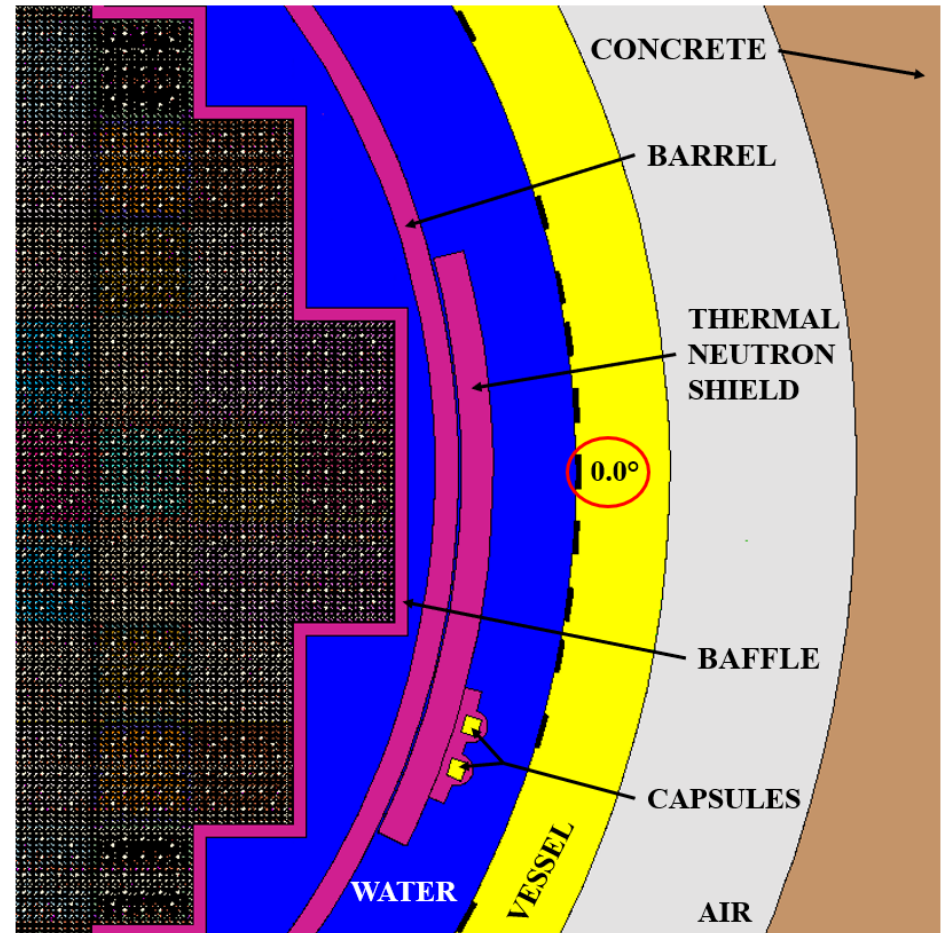


Recombination time
($t_c < t_f$ few ps)



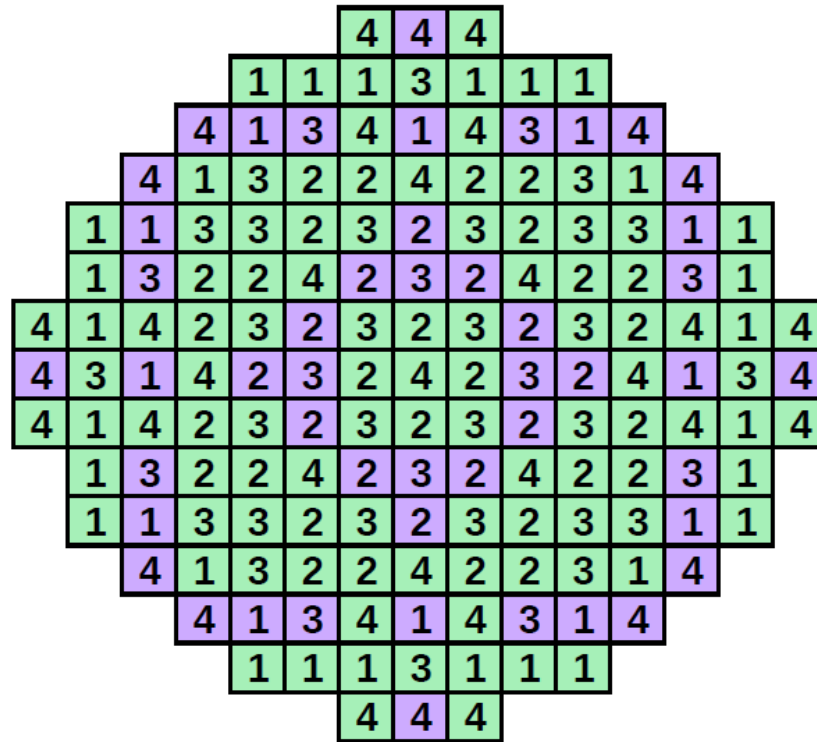
Case of study

- Representative of a French 900 MW_e PWR
- Fuel composition → middle of a UOX/MOX equilibrium cycle
- 0° in-vessel detector*
 - Neutron flux > 1 MeV



* : covers the entire active height of the core

Fuel loading



 UOX

 MOX

number = irradiation cycle

Data of perturbed assemblies

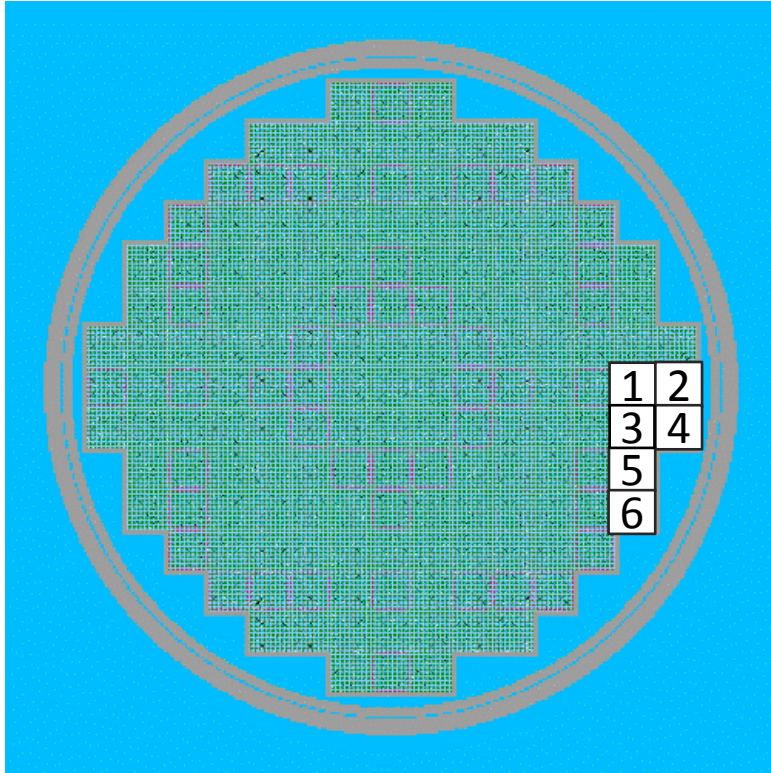
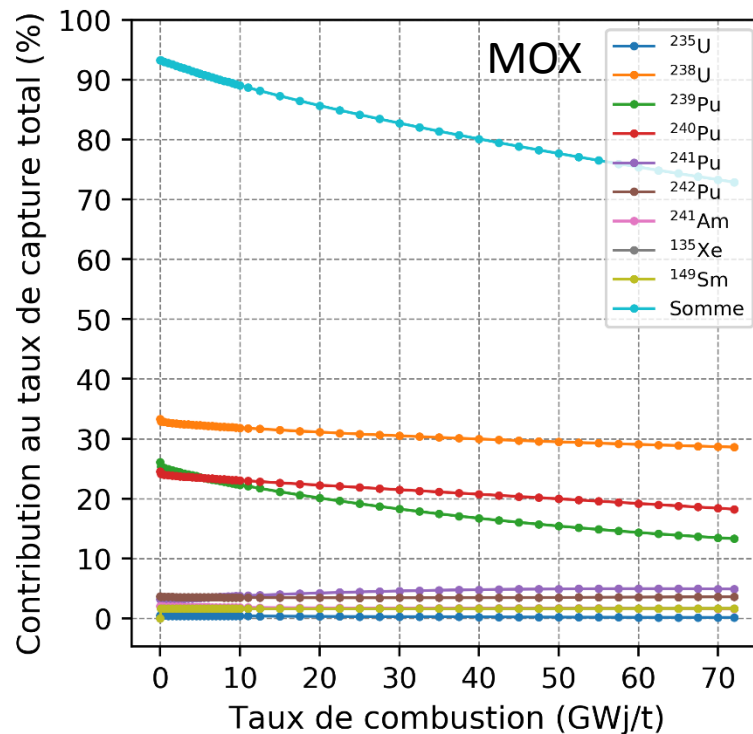
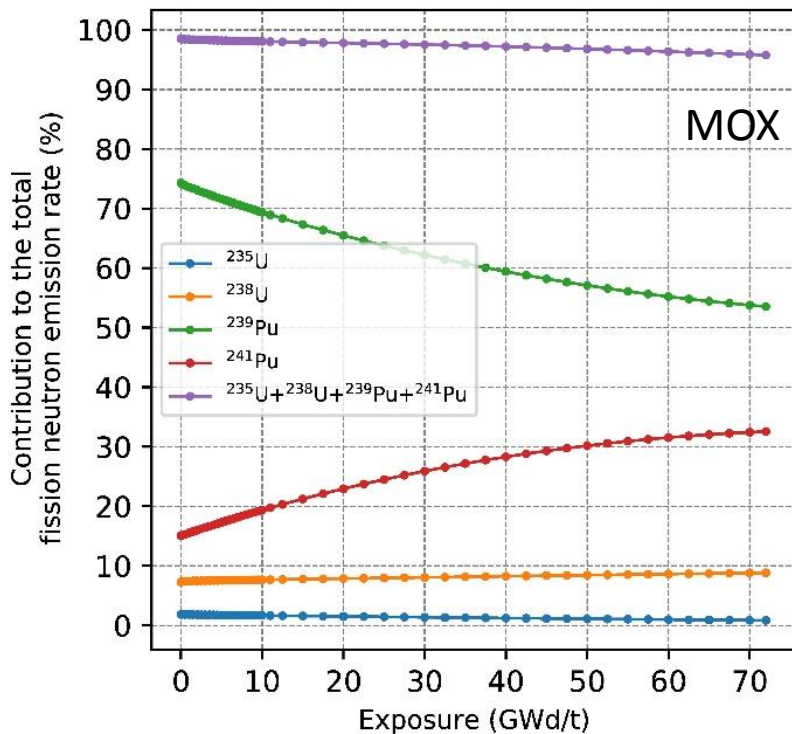


Table 1. Data of perturbed assemblies

Assembly number (cf. Fig. 1)	Fuel Type	Number of irradiation cycles	Contribution to the fast neutron flux at 0° (%)
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4	UOX	4	17
5	UOX	1	1
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Isotopes selection

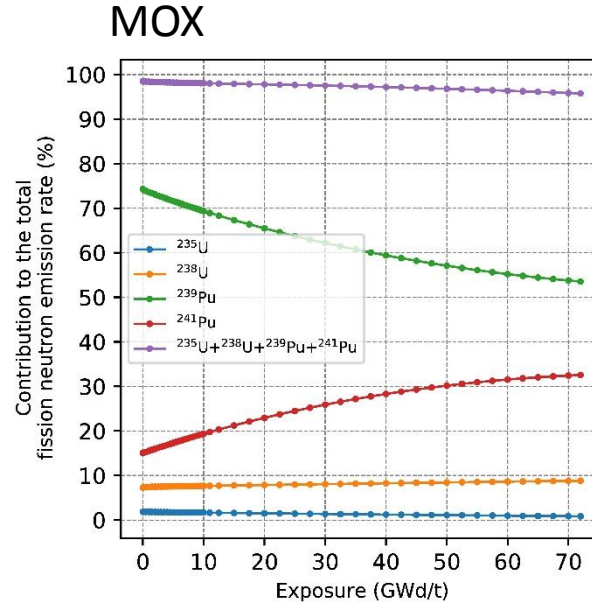
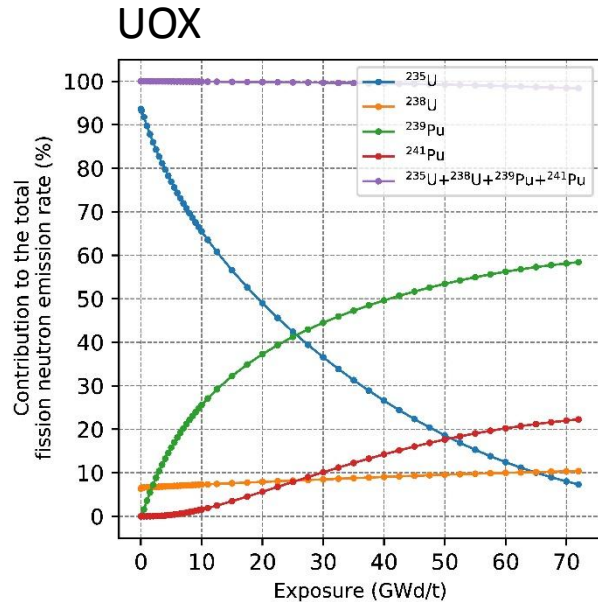
Criterion: contribution $\geq 1\%$ of the total emission or capture rate (for a UOX or a MOX assembly)



Isotopic fission spectrum

TABLE I. Data used for fission spectrum modeling

Nuclide	Incident neutron energy	Fission Spectrum type	a (MeV)	b (MeV ⁻¹)
²³⁵ U	Thermal	Watt	0.988	2.249
²³⁸ U	2.6 MeV	Watt	0.920	3.121
²³⁹ Pu	Thermal	Watt	0.966	2.842
²⁴¹ Pu	Thermal	Maxwell	1.3597	-

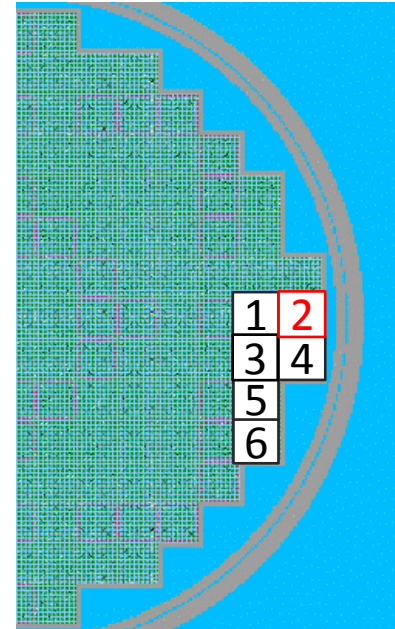
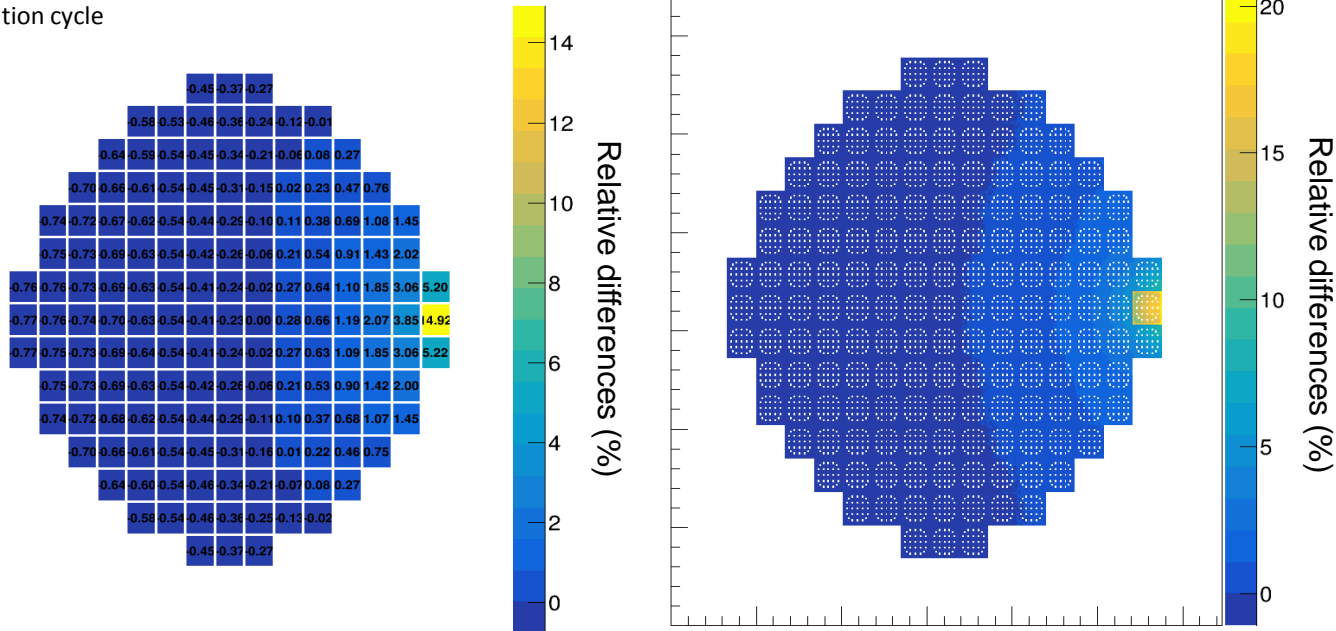


[Vuiart et al., NSE, 2021]

Impact of fuel composition perturbation on the neutron emission rate

Assembly n°2 = MOX
assembly in its 4th
irradiation cycle

Impact of a 30% increase of the ²³⁹Pu density for assembly n°3

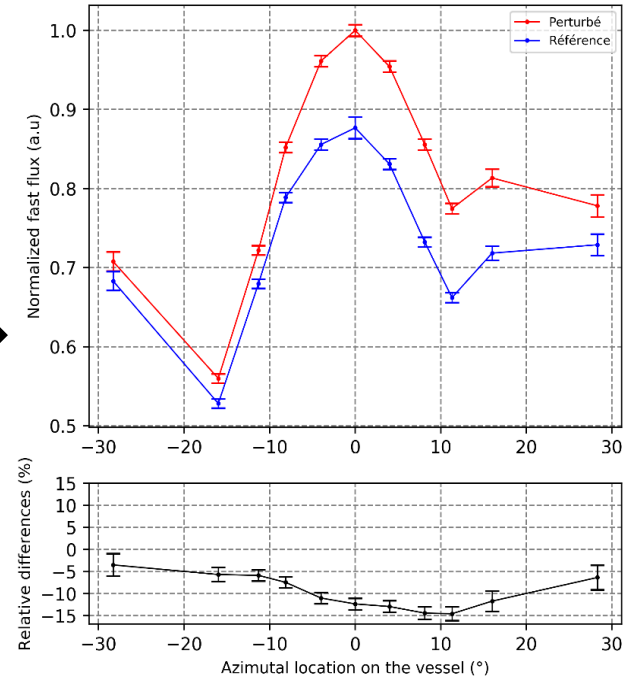
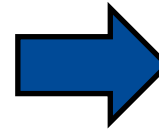
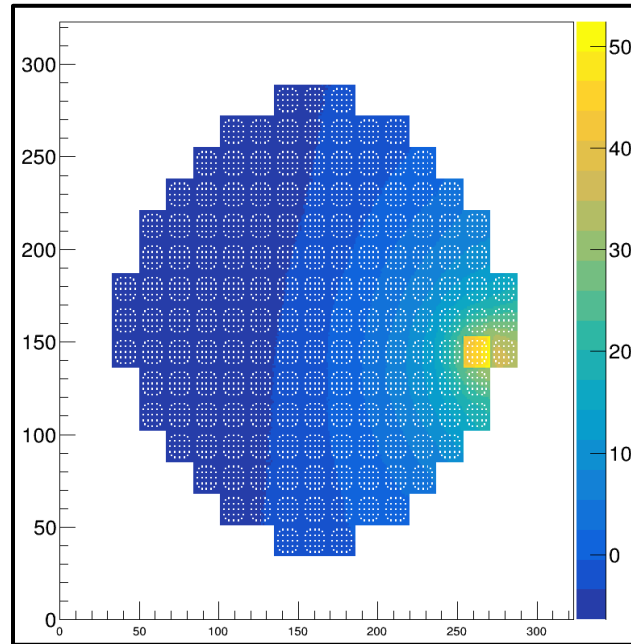
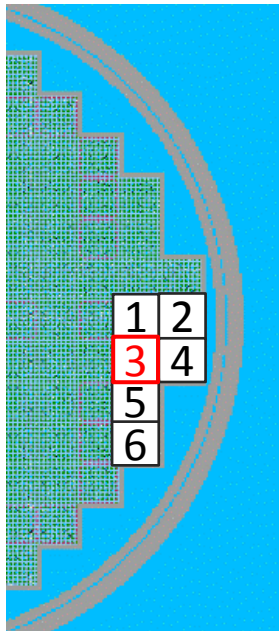


**Significant effect of composition perturbations on the fission neutron emission rate distribution
+ effect linear on the range [0% ; +30%]**

Impact of the fast neutron flux incident on the RPV

■ Composition perturbation in the MCNP6 calculation has no impact on the fast flux assessments

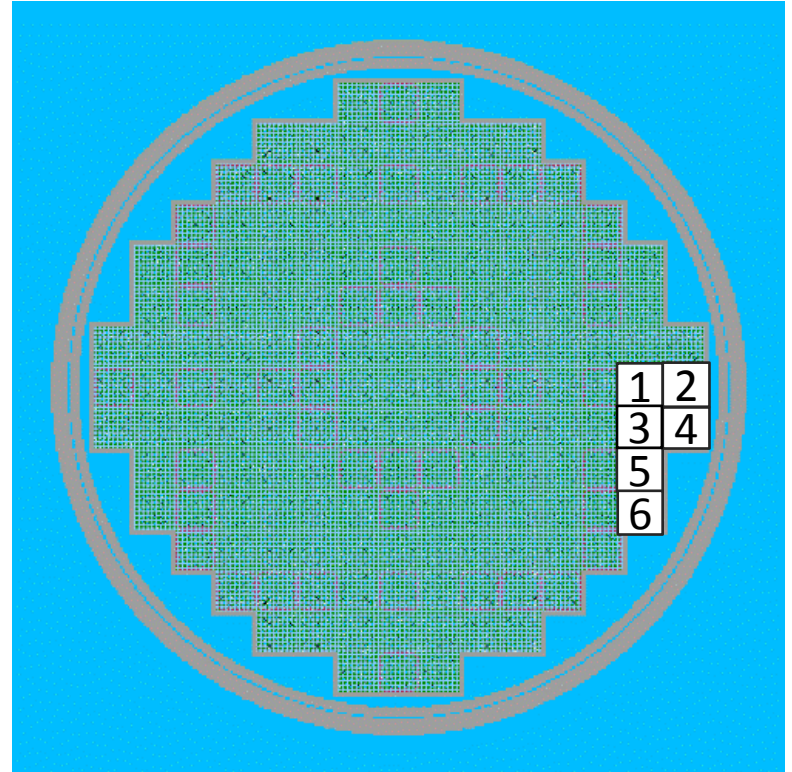
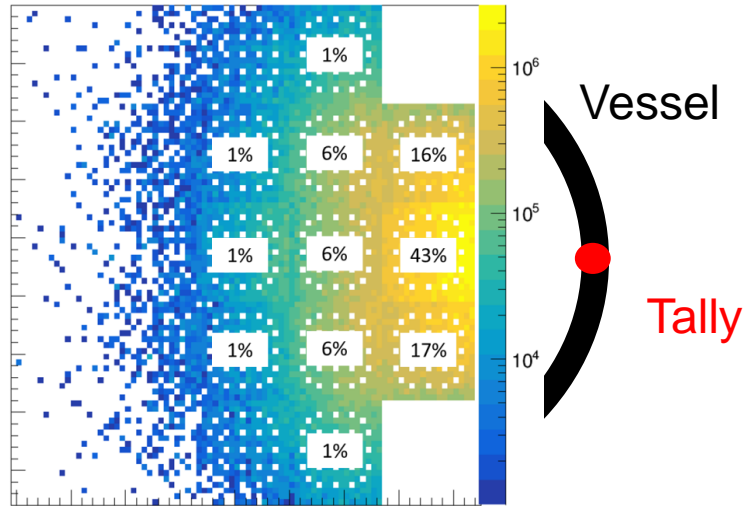
→ Propagation only of perturbed fission neutron emission distributions



Study Methodology

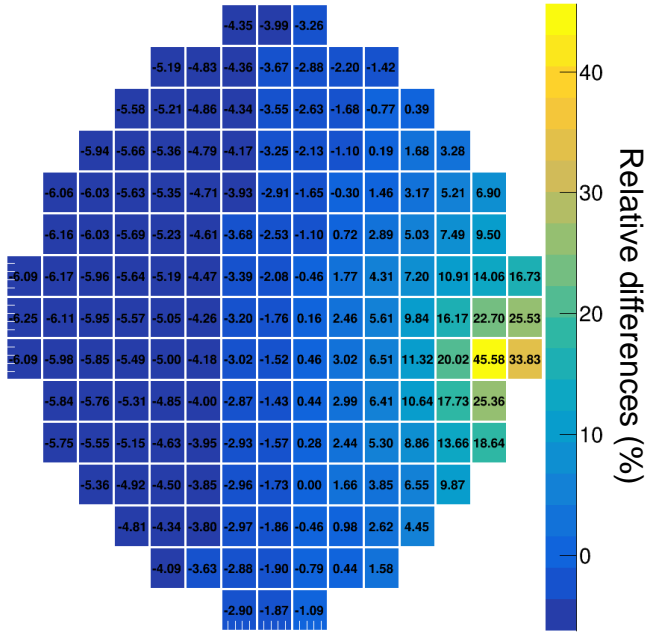
Assembly-by-Assembly Composition Perturbation (CASMO MxN):

Contributions of boarder assemblies to the fast neutron flux incident on the vessel (azimuth 0°)



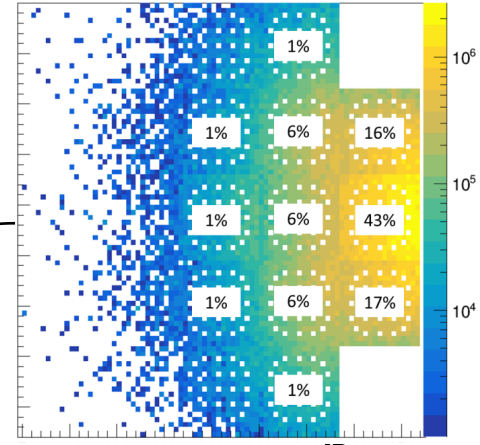
[Peron,
2018]

Calculation of a priori $C_{i,m}$ coefficients



Contribution of assemblies to the fast neutron flux at the vessel (at azimuth 0°)

≡ a priori $C_{i,m}$



[Peron, 2018]

Atomic density perturbation (%)

TABLE 3.1 – Coefficients de sensibilité du flux à la cuve à l'azimut 0° à la variation de la composition isotopique du combustible (et leur incertitude à un σ).

Assemblage	Nucléide	$C_{i,a}^0$ ($\% \phi_{>1MeV} / \% N_i$)	$C_{i,a}^0$ a priori ($\% \phi_{>1MeV} / \% N_i$)
N°1 (UOX - CYCLE 3)	²³⁵ U	0,42 ± 0,04	0,39
	²³⁸ U	-0,42 ± 0,03	-0,35
	²³⁹ Pu	0,33 ± 0,04	0,32
	²⁴⁰ Pu	-0,10 ± 0,03	-0,12
	²⁴¹ Pu	0,07 ± 0,04	0,10
	¹³⁵ Xe	-0,06 ± 0,03	-0,07
N°2 (MOX - CYCLE 4)	²³⁵ U	0,00 ± 0,03	0,01
	²³⁸ U	-0,12 ± 0,03	-0,08
	²³⁹ Pu	0,35 ± 0,04	0,29
	²⁴⁰ Pu	-0,15 ± 0,03	-0,15
	²⁴¹ Pu	0,24 ± 0,04	0,22
N°3 (UOX - CYCLE 1)	²³⁵ U	0,78 ± 0,04	0,82
	²³⁸ U	-0,40 ± 0,03	-0,41
	²³⁹ Pu	0,06 ± 0,04	0,11
	¹³⁵ Xe	-0,13 ± 0,03	-0,09
N°4 (UOX - CYCLE 4)	²³⁵ U	0,10 ± 0,04	0,10
	²³⁹ Pu	0,15 ± 0,04	0,14
N°5 (UOX - CYCLE 1)	²³⁵ U	0,53 ± 0,04	0,49
	²³⁸ U	-0,24 ± 0,03	-0,21
	²³⁹ Pu	0,07 ± 0,04	0,06
	¹³⁵ Xe	-0,03 ± 0,03	-0,05
N°6 (UOX - CYCLE 1)	²³⁵ U	0,20 ± 0,04	0,18
	²³⁸ U	-0,09 ± 0,03	-0,07