DE LA RECHERCHE À L'INDUSTRIE

Interpretation of the BALZAC-SI experiments

December 7th 2020

Sections of the PhD thesis of Amine Hajji, presented by Gérald Rimpault

In fast reactors, the diffusion length of neutrons is larger than in thermal reactors due to lower cross sections but also the flux level in the core is much larger

- Much more neutron leakage than in thermal reactors

Leaking neutrons may have several coonsequences

- Damage on the structures of the reactor
- Activation of secondary sodium

- To mitigate those effects, neutron shielding is used
- It is necessary to be able to design efficient and reliable neutron shielding

Calculation tools are needed to design neutron shielding

- These tools must be as efficient and precise as possible

Verification-Validation-Uncertainty Quantification process is required: experiments are needed to validate the calculation tools and the used nuclear data

- It is necessary to analyse experiments representing neutron shielding
- Many shielding experiments are analysed, including ASPIS, JANUS and BALZAC-SI
- In this presentation, we concentrate on the BALZAC-SI experiments

A set of experiments realised on the MASURCA critical mock-up at CEA Cadarache in 1988

- Aim of the experiments: validate calculation tools for internal storage

Internal storage (IS or SI in French) is often considered in fast reactors

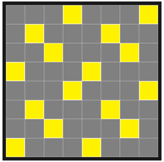
- The neutron flux reaching the internal storage should be as low as possible
- Neutron shielding is used

Three fissile zones:

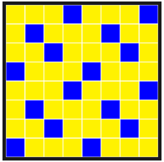
- ZONA1-POA: $UPuO_2$ with 18 % Pu content and a Pu vector with 91,6 % Pu239
- ZONA1-PIT: $UPuO_2$ with 18 % Pu content and a Pu vector with 76,7 % Pu239
- R1: metallic enriched U with 30 % U235

Axial and radial fertile blanket + IS in ZONA3: $UPuO_2$ with 12 % Pu content

Shielding zone:



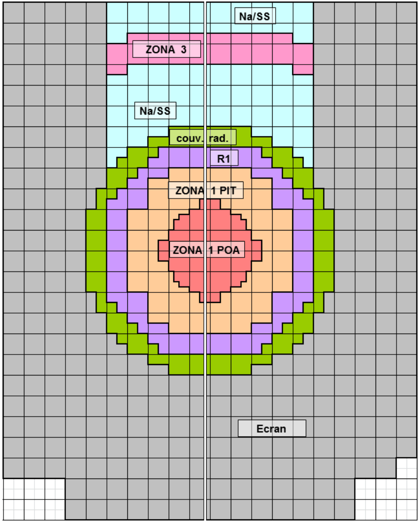
NA/SS assembly



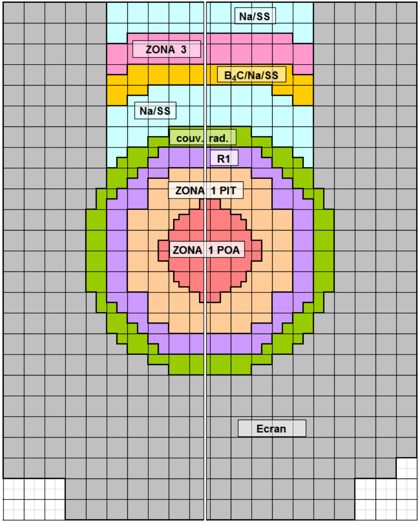
NA/SS/B4C assembly

- Steel: most used material in neutron shielding
- Natural boron carbide (20 % B10): highly efficient thermal absorber

Sodium Steel Boron carbide



BALZAC-SI1 experiment



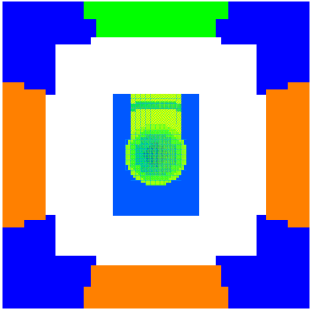
BALZAC-SI2 experiment

Measurments are performed in a radial channel:

- Uranium 235 fission chambers
- Depleted uranium fission chambers
- Plutonium 239 fission chambers
- Neptunium 237 fission chambers
- Boron 10 ionisation chambers
- Uranium 235 activation detectors

- Multiple measurments for different energy domains
  - Presentation of the results obtained for the uranium 235 and depleted uranium fission chambers

The Monte-Carlo code TRIPOLI-4® is used to interpret the BALZAC-SI experiments



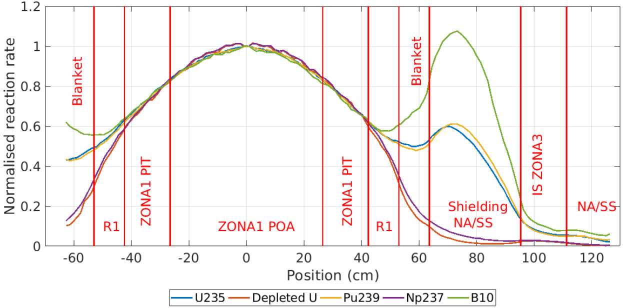
Several nuclear data libraries are used :

- JEFF-3.1.1
- JEFF-3.2
- JEFF-3.2 + Fe56 ENDF/B-VIII.0
- JEFF-3.2 + Fe56 JENDL-4.0
- JEFF-3.1.1 + Fe56 ENDF/B-VIII.0

The geometry is modelled in 3D, assumptions are made for the walls around the core

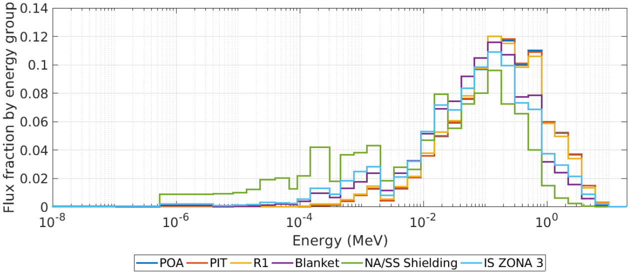
Criticallity calculations are performed, variance reduction techniques are **not used**, 2.5 to 5.0×10^9 neutron stories are simulated

Reaction rates measured during the experiment



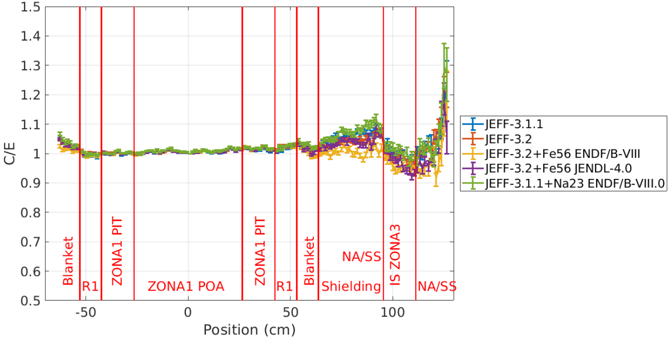
- Different behaviour for thermal (U235, Pu239, B10) and for fast (Depleted U, Np237) chambers
- 2 to 3 decades decrease in the reaction rates

Neutron spectra calculated by TRIPOLI-4®



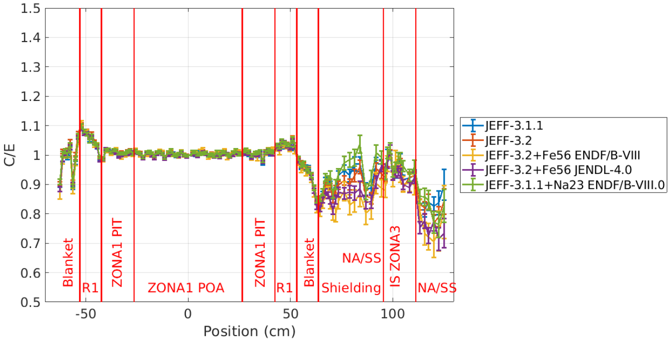
- Large variation in the neutron spectra inside the shielding
  - Thermalisation of flux in the shielding
  - Fast flux in the internal storage

Comparison between the calculation and the experiment, uranium 235 chamber



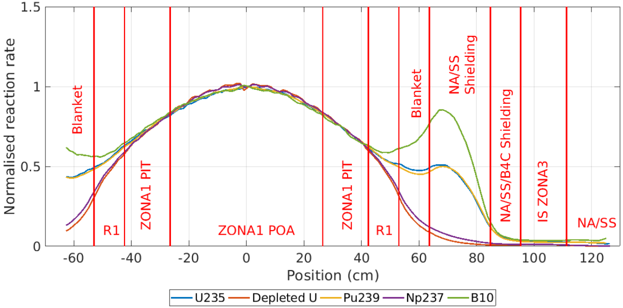
- Overestimation of reaction rates by 10 %, similar behaviour obtained with JANUS Phase 1
- Low dependancy on the nuclear data of Fe56 and Na23

Comparison between the calculation and the experiment, depleted uranium chamber



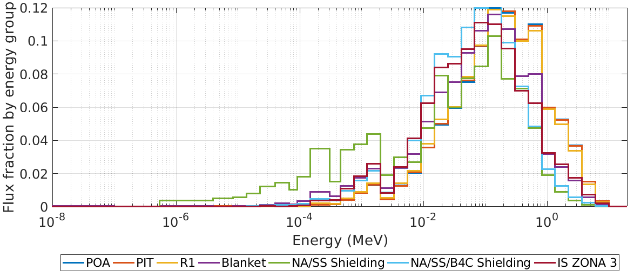
- Underestimation of reaction rates by 20 %
- Low dependancy on the nuclear data of Fe56 and Na23

Reaction rates measured during the experiment



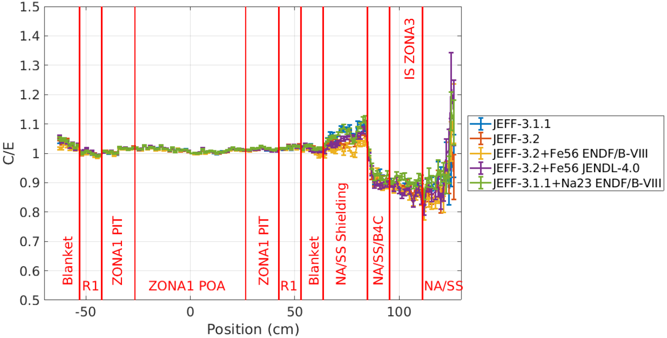
- Similar behaviour to BALZAC-SI1
- Larger decrease in reaction rates

Neutron spectra calculated by TRIPOLI-4®



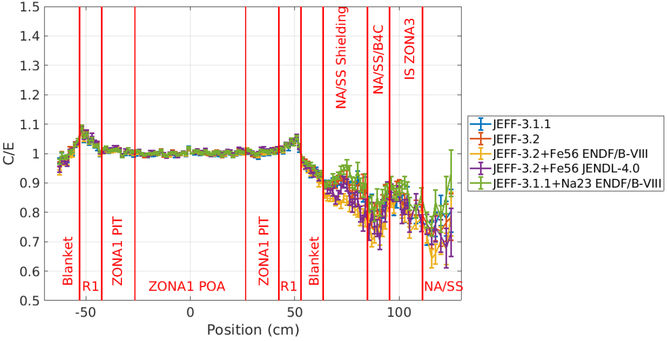
- Fast neutron flux in the B4C shielding: thermal absorber

Comparison between the calculation and the experiment, uranium 235 chamber



- Overestimation then underestimation of reaction rates by 10 %

Comparison between the calculation and the experiment, depleted uranium chamber



- Underestimation of reaction rates by 20 %

Monte-Carlo calculations can be very costly in neutron sheilding

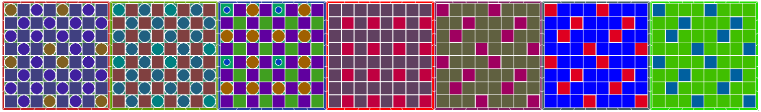
- Large statistical uncertainties

Deterministic calculations are less costly and more flexible

- However, proper calculation schemes are necessary

In this part, the APOLLO3® code using recommanded calculation schemes is used

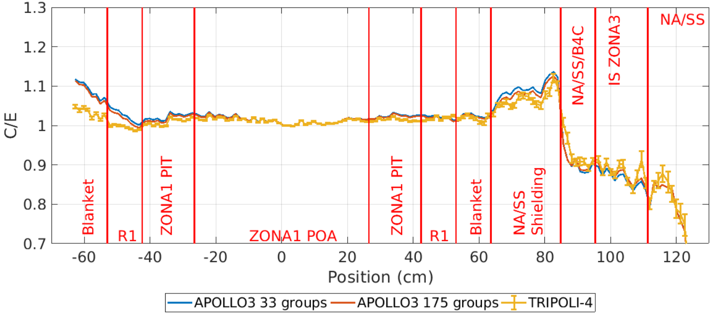
- Traverse model for shielding assemblies



- 2D-1D model for fissile assemblies, P_3 scattering law
- Condensation of cross sections using the angular moments of the flux

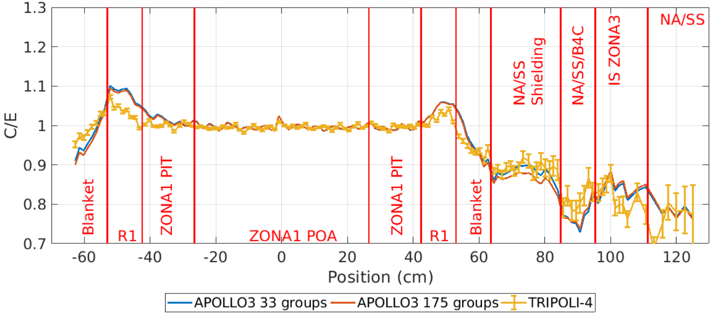
For the sake of clarity, results are presented for the BALZAC-SI2 experiment only

Calculation-experiment comparison, U235 fission chamber, JEFF-3.1.1, no wall model



- Dererministic results very close to Monte-Carlo
- Much lower calculation cost ($\leq$ 24 h on 24 CPU instead of several weeks)

Calculation-experiment comparison, Depleted U fission chamber, JEFF-3.1.1, no wall model



- Dererministic results very close to Monte-Carlo

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Discrepancies up to 20 % can be found between the calculation and the experiment

- These discrepancies can be due to the uncertainties on nuclear data

This bias will be acceptable if lower than uncertainties induced by nuclear data

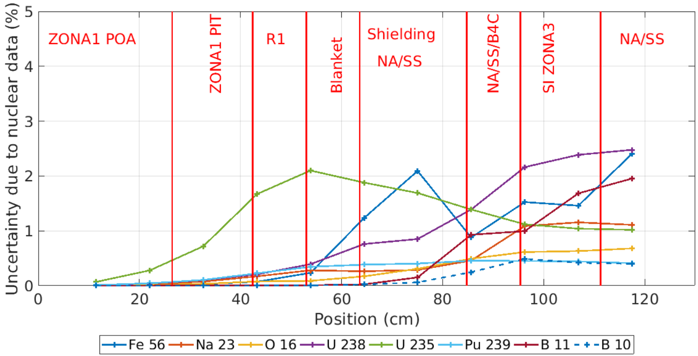
To calculate these uncertainties, we need sensitivities and a covariance matrix:

Sensitivity calculations are performed with the Generalised Perturbation Theory module of the APOLLO3® code

Covariance matric used: COMAC-v2.0 + JENDL-4.0 for JEFF-3.1.1

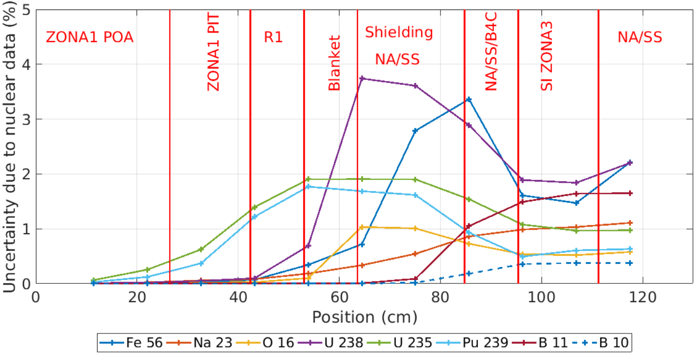
Results are presented only for the BALZAC-SI2 experiment

Uncertainties by isotope, fission of U235



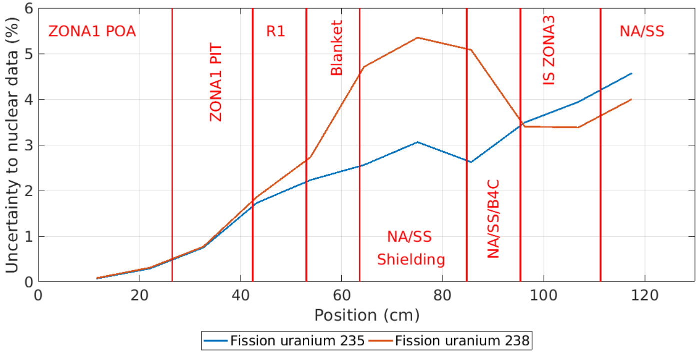
- Largest uncertainties due to fissile isotopes (U235, Pu239) and isotopes present in the shielding (U238, Fe56, Na23, B)

Uncertainties by isotope, fission of U238



- Similar tendencies to those obtained with the fission of U235

Presentation of the calculated uncertainties



- Non-negligible uncertainties due to nuclear data ($\sim$ 5%)
- Uncertainties cannot explain all the obtained discrepancies (15-20 %)

The BALZAC-SI experiments were analysed with the Monte-Carlo code TRIPOLI-4®and the deterministic code APOLLO3®

- Discrepancies between the calculation and the experiment around 10 to 20 %
- Low dependancy on the nuclear data used for iron 56 and sodium 23
- Deterministic-stochastic bias very low ($\leq$ 5 %), making the deterministic calculation very cost effective

Uncertainties due to nuclear data were analysed

- Uncertainties mainly due to iron 56, sodium 23, uranium 235, uranium 238, plutonium 239, boron 10 and boron 11
- Non-negligible uncertainties ($\sim$ 5 %), but cannot explain all the obtained discrepancies

Study	C/E discrepancies		Deterministic-MC discr.		ND Uncertainties	
	Thermal	Fast	Thermal	Fast	Thermal	Fast
BALZAC-SI1	10 %	15-20 %	$<$ 5 %	$<$ 5 %	3 %	5 %
BALZAC-SI2	10 -15 %	15-20 %	$<$ 5 %	$<$ 5 %	5 %	5 %
Calculation cost	$\geq$ 14 days on 24 CPU		3 h on 24 CPU, 21 Gb RAM		-	
ASPIS Iron 88	$<$ 10 %	20-40 %	$<$ 10 %	$<$ 10 %	5 %	$>$ 30 %
JANUS Phase 7	20 %	20-50 %	$<$ 10 %	$<$ 10 %	10-20 %	5-20 %
Calculation cost	1-7 days on 24 CPU		20-60 Gb RAM 4 à 6 h on 24 CPU		- -	

- Significant improvement of accuracy and calculation costs
- Uncertainties due to nuclear data studied and analysed

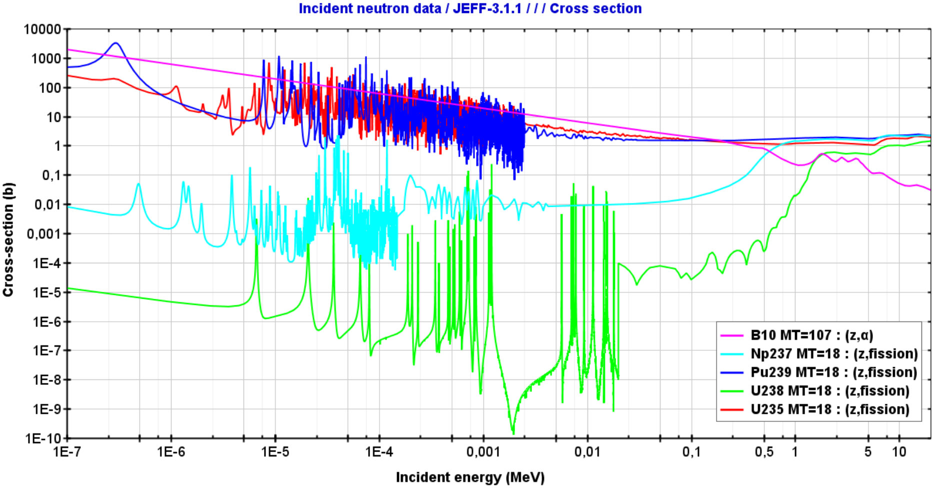
Develop methods for the use of variance reduction techniques in Monte-Carlo calculations

Uncertainties due to nuclear data

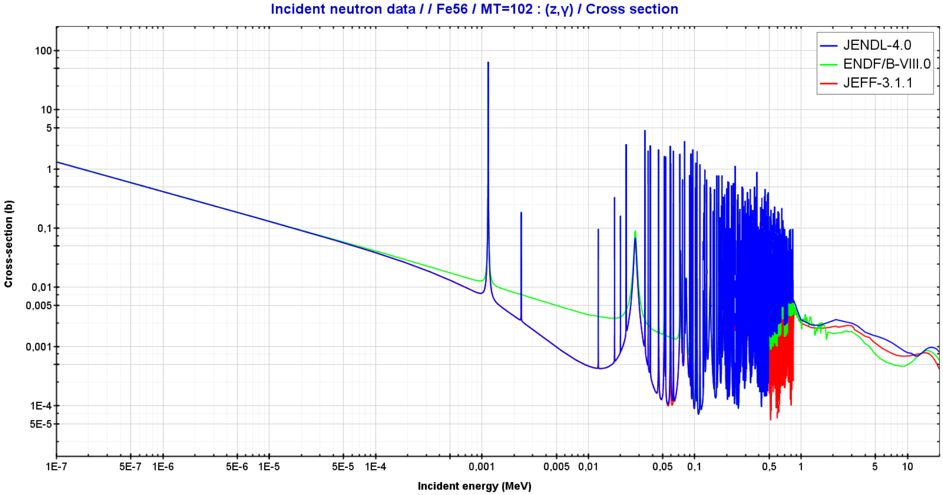
- Sensitivities calculated only for the cross sections
- Uncertainties maybe underestimated (uncertainties on angular distributions not considered)

Thank you for your attention

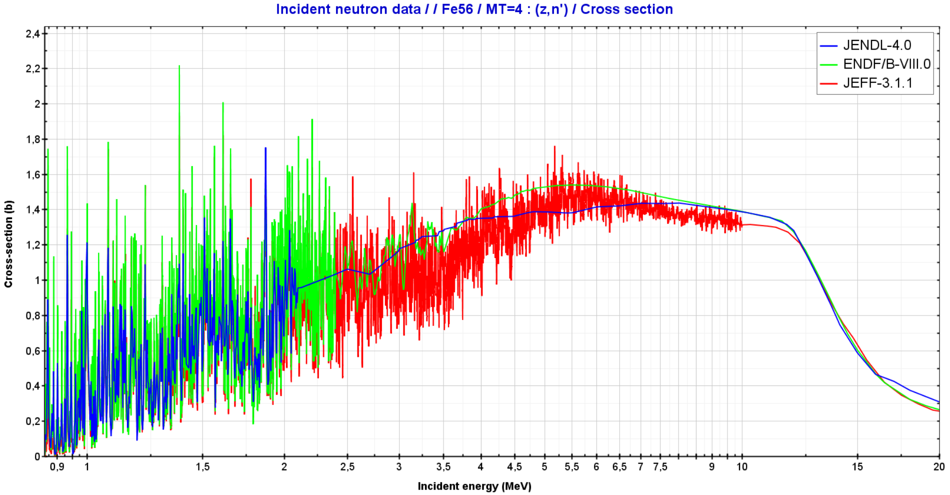
Reactions used in the chambers



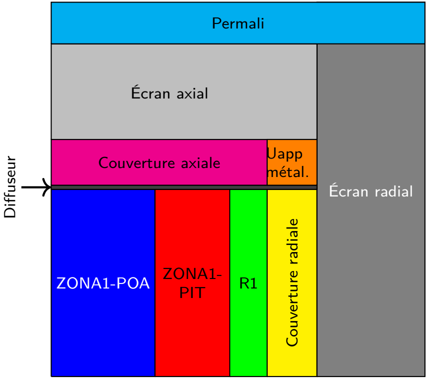
Radiative capture cross section of iron 56



Inelastic scattering cross section of iron 56



RZ description of the BALZAC core

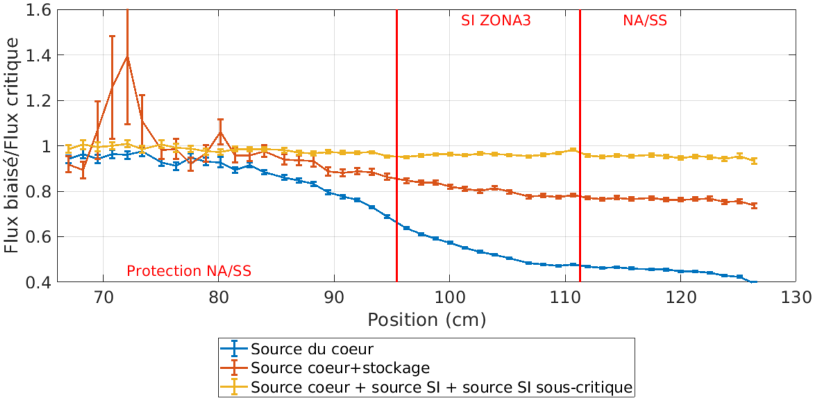


In order to use variance reduction techniques, it is necessary to determine the fission source

- However, there are fissions in the internal storage

3 sources are calculated with TRIPOLI-4®

1. Fission source of the core, without the internal storage
2. Fission source of the internal storage caused by fissions in the core (source 1 + variance reduction techniques)
3. Fission source of the internal storage caused by fissions in the internal storage (source 2 + fixed sources criticallity)

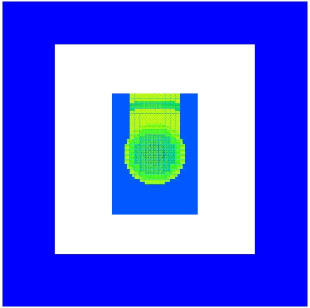


- Large contribution of fissions in the internal storage

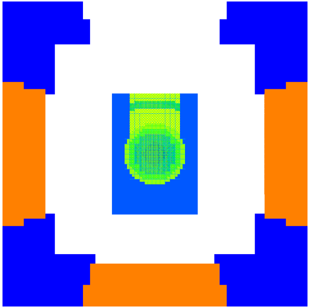
During the BALZAC-SI experiments, measurments are performed until the end of the experimental configuration

Structures around the core may affect the measurments

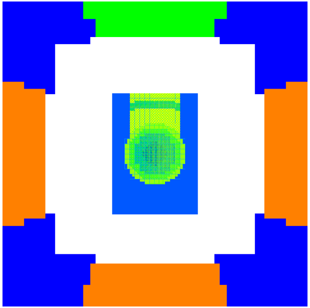
Description of the structures is incomplete, several configurations are attempted:



Simple block



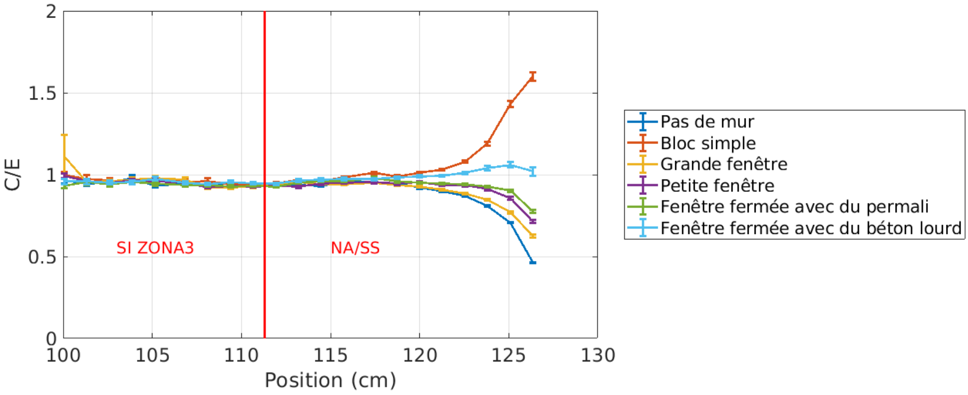
Open window



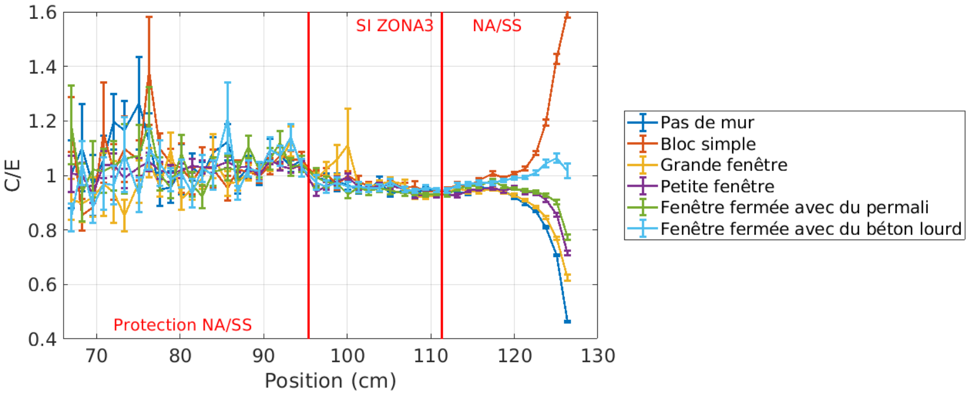
Closed window

Light concrete   Heavy concrete   Heavy concrete or permali

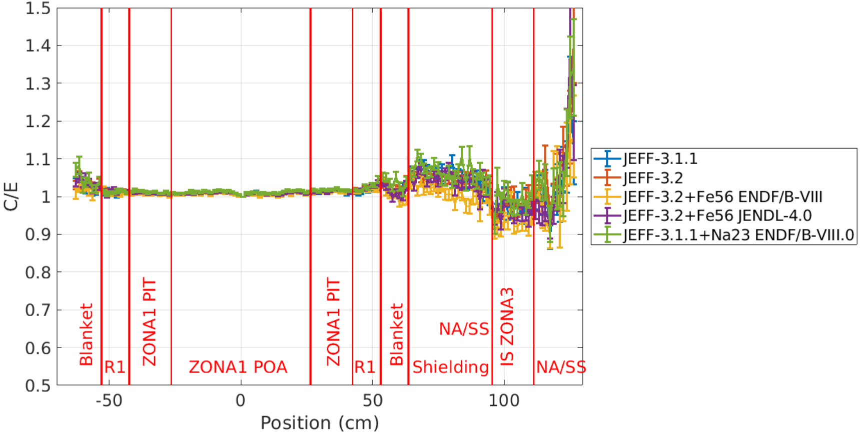
Fission of uranium 235



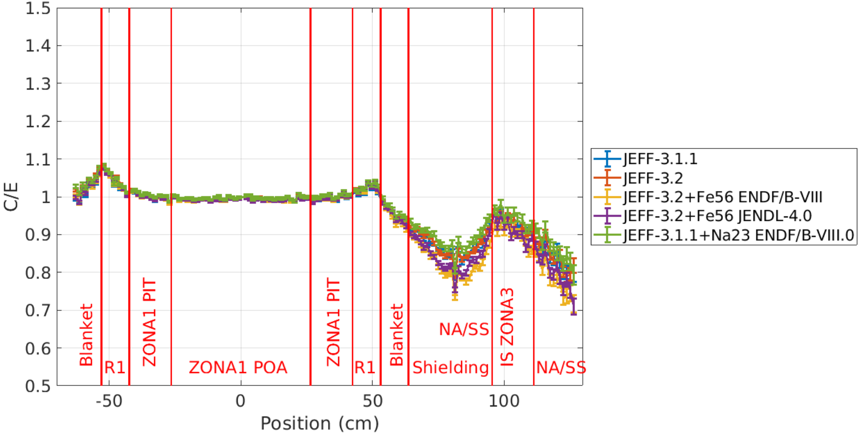
Fission of plutonium 239



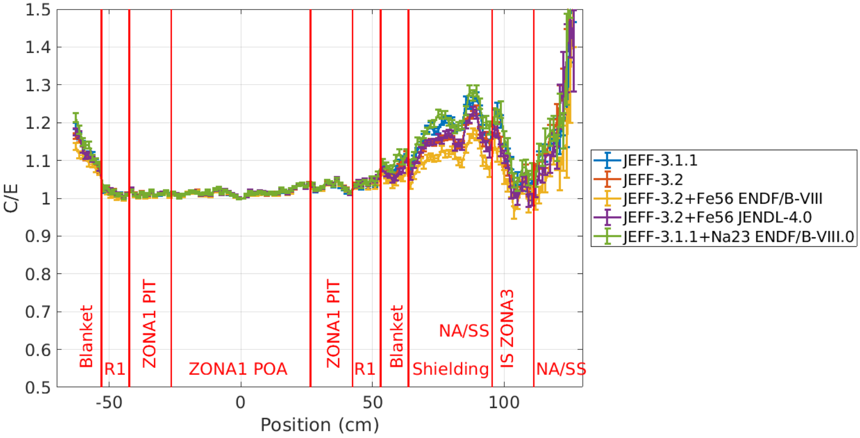
Plutonium 239 fission chamber, BALZAC-SI1



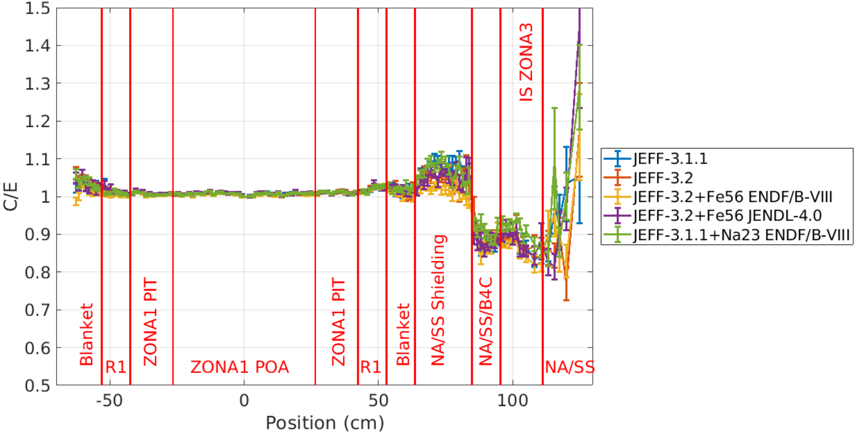
Neptunium 237 fission chamber, BALZAC-SI1



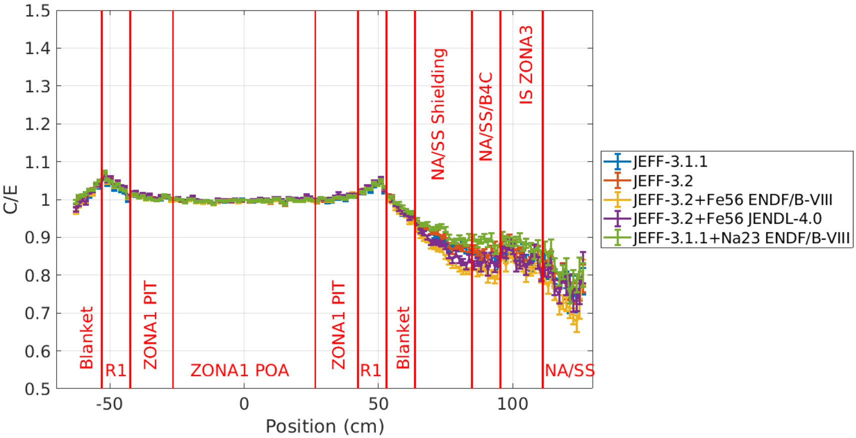
Boron 10 ionisation chamber, BALZAC-SI1



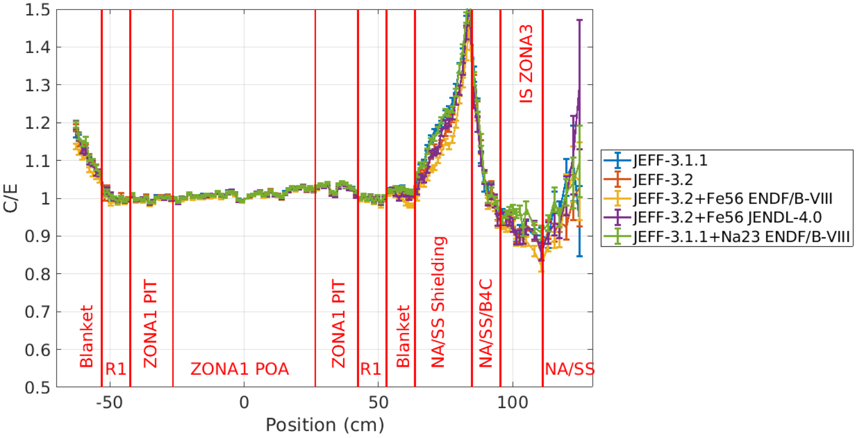
Plutonium 239 fission chamber, BALZAC-SI2



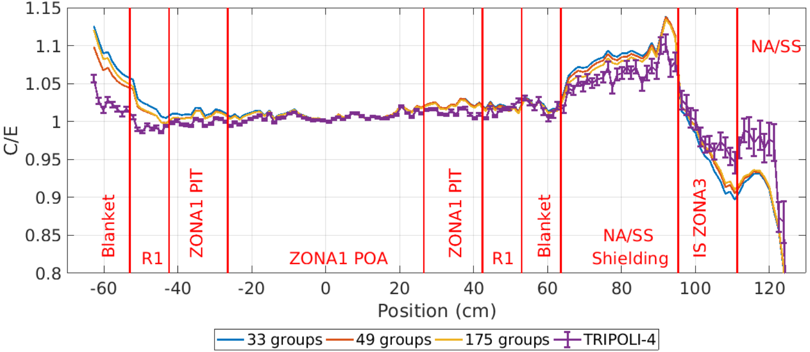
Neptunium 237 fission chamber, BALZAC-SI2



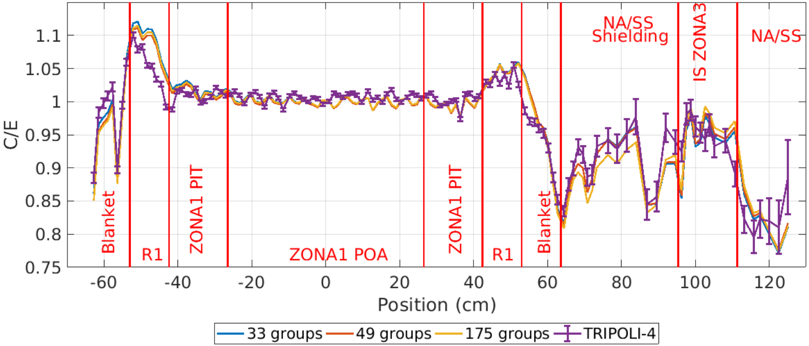
Boron 10 ionisation chamber, BALZAC-SI2



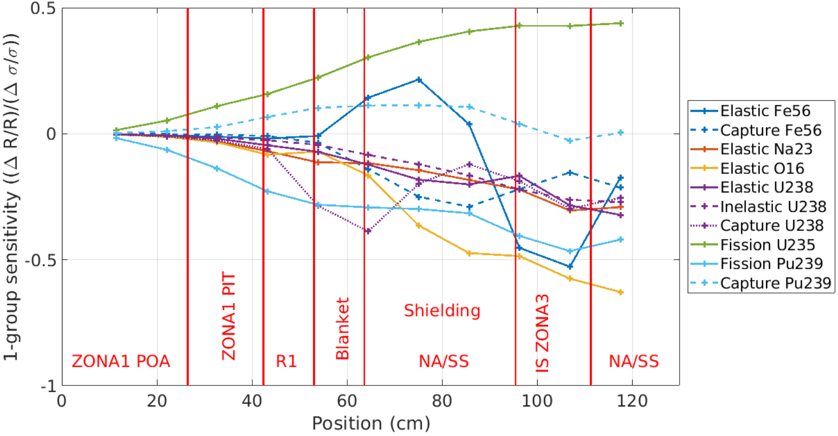
Uranium 235 fission chamber



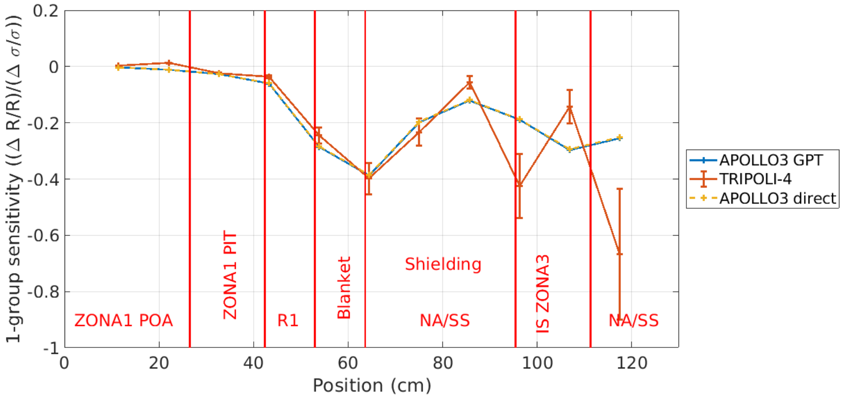
Depleted uranium fission chamber



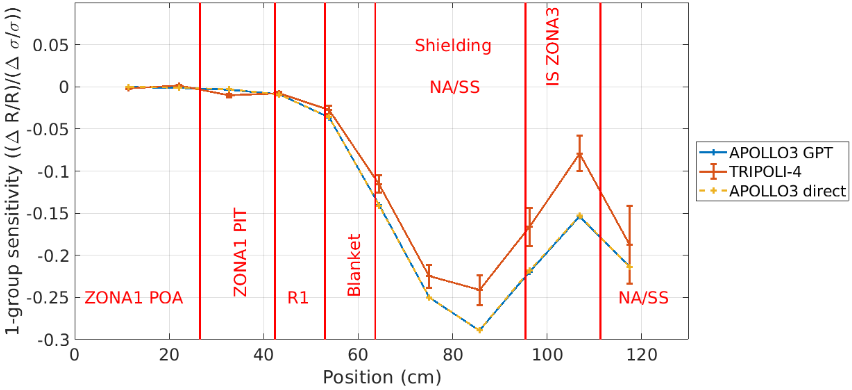
Fission of uranium 235



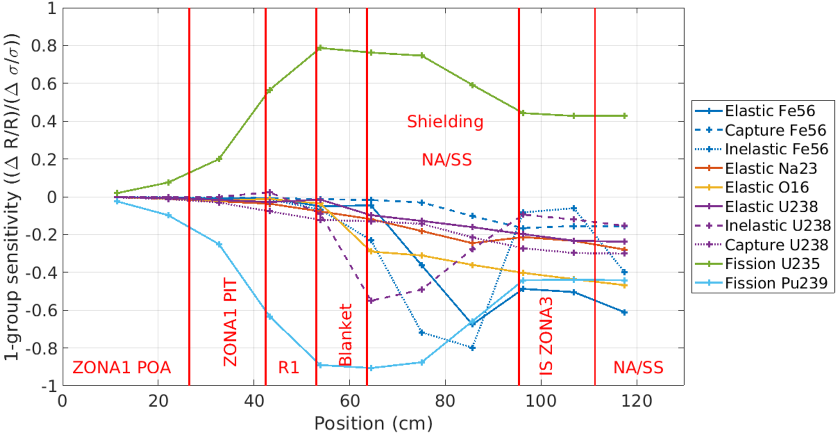
Sensitivity to the capture of uranium 238, fission of uranium 235



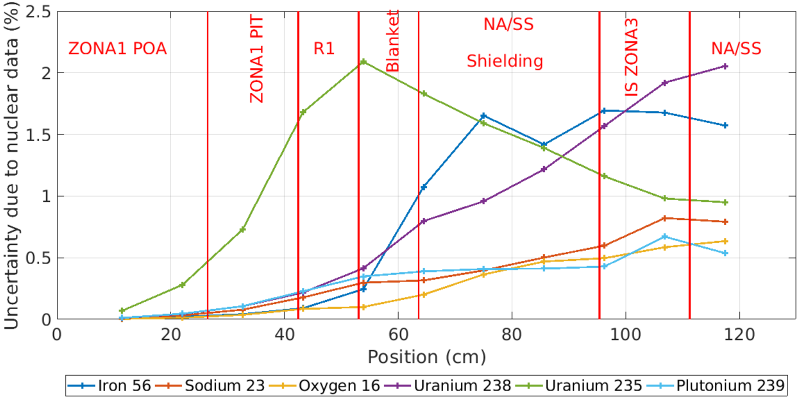
Sensitivity to the capture of iron 56, fission of uranium 235



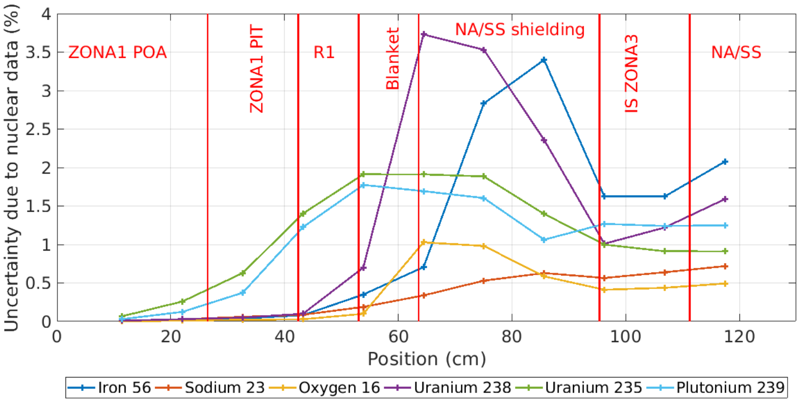
Fission of uranium 238



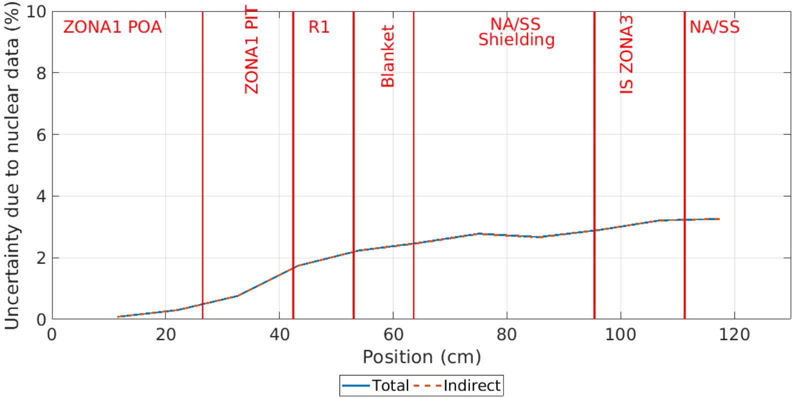
Partial uncertainties, fission of uranium 235



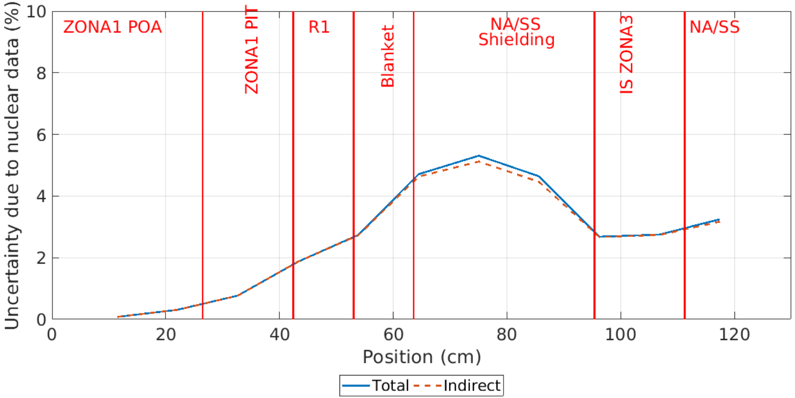
Partial uncertainties, fission of uranium 238



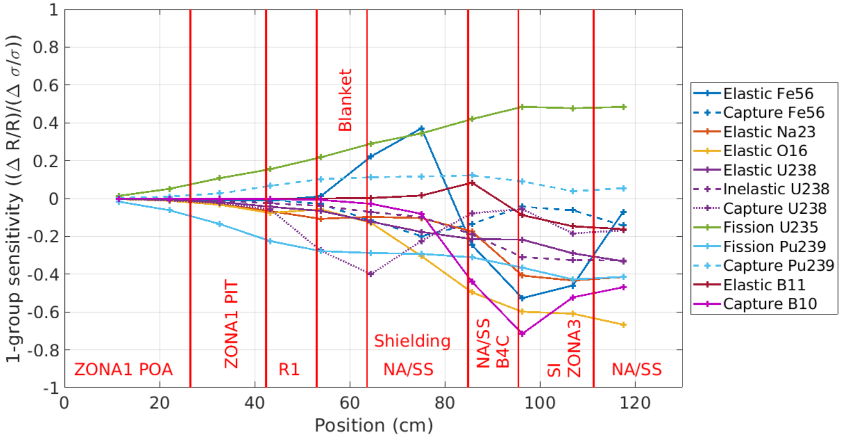
Direct effect, fission of uranium 235



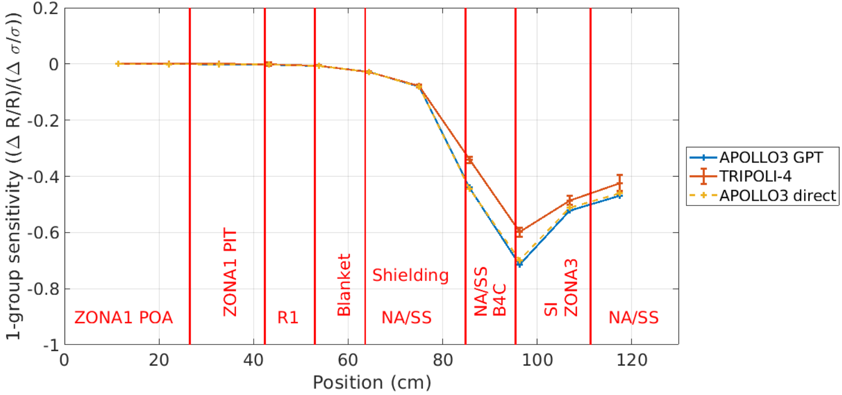
Direct effect, fission of uranium 238



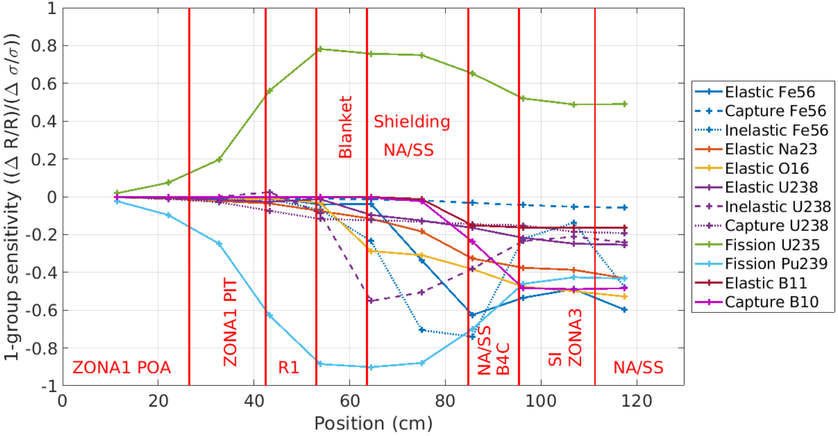
Fission of uranium 235



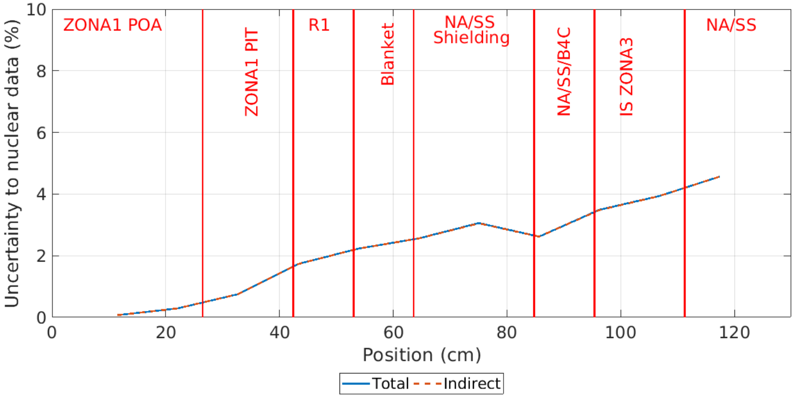
Sensitivity to the capture of boron 10, fission of uranium 235



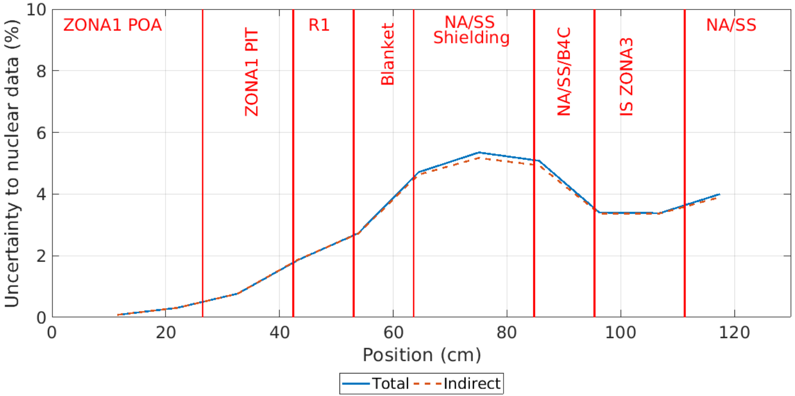
Fission of uranium 238



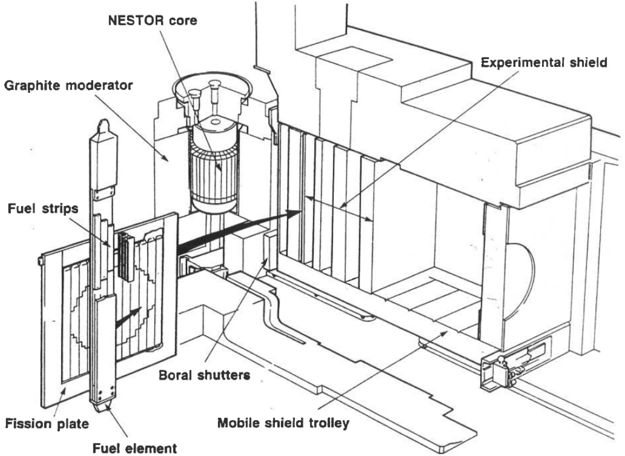
Direct effect, fission of uranium 235



Direct effect, fission of uranium 238



Description of the experiment



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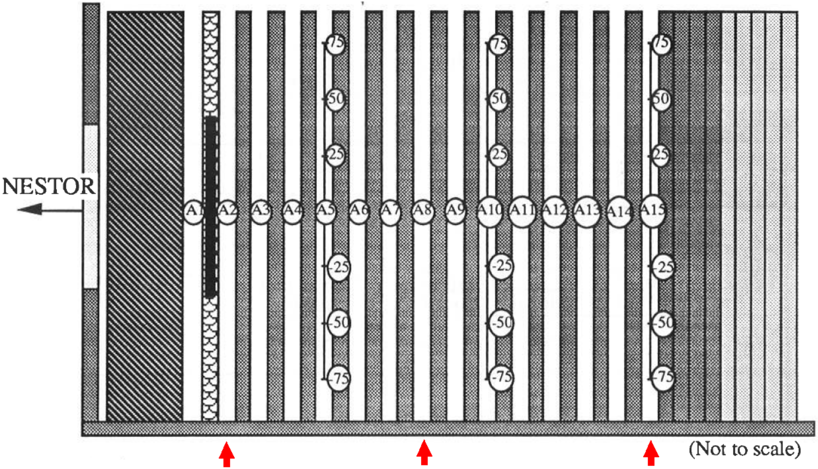
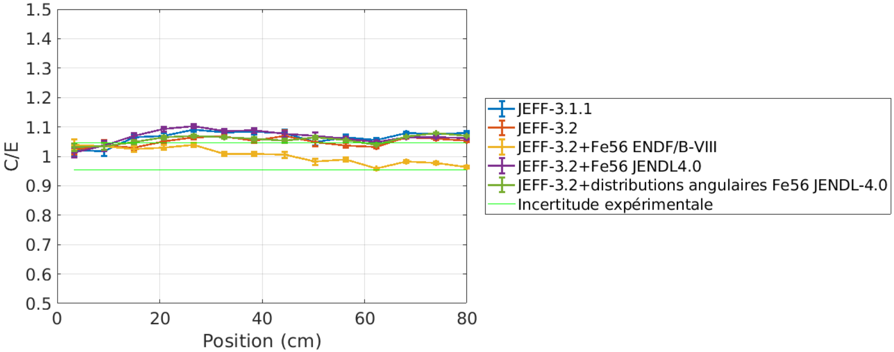
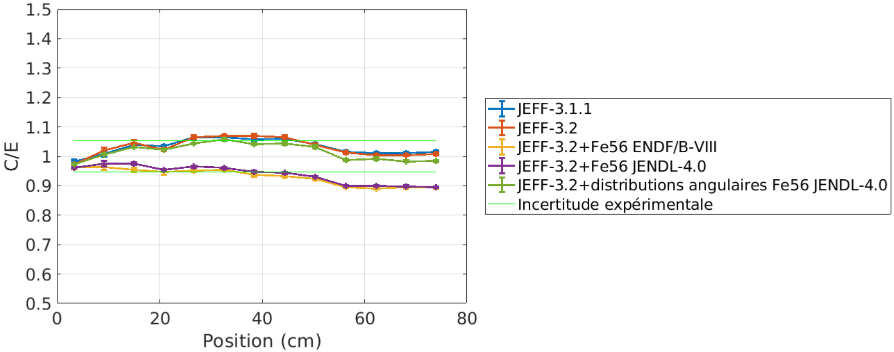


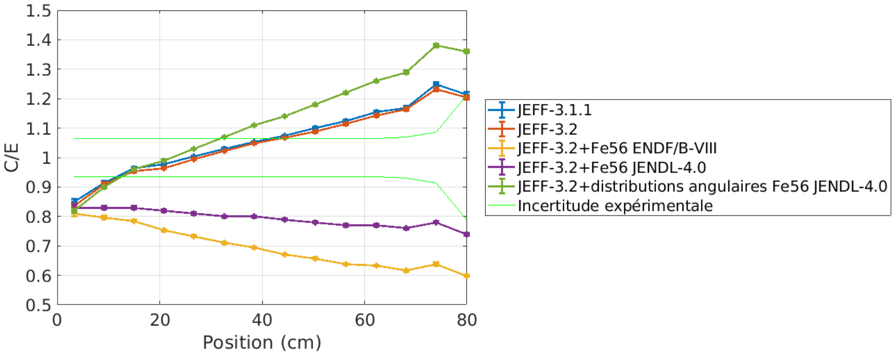
Gold detector



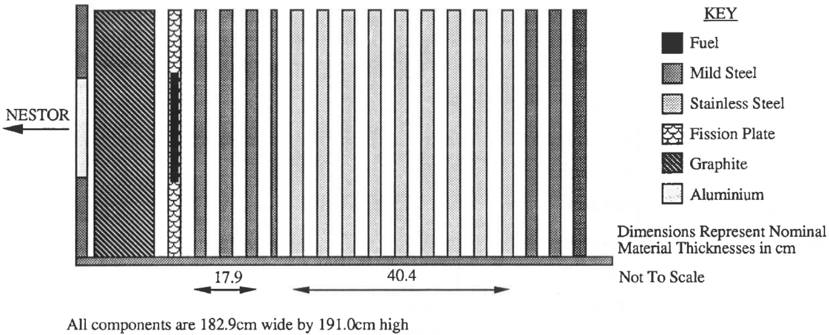
Rhodium detector



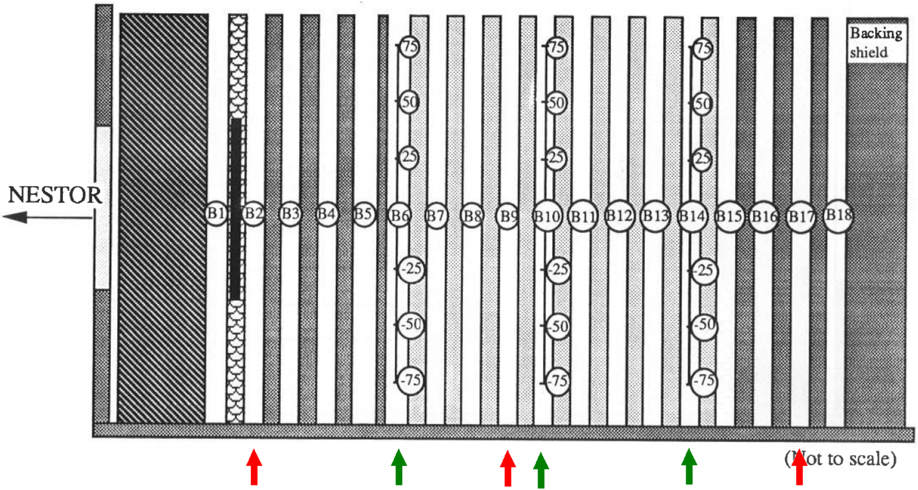
Sulphur detector



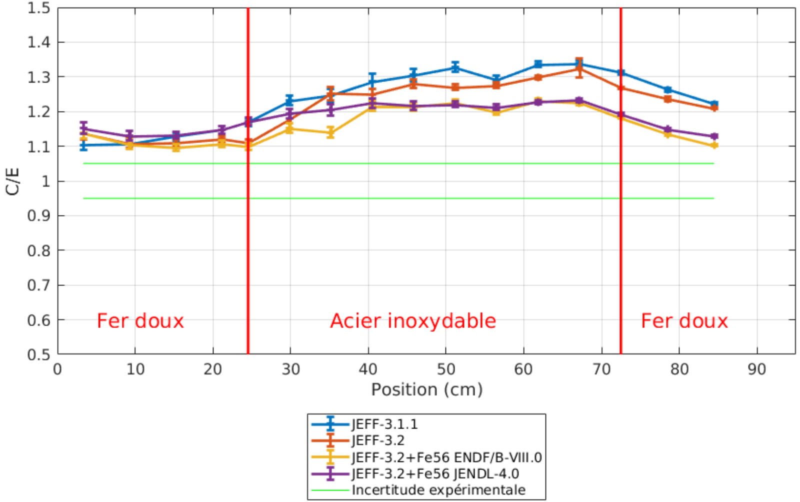
Description of the experiment



Description of the experiment



Gold detector



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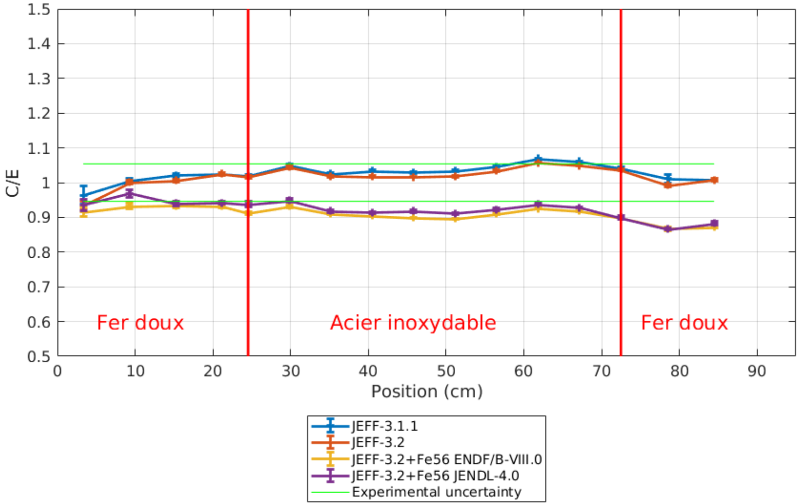
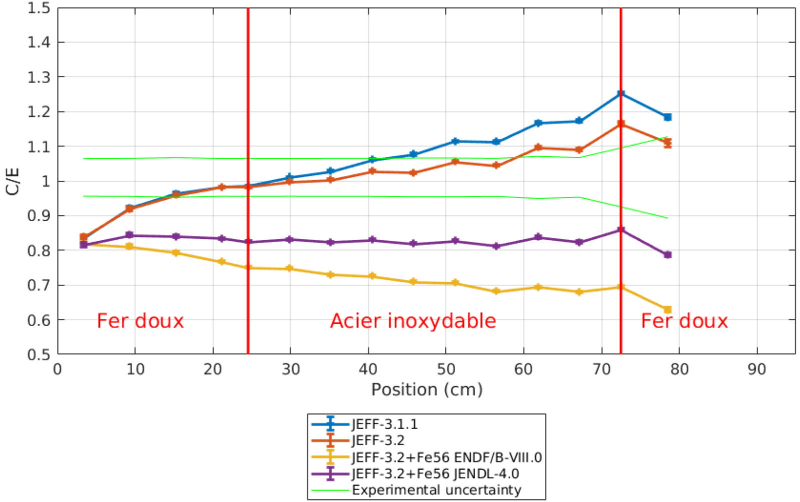
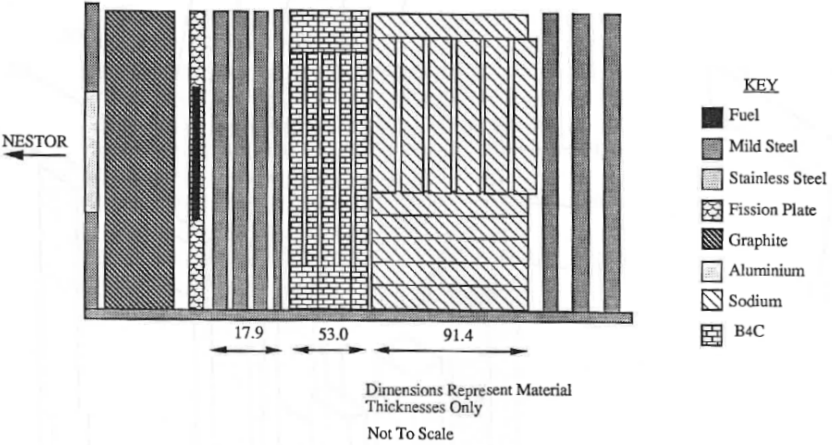


Sulphur detector



Description of the experiment



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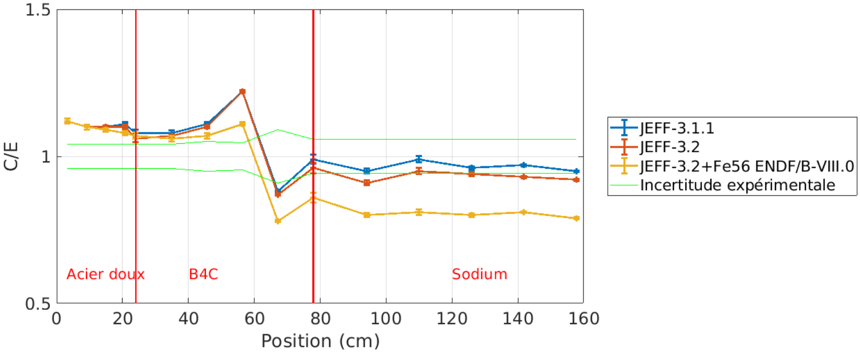
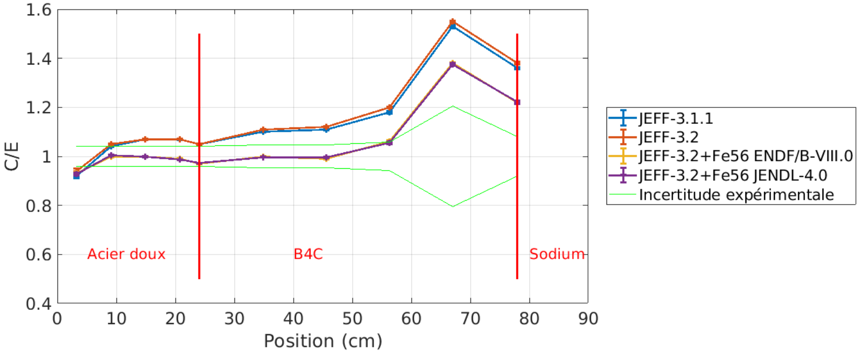


Rhodium detector



Sulphur detector