IRSN
INSTITUT
DE RADIOPROTECTION
ET DE SÛRETÉ NUCLÉAIRE

Enhancing nuclear safety

Quantifying the indicators of the ageing under irradiation

IRSN – Laboratory of neutronics

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MEMBRE DE

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Meeting of Subgroup 47 on Use of Shielding Integral Benchmark Archive and Database for Nuclear Data Validation

IRSN : French Technical Support Organization

Safety assessment and R&D

Laboratory of neutronics: R&D to ensure the safety for NPPs, anticipate ageing of materials, criticality in installations, during transport, …

Content

- Ageing under irradiation issues
- Variance reduction methods benchmarking
- Fluence calculations
- Ageing indicators: DPA, arc-DPA, RPA, …
- Experimental validation

Motivation for nuclear safety

IRSN have to give a technical opinion on the safety assessment for:

the nuclear reactor lifetime extension, new reactors,…

➡ Motivation to have **(validated) tools with precise physical phenomena** description to anticipate the ageing effects

Radiation characterisation in nuclear reactors

Fission distribution in the core ⇨ Variance reduction parameters optimisation ⇨ Monte Carlo particles transport towards neutrons ⇨ Fluxes, DPA or activation

Calculate the fluxes φ(E) for neutrons and gamma

Several steps will be adressed in this presentation

Ageing under irradiation issues

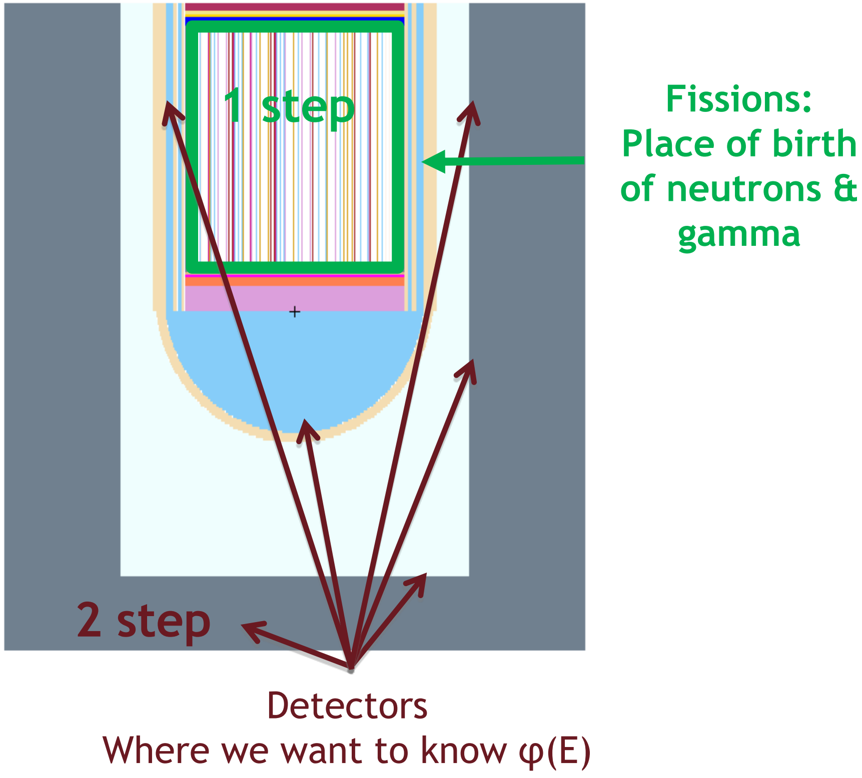
To quantify the indicators of the ageing of materials (Fluence, DPA, …)

We need to be able to :

Characterize the neutron/photon flux at distant positions

In NPP for example:

- 1 step - Fission distribution in the core
  - Monte-Carlo or Deterministic codes
- 2 step - Shielding calculation
  - Monte Carlo codes using of variance reduction methods



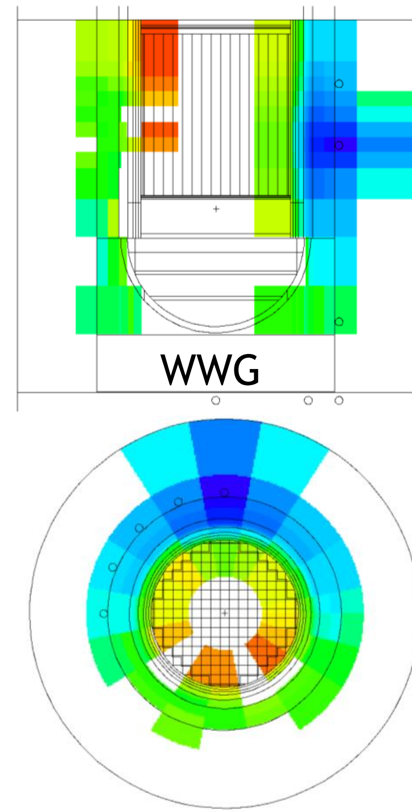
Methods comparison

Using variance reduction methods wrongly can give ***wrong answers !***

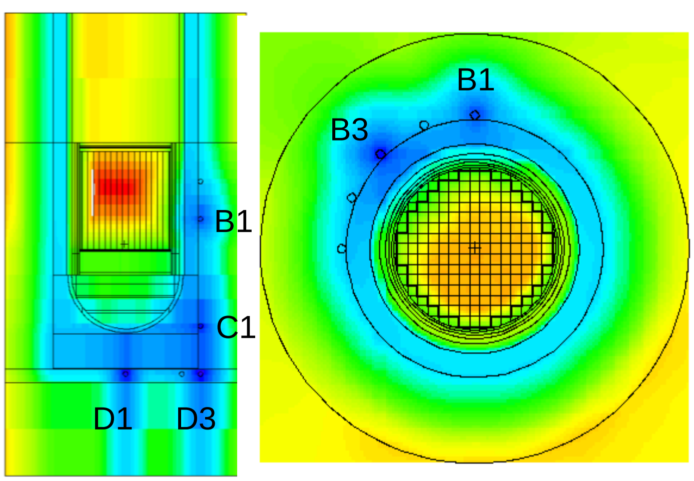
Benchmark the methods ➡ *to better understand them!*

Code to code benchmarking

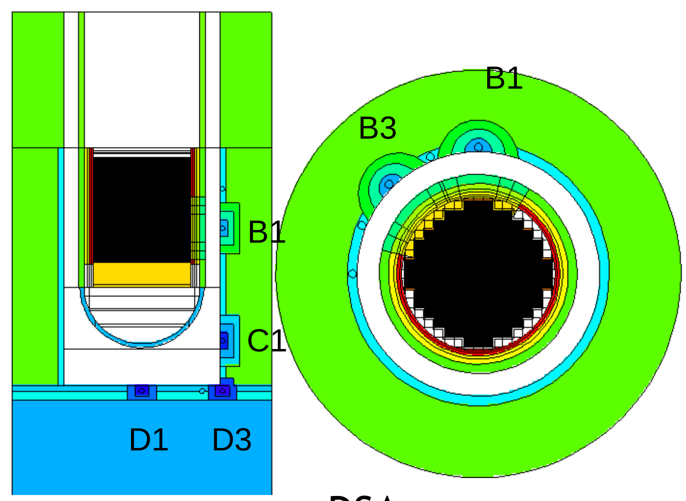
- Detectors placed in the concrete: neutron and gamma fluxes
- Methods used to generate the importance maps:
  - WWG (MCNP)
  - ADVANTG (DENOVO-MCNP), developed at ORNL, USA
  - DSA (MCNP), developed at ENEA, Italy



WWG



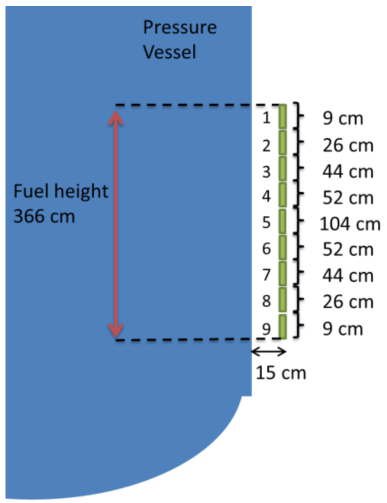
ADVANTG



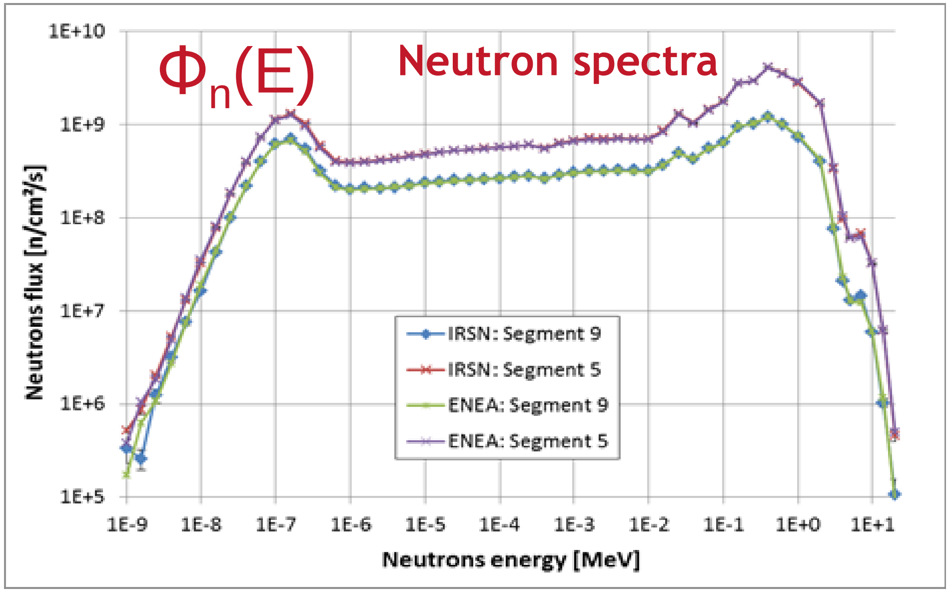
DSA

Fluence calculations

Flux outside the vessel

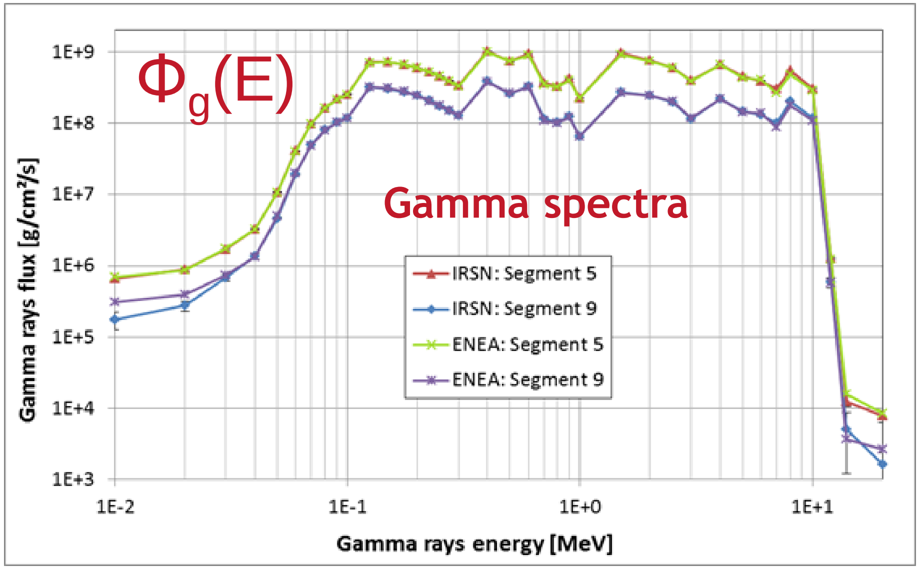


Code to code benchmarking



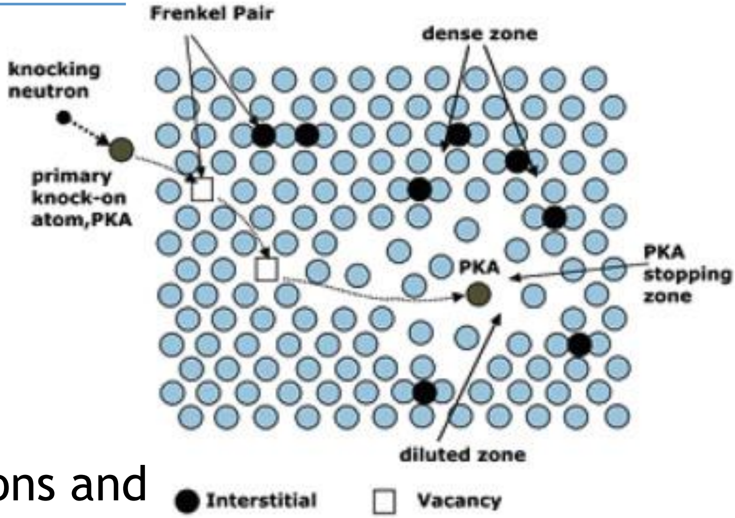
IRSN & ENEA collaboration:

- Use of different modelling choices
- Nuclear Data bases
  - IRSN: ENDF/B-VII.I
  - ENEA: JEFF-3.1



Spectra Φ(E) ⇨ DPA, activation, …

Neutron DPA: number of displacements per atom



Methods comparison:

1) **NRT** formula (mono-atomic) using MCNP+NJOY

$$dpa = 0.8 * \frac{Ec}{2*Ed}$$

2) **DART** code (CEA, France) with poly atomic solid target, solves ion-atom collisions analytically

3) **MCNP + SRIM**: MCNP handles neutron-ion collisions and SRIM: ion-ion collisions both using Monte-Carlo methods

	DPA
NRT	0.057
DART	0.098
SRIM	0.17

Code to code comparison: High impact factor 2-4

Work performed by IDOM and JSI consertium

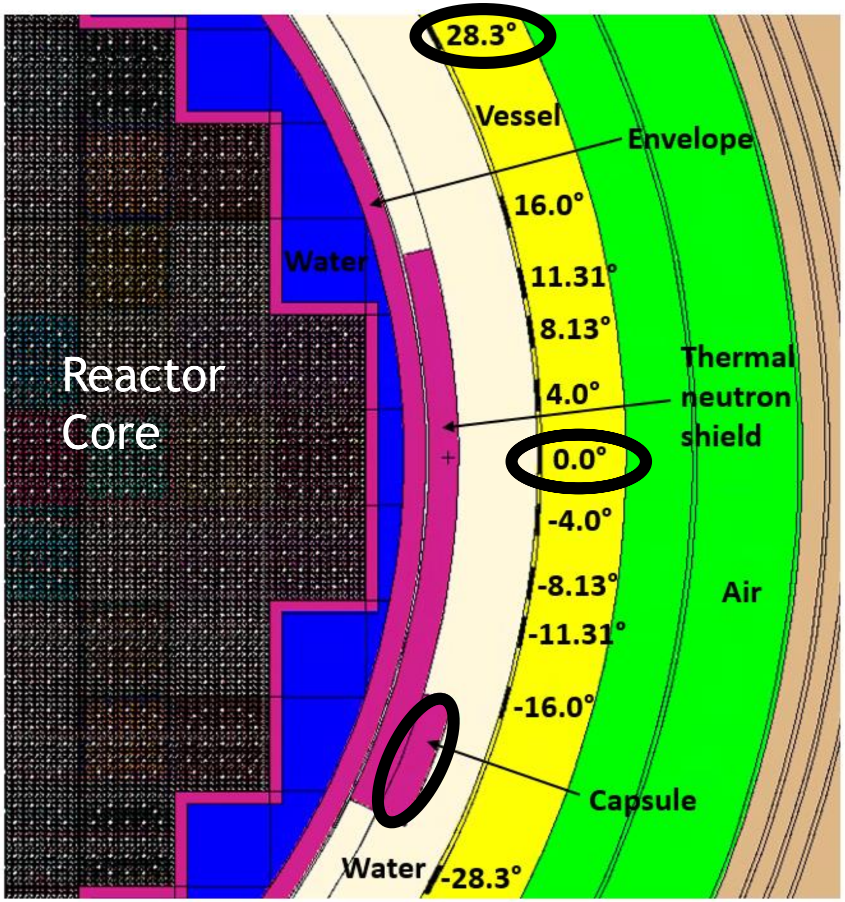
+ Other more precise methods will be tested in the future (collaboration with Materials R&D dep. at IRSN: molecular dynamics, …)

To prioritize the important parameters for safety:

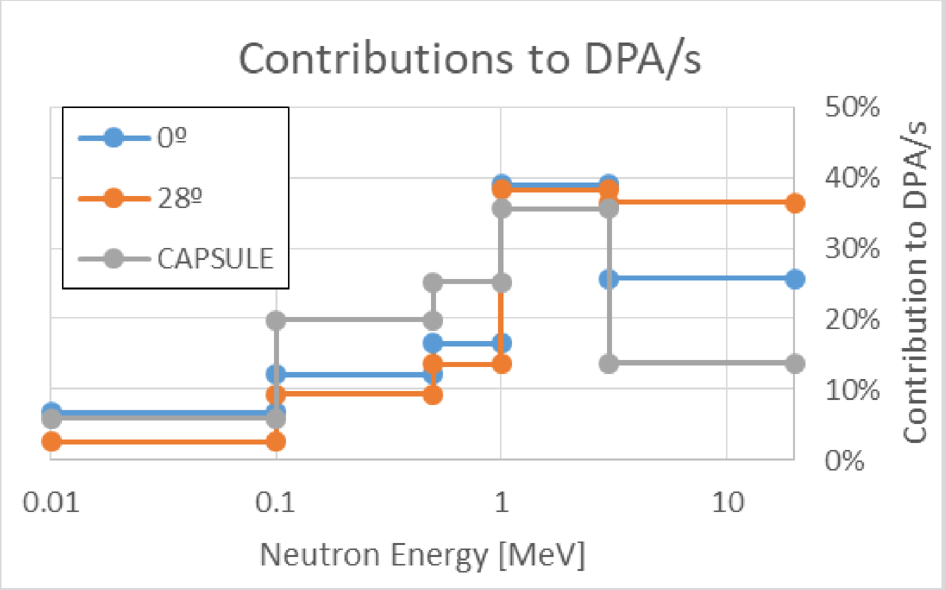
we look at the sensitivities to composition, spectra sensitivity, binding energy, …

Neutron DPA

Neutron spectrum depends on the position on the vessel/capsule



Using NJOY DPA-NRT formula



Different behaviour at 0° and 28° azimuthal position

Is the damage caused by a 1 MeV neutron the same as 5 MeV ?

Does the fluence surveillance cover these effects ?

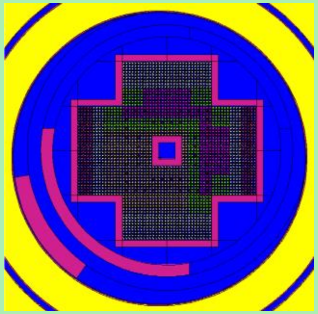
Other indicators than DPA will be tested.

Validation of each or all steps

Fission distribution in the core ⇨ Variance reduction parameters optimisation ⇨ Monte Carlo particles transport towards neutrons ⇨ Fluxes, DPA or activation

Some experimental benchmarks were done, but many still need to be done!

Venus-3 PWR Vessel dosimetry



Done!

Ni, Al, In dosimeters

Experimental uncertainty 5-10%

C/E -1 mainly within 1σ

Foreseen for this year:

SINBAD benchmark (NEA-1517/96) « H.B. Robinson-2 Pressure Vessel Dosimetry Benchmark ROBINSON »

SINBAD benchmark (NEA-1553/55) « FNG-ITER Dose Rate Experiment »

- Using **MCNP6 + VESTA** depletion code
- Testing different nuclear data for transport and for **dosimetry reactions** (IRDFF2.0, JEFF3.3/Act)
- Contributing to **new ND evaluations** (Fe, U5, Pu9,…) testing
- Testing **modeling** approximation + calculation **methods**

https://www.oecd-nea.org/science/docs/2000/nsc-doc2000-5.pdf

Summary and perspectives

- **IRSN as TSO** is asked to give technical opinion on different ageing under irradiation issues

- For safety issues: need to have **precise and validated tools** that are able to characterize the neutron and gamma fluxes

- Additionally to "code to code" comparison, we increase the **experimental validation** data base for shielding applications; with critical experiments and PIE, it will provide a larger validation domain for the **new Nuclear Data evaluation**.

  → **SINBAD**

- Participate in European project **ENTENTE**: multi-scale tools and experimental database for ageing of metallic material; our contribution is the sensitivity analysis of the different descriptors to neutron spectrum

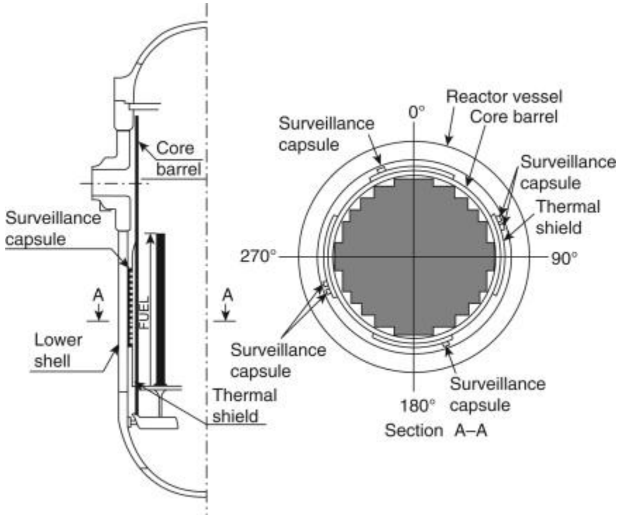
- Study different ageing descriptors: DPA (sensitivity of methods, neutron energy, composition, …), other descriptor: ARC-DPA, RPA, PKA, gamma-DPA …

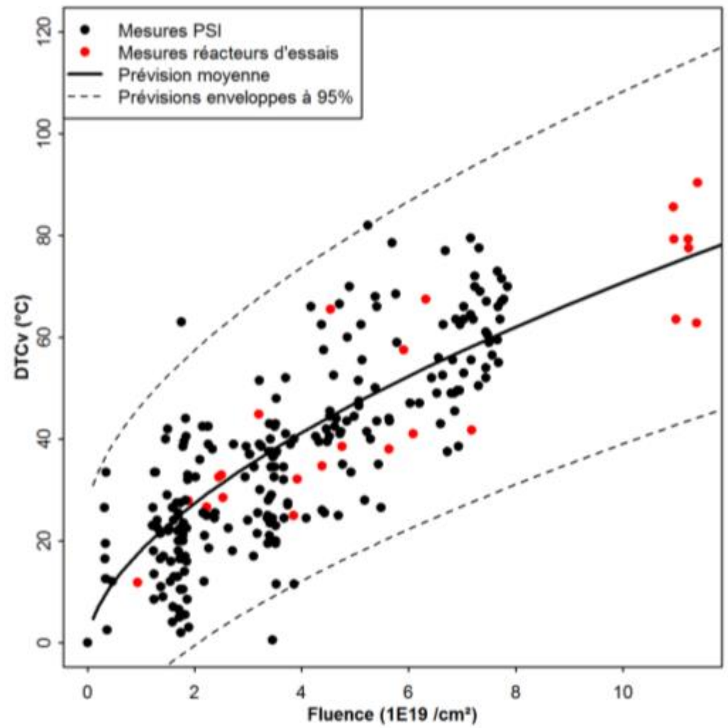
BACK-UP

Estimation des caractéristiques matériaux à « VD4 + 10 ans »*

* 4ème Visite Décennale + 10 ans = exploitation de la centrale après ses 40 ans pour 10 ans supplémentaire

- Programme de surveillance d'irradiation (PSI) dans le parc français mené par EdF





LE VIEILLISSEMENT SOUS IRRADIATION DE L'ACIER DE CUVE, H.Churier-Bossennec, et al (EDF), Journées de la SFEN, 2011

- Formule de prévision de la fragilisation sous irradiation

$$\Delta RT_{NDT} = A[1 + 35{,}7(P - 0{,}008) + 6{,}6(Cu - 0{,}08) + 5{,}8Ni^2Cu]\Phi^{0{,}59} + 2\sigma$$

Où A = 15,4 et σ = 10,4 °C pour le métal de base (MdB)
A = 15,8 et σ = 13,3 °C pour les joints soudés (JS)

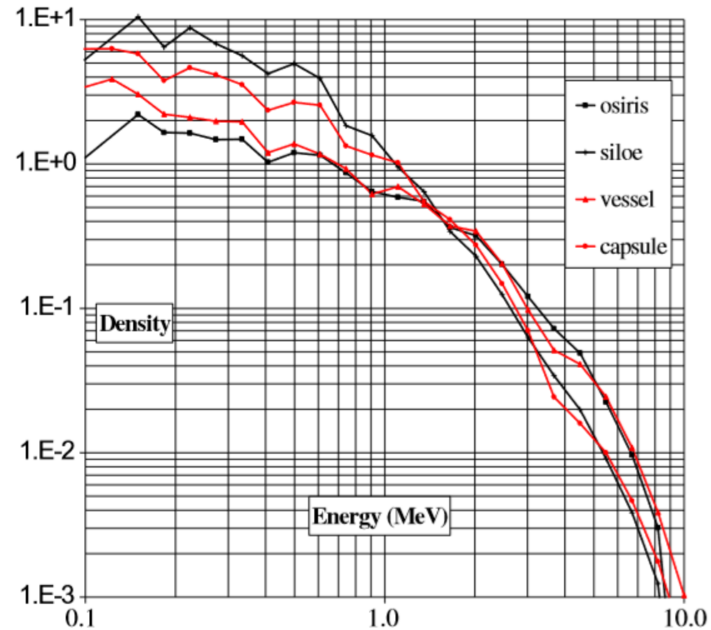
Fluence de neutrons E > 1 MeV (n/cm2)

P, Cu, Ni proportion massique de phosphore, cuivre, nickel

Limites et domaine de validité

Historique:

- Programme **ESTEREL** :
  - ➢ 2 expériences d'irradiations réalisées (SILOE et OSIRIS) avec deux spectres proches de la cuve et des capsules du PSI
  - ➢ Recherche d'une grandeur **scalaire** permettant de prédire au mieux les dommages d'irradiation sur les échantillons de cuve
  - ➢ Trois grandeurs testées: flux > 1 MeV, flux > 0,1 MeV et « dpa » (?)
  - ➢ **Flux > 1 MeV** retenue comme la plus pertinente (linéaire)



Simulation of irradiation effects in light water reactor vessel steels – experimental validation of RPV-1, S. Jumel, EDF, Journal of Nuclear Materials 366 (2007) 256-265

→ *En réalité les neutrons **en dessous d'1 MeV** créent également des dommages*

Fission distribution in the core

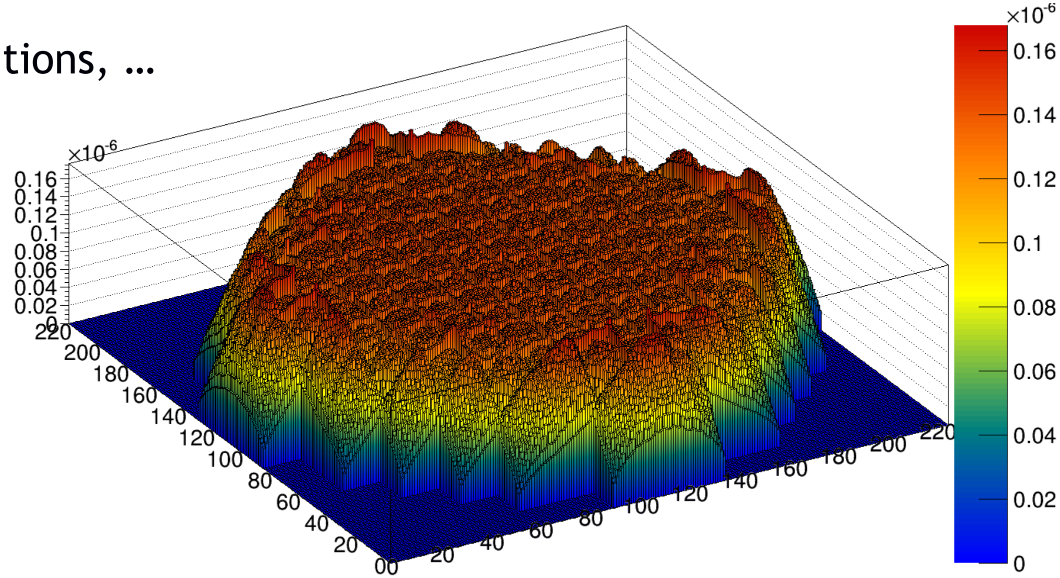
3D Monte Carlo fission distribution

- Time expensive calculations (many particles to be simulated)
- Thermal, burn-up, operational conditions, …

  ⟹ difficult to simulate in MC

≈35 000 fuel pins
max std. dev. 0.5% in each pin

200 axial segments
(unique distribution for the core)



Deterministic fission distribution

2 sub-steps : Assembly level cross section ⟹ Diffusion 3D calculations

- Fast calculations
- Thermal, burn-up, operational conditions, … can be easily followed
- Neutronics - approximated (effect especially near the reflector)

Used by the industry