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INSTITUT DE RADIOPROTECTION ET DE SÛRETÉ NUCLÉAIRE

IMPORTANCE OF THE AXIAL BURN-UP MODELLING FOR FUEL ASSEMBLY NOZZLES ACTIVATION CALCULATION

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MEMBRE DE ETSON

Plan

- Context
- Fuel assembly model
- 3D Monte-Carlo depletion
- Axial burn-up modelling
- Conclusion

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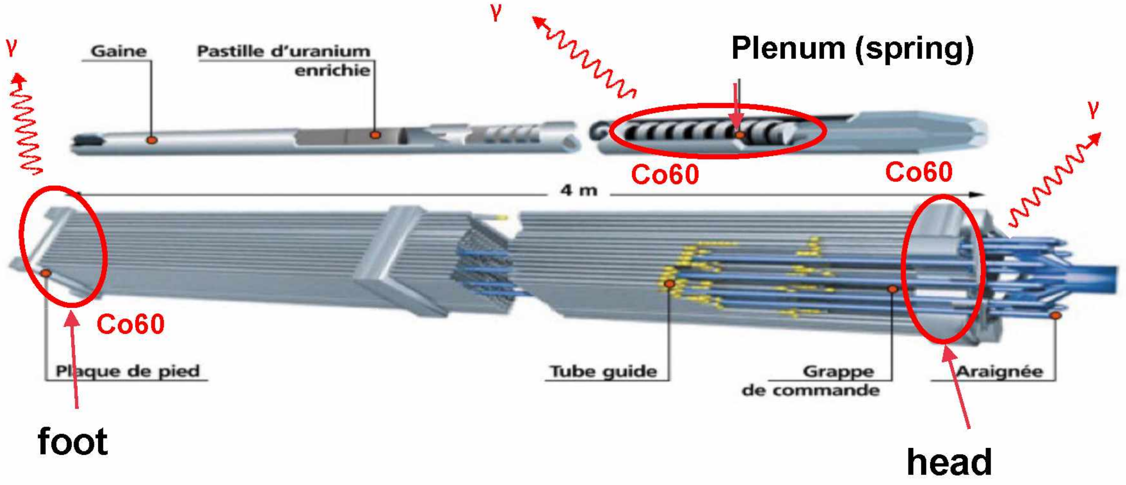
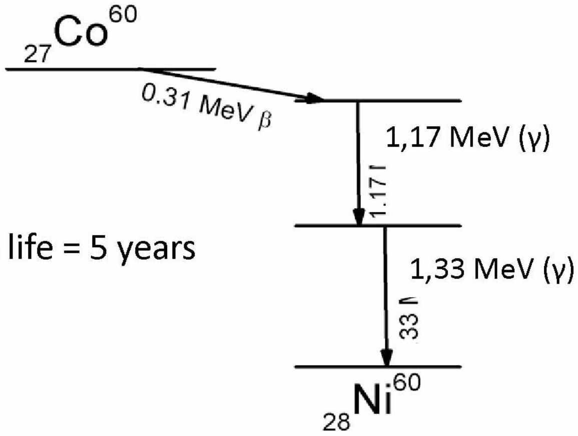
Context

- 3 zones of fuel assembly has steel component: head, plenum and foot, contain cobalt 59 impurity, that activates during reactor operation:

$$^{59}Co + n \longrightarrow {}^{60}Co$$

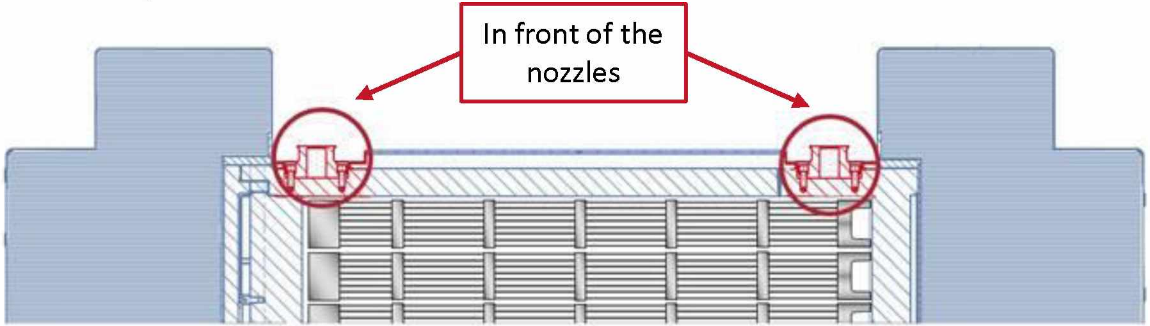




½ life = 5 years

Context

- Transport:
  - Gamma activity has to be characterized for the radiation protection during the transport of the used assemblies
  - The nozzles are sometimes situated close to trunnions in the transport casks leading to a local lower gamma shielding



Source: Orano NPS – caskTN 112

- Reprocessing unit: the nozzles are separated from the fuel

- Radioactive waste management

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Fuel assembly model

*What is the « **good** » calculation method to be used for **safety** assessment ?*

Focus on 2 approaches:

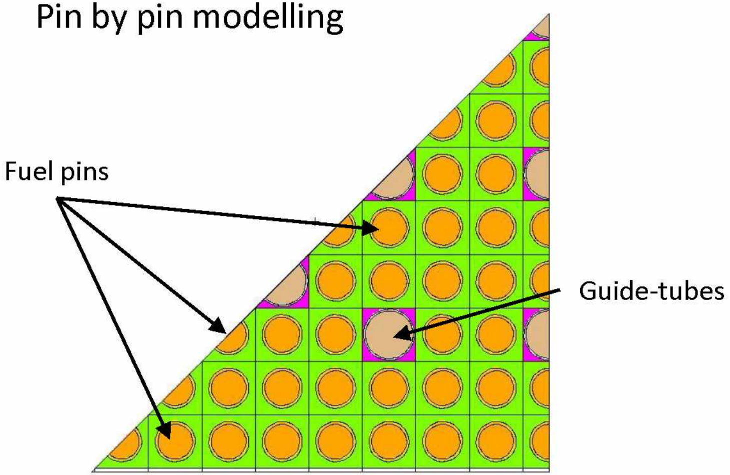
- ***Precise but time consuming (and challenging!) calculation***
- *Simplified, fast but penalizing (maximizing the activity)*

Activation calculation with 3D Monte-Carlo depletion

- Limited number of hypotheses
- As precise as possible → used as **reference**
  - Focused on the calculation methodology (not compared to measurement)
  - Tests of different hypothesis
  - Very simple modelling of the head and foot zones due to lack of information

Fuel assembly model

Pin by pin modelling

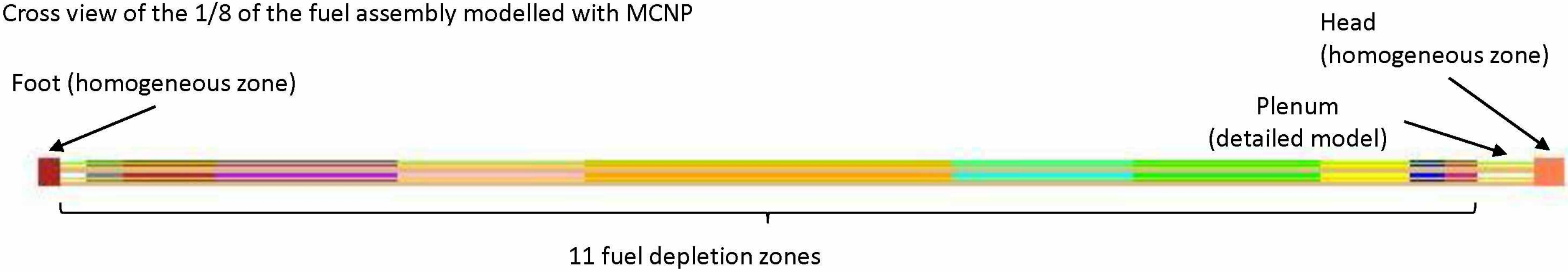


Cross view of the 1/8 of the fuel assembly modelled with MCNP

VESTA (Monte-Carlo depletion tool)

- Neutronic calculation: MCNP
- 11 + 3 axial zones that are depleted
- UOX: 1 fuel composition for each axial zone
- 1/8 assembly model with reflective boundary cond.

→ axial effects should play a more important role for the axial leakage calculation



Fuel assembly model

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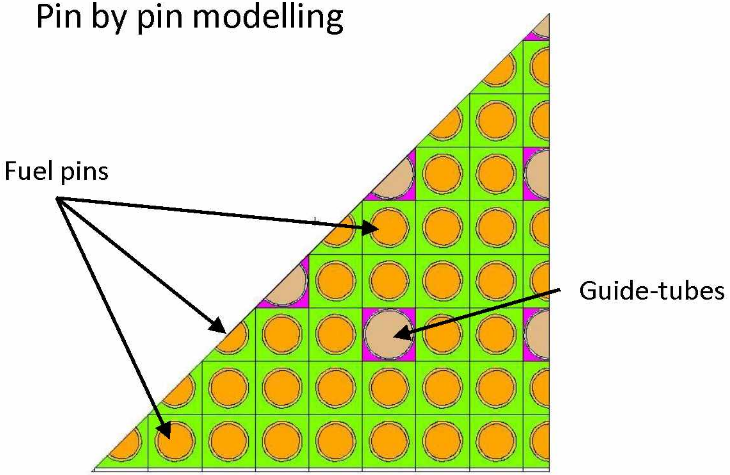
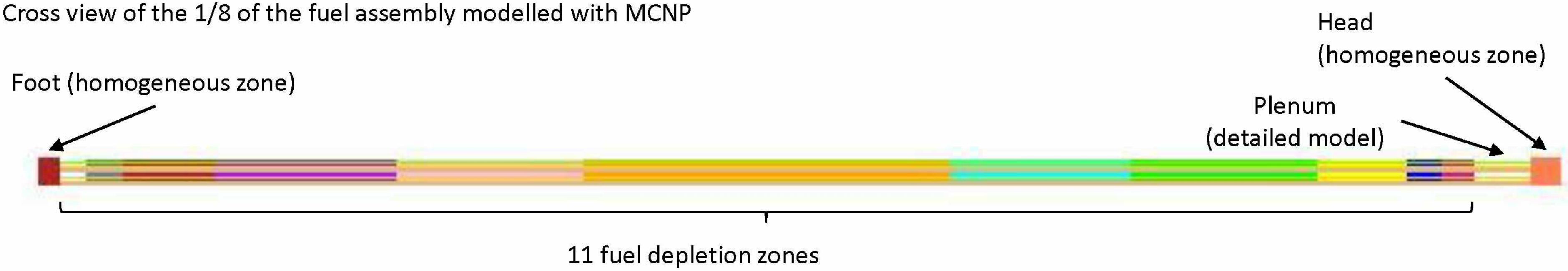


Cross view of the 1/8 of the fuel assembly modelled with MCNP

Type	PWR		**Irradiation cycles**	3	
Thermal power per assembly	4400/157	MW	**Cycle duration**	345	day
Fuel type	UO_2		**Decay time between cycles**	30	day
$^{235}U/U$	4	%	**Total irradiation**	1035	day
Final burn up	55	GWd/t_{HM}	**Decay time**	1000	day
Assembly pitch	21.611	cm	**Moderator XS temperature**	600	K
Lattice type	17x17		**Fuel temperature**	900	K
Cobalt59 content in steel	0.2	%w	**Boron concentration**	900	ppm
Steel mass in head	8.5	kg	**Nuclear Data**	JEFF-3.2	
Steel mass in foot	6	kg	**Neutronic code**	MCNP	
Steel mass in plenum (springs)	2.8	kg	**Depletion code**	Phoenix (VESTA)	



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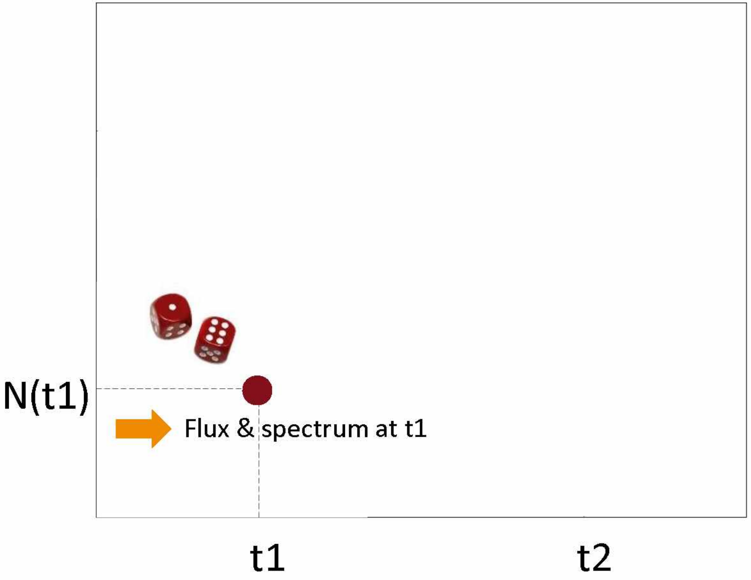
3D Monte Carlo depletion

- Predictor method:



- Material composition N(t1) at time t1
- Evolution till t2 ➔ $N^{pred}(t2)$
- MC calculation at time t2
  - Re-evaluation of multigroup cross sections
  - **New $\sigma\langle\phi\rangle$ in the Bateman equations**
- Evolution from t1 to t2 using the new reaction rates ➔ $N^{corr}(t2)$

3D Monte Carlo depletion

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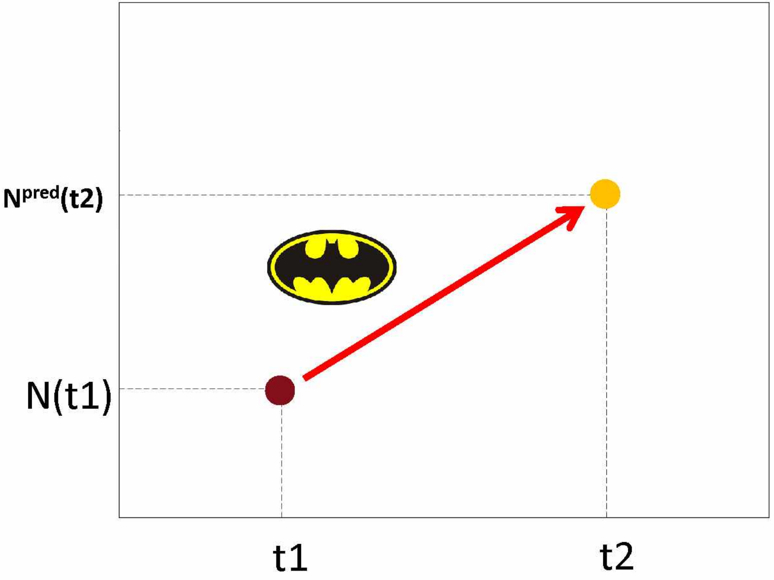

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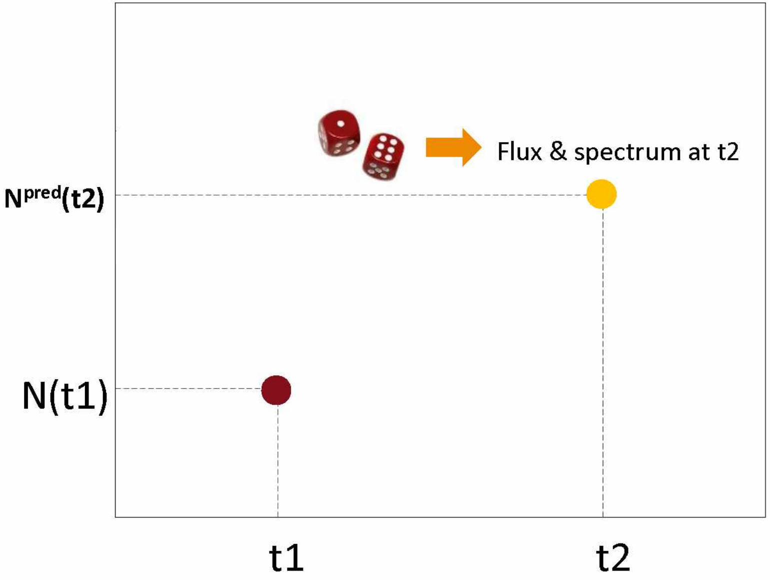
3D Monte Carlo depletion

- Predictor-corrector method:
  - Averaged composition using the reaction rates calculated at the following step



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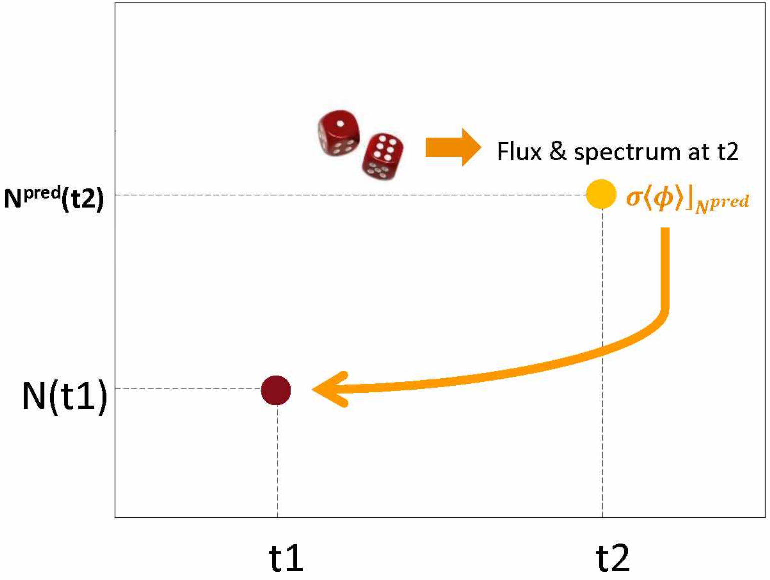

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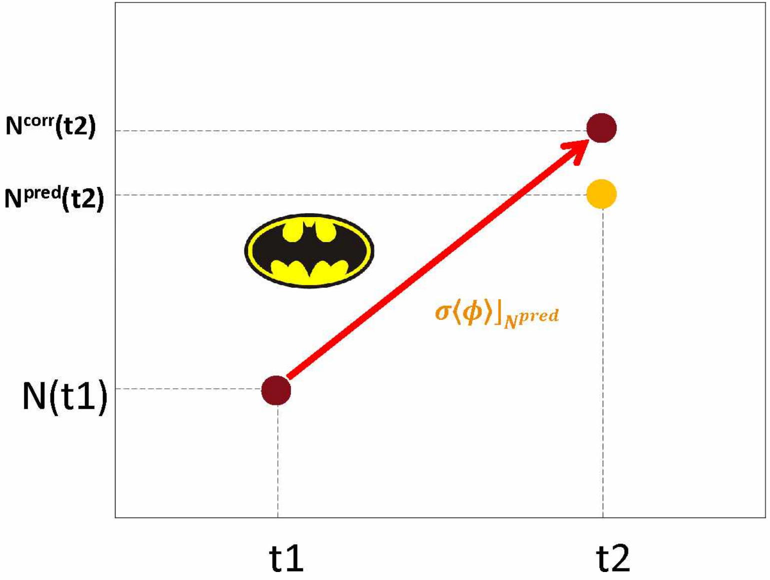

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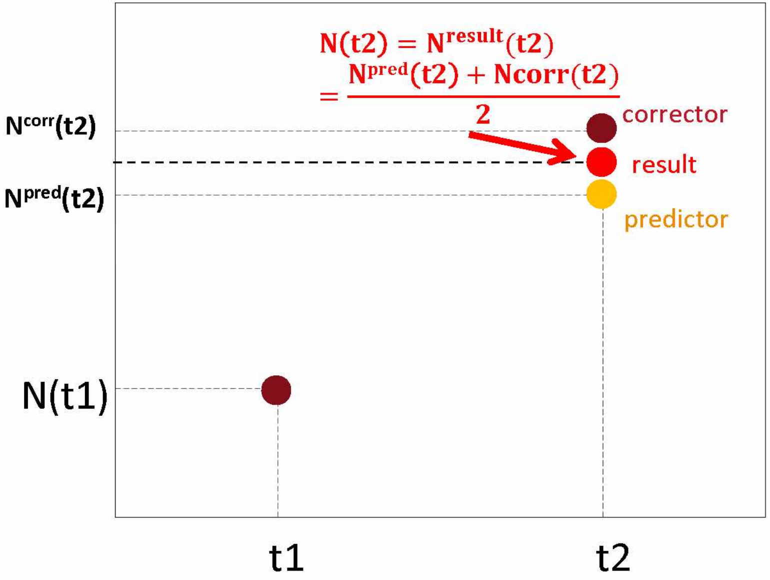

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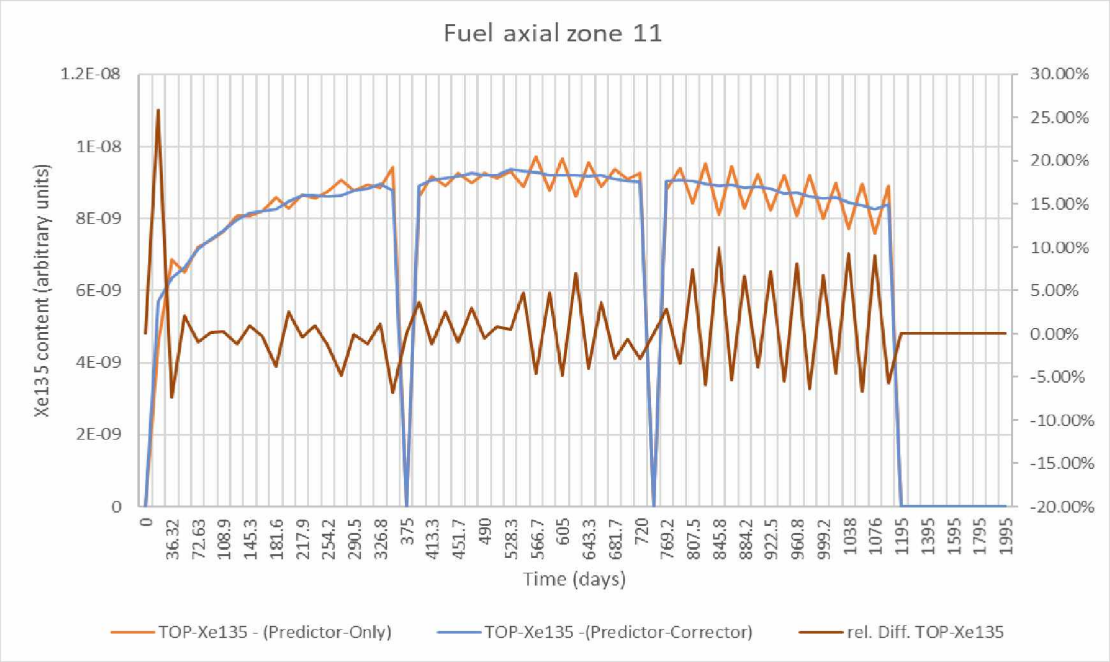
- MC calculation at time t2
  - Re-evaluation of multigroup cross sections
  - New $\sigma(\phi)$ in the Bateman equations
- Evolution from t1 to t2 using the new reaction rates ➔ $N^{corr}(t2)$

$$N(t2) = \frac{N^{pred}(t2)+Ncorr(t2)}{2}$$

3D Monte Carlo depletion

Predictor only method vs Predictor-corrector method

- Predictor corrector method requires <u>**2 x more**</u> MCNP calculations
- Adapted when the composition varies strongly between t1 and t2



Choice: predictor-corrector method

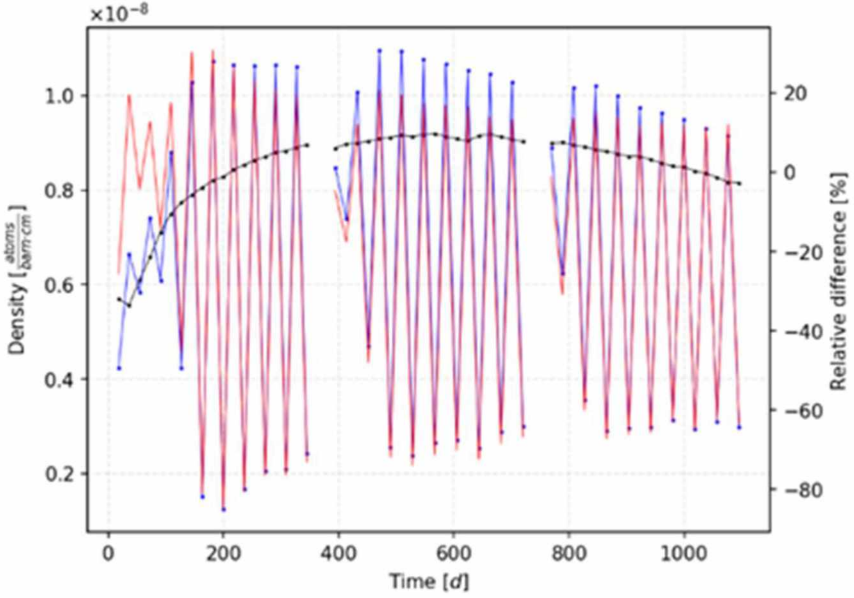
- Xe135 content in each axial zone is very sensitive to statistical uncertainty
  - ➢ Feedback on the neutron absorption in the next MC calculation
  - ➢ Causing “artificial” oscillations ~10% for the predictor only method

3D Monte Carlo depletion

Monte Carlo simulation parameter

- With predictor only method:
  - ➢ Same total number of simulated particles

	Set 1	Set 2
Particles per cycle	2 000 000	200 000
Inactive cycles	20	200
Active cycles	50	500



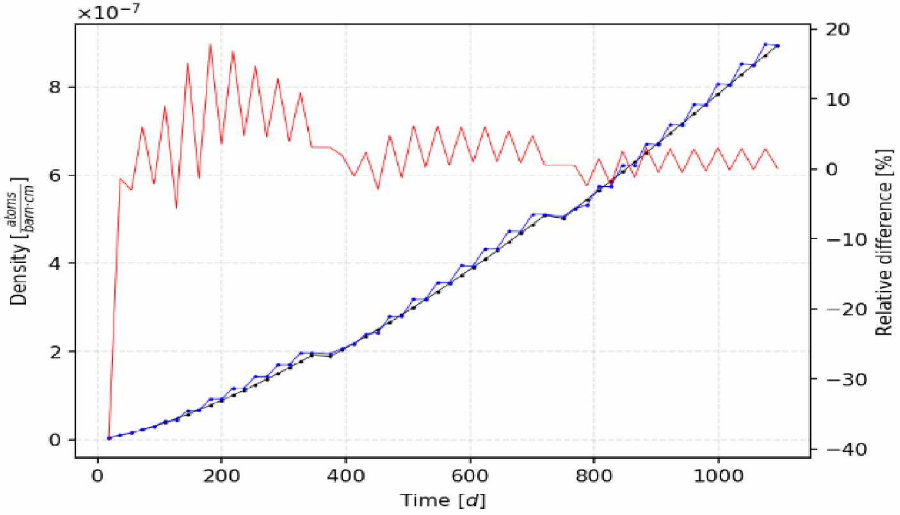
Xe135 content in fuel zone 11
- Param Set 1 – Ref
- Param Set 2
- Relative diff

- Xe135 "artificial" oscillations ~60% for the Set 2

3D Monte Carlo depletion

Monte Carlo simulation parameter

- With predictor only method:
  - Same total number of simulated particles



Co60 content in the head
Param Set 1 — Param Set 2 — Relative diff

	Set 1	Set 2
Particles per cycle	2 000 000	200 000
Inactive cycles	20	200
Active cycles	50	500

- Co60 content impacted by oscillations only ~5%

Choice: higher number of neutrons per cycle

Finally: predictor-corrector method + set 1 simulation parameters

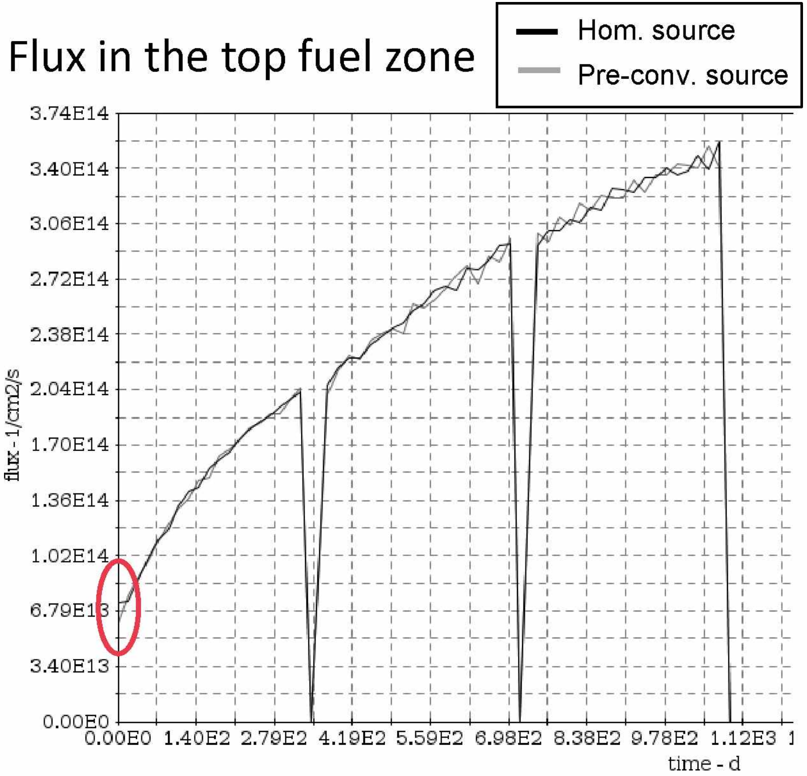
3D Monte Carlo depletion

Initial neutron source distribution

- VESTA uses the source distribution (srctp file) from the previous MCNP calculation for each MC calc.
- Reference calculation performed starting with spatially homogeneously distributed source definition

Initial source definition: no significant impact

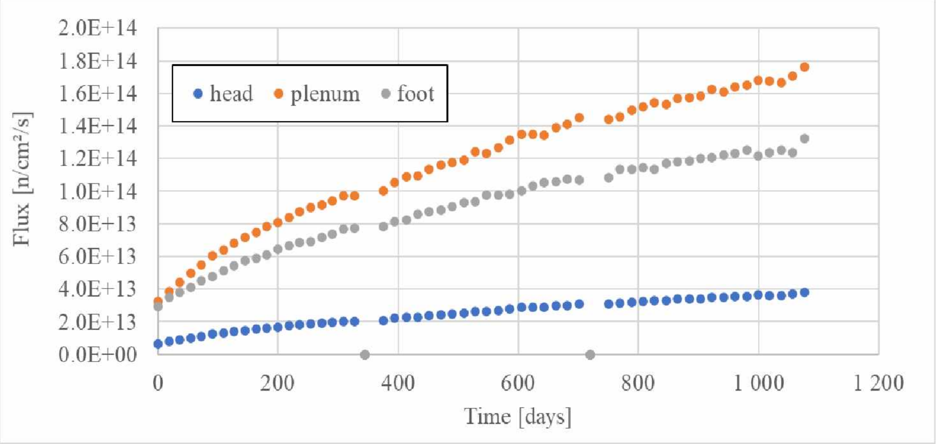
Flux in the top fuel zone



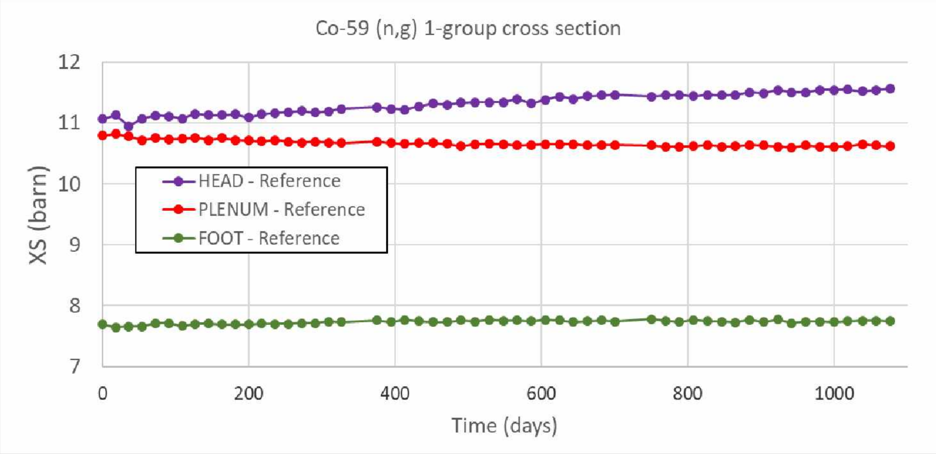
3D Monte Carlo depletion

Flux and XS in the nozzles

- Flux is maximal at the end of irradiation
- Co59 (n,g) 1 group XS:
  - Almost constant with BU
  - Very different in each nozzle = depends on the model and the water content



Last BU step of the 3D calculation	HEAD	PLENUM	FOOT
1-group XS Co-59 (n,γ) (bn)	11.6	10.6	7.75
Flux (n/cm²/s)	3.9E+13	18E+13	13E+13
Co-60 activity after 1000 days (10^{13}Bq)	1.1	1.5	1.9



Activity provided directly by VESTA: composition evolution calculated in the nozzles during irradiation and decay (no additional assumptions)

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Axial burn-up modelling

2D method

To avoid long and tricky 3D monte-Carlo depletion calculation a simplified approach "2D method" is studied, based on 3 steps:

1. 2D Monte-Carlo depletion calculation — **fuel composition** at the end BU
2. Static 3D Monte-Carlo calculation — **flux and 1-group XS** in the nozzles
3. Activity calculation after decay with simplified formula (constant irradiation conditions):

$$A(Co^{60}) = \sigma_{(n,\gamma)Co59} \cdot \varphi \cdot N_0^{Co59} \cdot \left(1 - e^{-\lambda_{Co60} \cdot T_{irrad}}\right) \cdot e^{-\lambda_{Co60} \cdot T_{cool}}$$

Axial burn-up modelling

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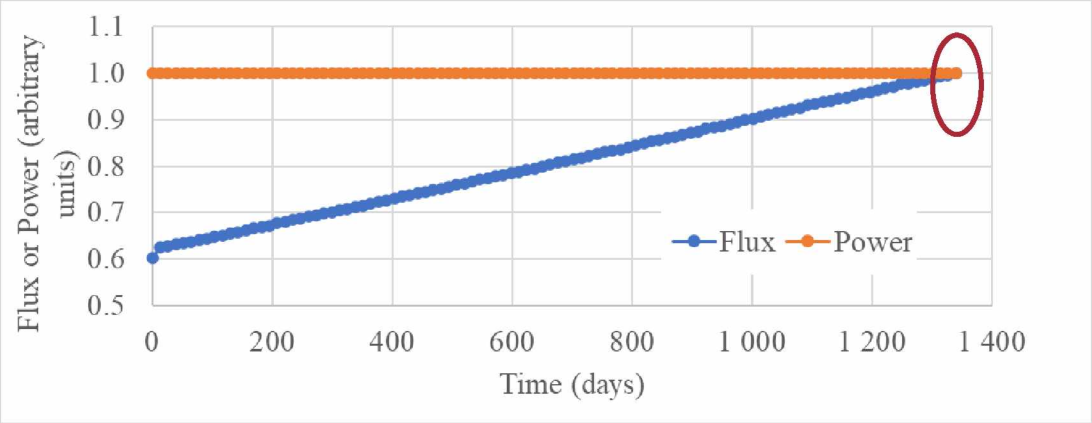

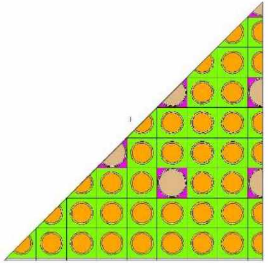

Axially reflected (2D) VESTA calculation: 1 depletion zone

Fuel composition corresponds to the **axially averaged** end BU

2. Static 3D Monte-Carlo calculation **flux and 1-group XS** in the nozzles
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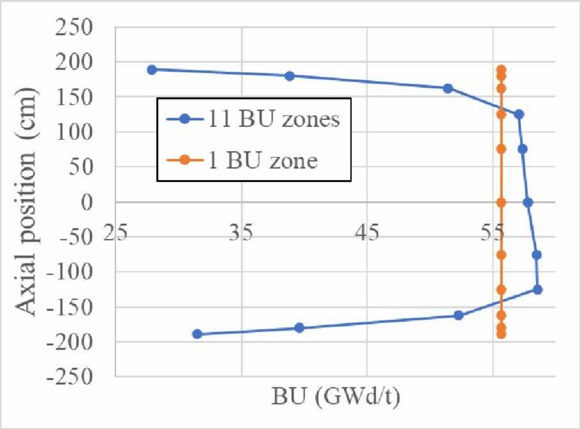

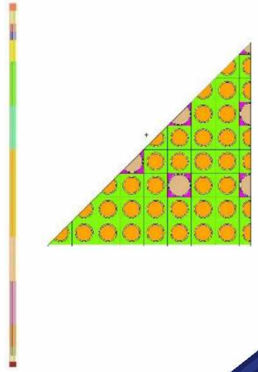

3D MCNP calculation with only **one fuel zone**

Leakage from the fuel is evaluated at the final BU: **Flux and 1-group cross section** in the nozzles

3. Activity calculation after decay with simplified formula (constant irradiation conditions):

$$A(Co^{60}) = \sigma_{(n,\gamma)Co59} \cdot \varphi \cdot N_0^{Co59} \cdot \left(1 - e^{-\lambda_{Co60} \cdot T_{irrad}}\right) \cdot e^{-\lambda_{Co60} \cdot T_{cool}}$$

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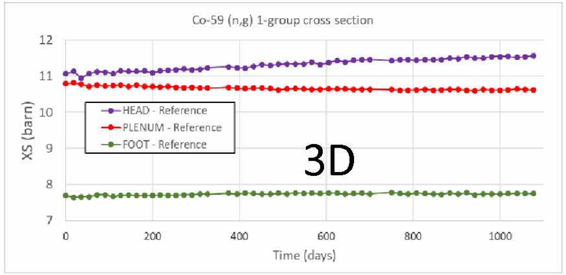
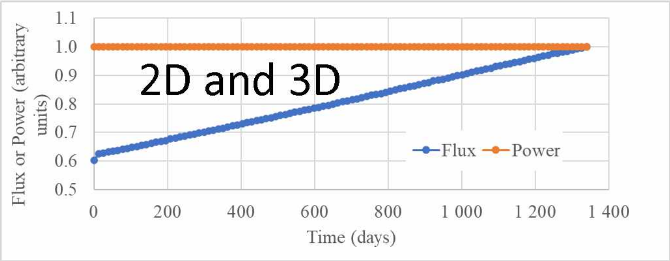
Taken at the end of cycle = Penalizing assumptions for safety



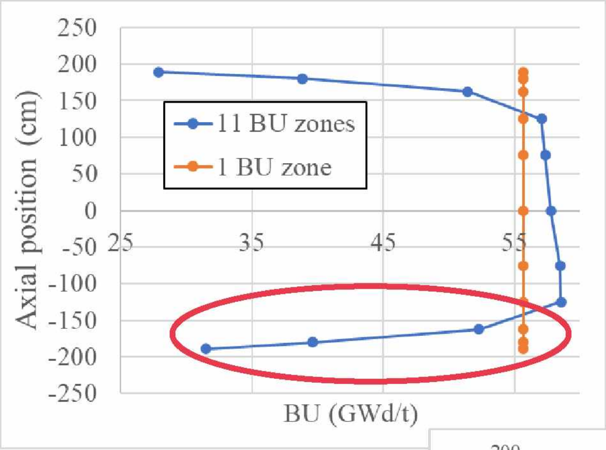
XS ~cst with BU



Flux increases with BU

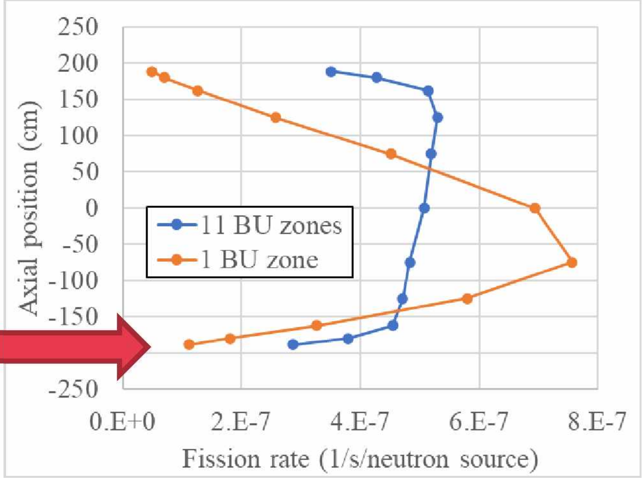
Axial burn-up modelling

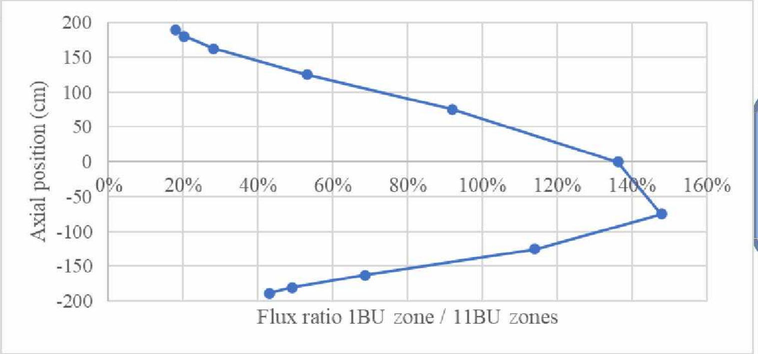
Results: 2nd step analysis 1 fuel zone vs 11 fuel zones



Fissions are more likely to take place in the lower BU zones. (UOX fuel BU < 70GWd/t)

11 fuel zones model **favores the fissions at the ends** of the fuel rod compared to 1 fuel zone model





As result, the flux at fuel rod ends is **poorly modelled with 1 axial fuel zone** (underestimation up to a factor 6!)

Conclusion

- Challenging 3D Monte Carlo depletion calculation
  - 4m high = highly decoupled system, strong underestimation of the statistical uncertainty
  - Simulation parameters and methods found for safe results:
    - Maximizing the number of particles per cycle
    - Predictor-corrector method
  - Reference method to verify different assumptions
- Tested 3-step method based on a 2D depletion calculation
  - Underestimates the flux at the nozzles (up to a factor 6!)
  - Importance of the axial burn-up profile modelling
    - requirement to model **several BU fuel zones** to correctly calculates the nozzle activation