Coupled CLASS and DONJON5 3D full core calculations and comparison with the neural network approach for fuel cycles involving MOX fueled PWRs

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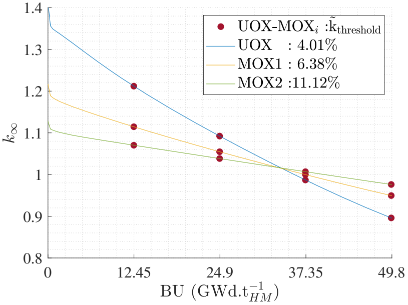
Summary

Project : full core calculation impact on scenario studies

Current situation

1. No full core calculations in scenarios (too costly)
2. Infinite assembly extrapolated models (MLP) based on $k_{threshold}$.



The project

1. Build full core models and associated databases
2. Build similar neural networks databases
3. Run elementary and complex scenarios with effectively coupled full core calculations

$$k_{threshold} = \frac{1}{N_{ass}} \sum_{n=1}^{N_{ass}} k_n(BU_{reload})$$

Calculation geometries

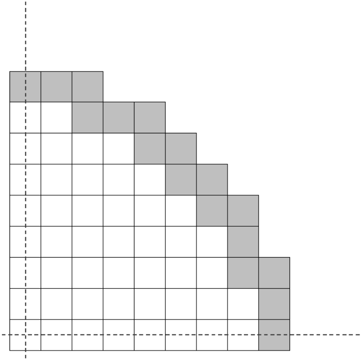


Figure 1: Quarter core

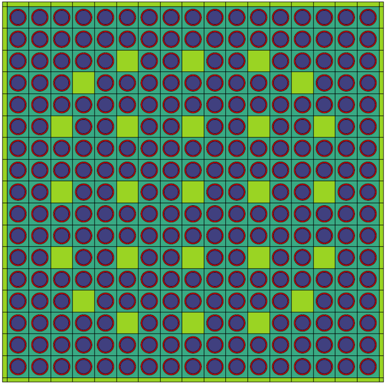


Figure 2: Assembly

- Complete assembly homogenization and two groups condensation.

Critical boron concentration

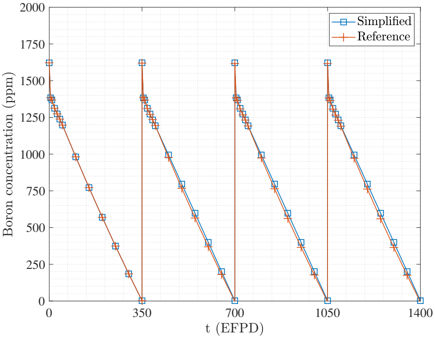


Figure 3: UOX

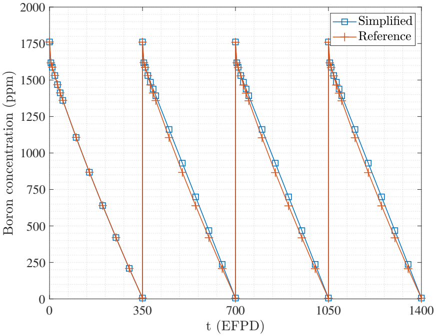


Figure 4: MOX

- 75% calculation cost reductions and very similar results with linear interpolation

Initial burnup predictions

- Two different refueling schemes are used for UOX and MOX reactors.

Isotopic composition correction

$$Corr_{MOx} = \frac{\%_{Fissile} - \%_{Ref}}{\Delta\%}$$

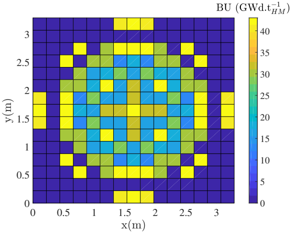
Cycle length correction

$$Corr_T = \frac{T}{T_{Ref}}$$

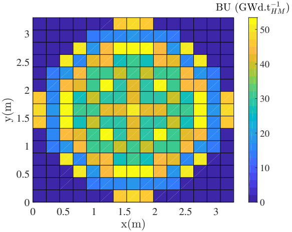
Spatial burnup final prediction

$$BU_{iCorr} = (BU_{iRef} \pm Corr_{MOx} \times \Delta BU_i) \times Corr_T$$

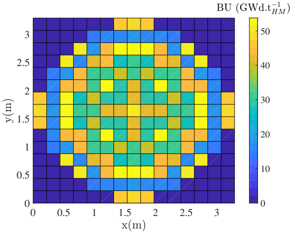
UOX burnup prediction accuracy



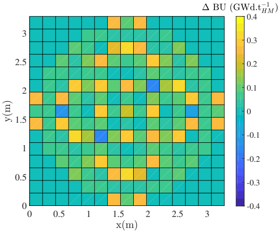
(a) Burnup at refueling



(b) End of cycle 1

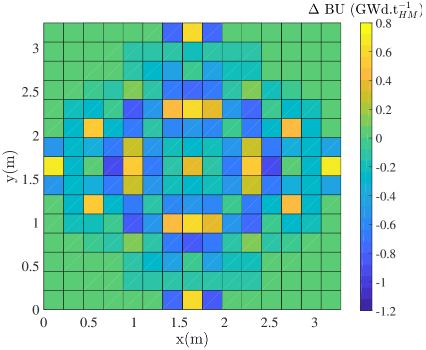


(c) End of cycle 4

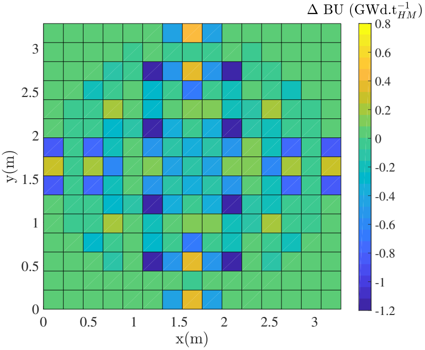


(d) Cycle 1 to 4 deviation

MOX burnup prediction accuracy



(a) MOX1



(b) MOX2

- burnup prediction leads to very low bias ($\leq$ 1 GWd.t$_{HM}^{-1}$ for a 50 GWd.t$_{HM}^{-1}$ burnup target).

$k_{threshold}$ accurate determination

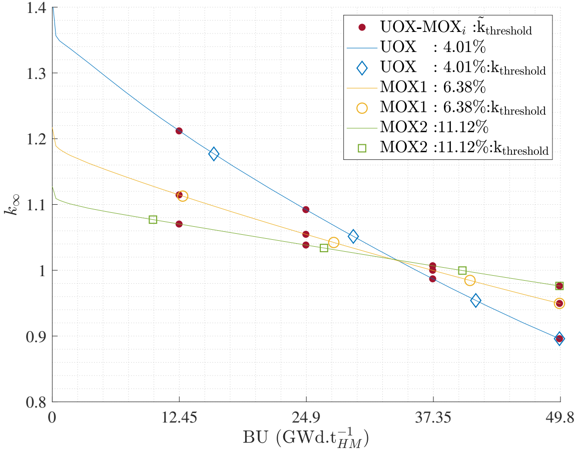
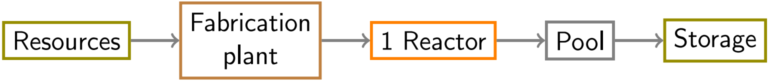


Figure 7: $k_{threshold}$ determination

$$k_{threshold} = \frac{1}{N_{ass}} \sum_{n=1}^{N_{ass}} k_n(BU_{reload})$$

Elementary scenarios

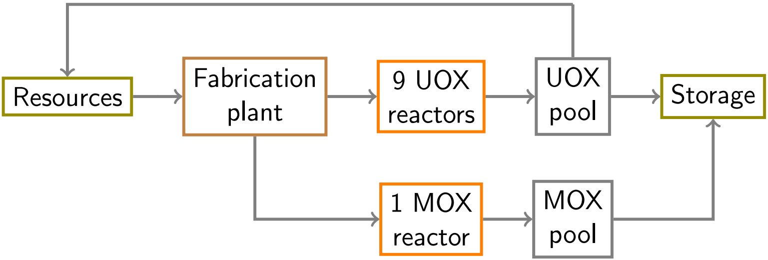


- Relative deviation (%) $= \frac{\text{MLP}-\text{Full core diffusion}}{\text{Full core diffusion}} \times 100$

Comparison of CLASS-MLP and CLASS-DONJON5 results for elementary scenarios

UOX Chemical element	with **fitted** $k_{threshold}$ values Relative deviations (%) on unloaded inventories
Uranium (except ^{238}U)	-12 %
Plutonium	+2 %
Minor Actinides	+25 %
MOX Chemical element	with **fitted** $k_{threshold}$ values Relative deviations (%) on unloaded inventories
Plutonium	-4 %
Minor Actinides	+4 %

Complex scenarios with UOX-MOX interactions



Comparison of CLASS-MLP and CLASS-DONJON5 results for complex scenarios

Scenario OneBU	with **fitted** $k_{threshold}$ values
Chemical element	Relative deviations (%) on end of scenario inventories
Plutonium	+1 %
Minor actinides	+5 %
Scenario TwoBU	with **non fitted** $k_{threshold}$ values
Chemical element	Relative deviations (%) on end of scenario inventories
Plutonium	+2 %
Minor actinides	+8 %

Scenario TwoBU

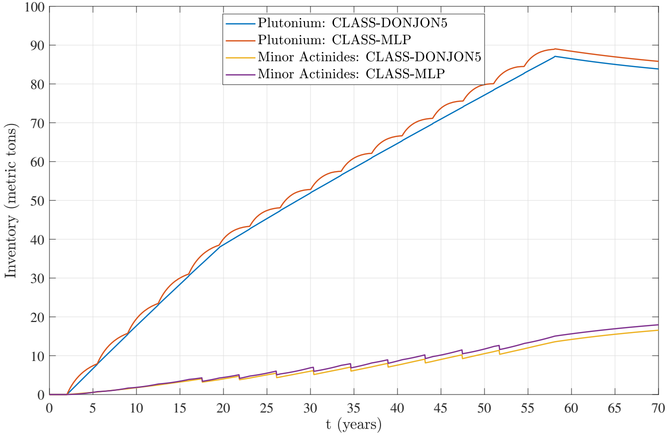


Figure 8: Pu and Minor Actinides in fuel cycle (scenario TwoBU)

Conclusion

Not computing full core simulations in scenarios implies :

- $\simeq$ 5 % deviation on loaded ^{235}U inventories ($\rightarrow$ impact on consumed ore)
- $\simeq$ 5 % deviation on unloaded Pu inventories ($\rightarrow$ impact on available fissile materials for reprocessing)
- $\simeq$ 10 % deviation on unloaded MA ($\rightarrow$ impact on long term hot waste inventories)

$k_{threshold}$ models (varying with isotopic compositions) provides a way to reduce error on Pu inventories by 50 %

End

Thank you, any question ?

Complex scenarios description

Scenario OneBU			
UOX (9 reactors)		**MOX (1 reactor)**	
Starting time (y)	Burnup (GWd.t_{HM}^{-1})	Starting time (y)	Burnup (GWd.t_{HM}^{-1})
2.0	49.8	25.0	49.8
Scenario TwoBU			
UOX (9 reactors)		**MOX (1 reactor)**	
Starting time (y)	Burnup (GWd.t_{HM}^{-1})	Starting time (y)	Burnup (GWd.t_{HM}^{-1})
2.0	45.5	19.5	55.4

Scenario OneBU

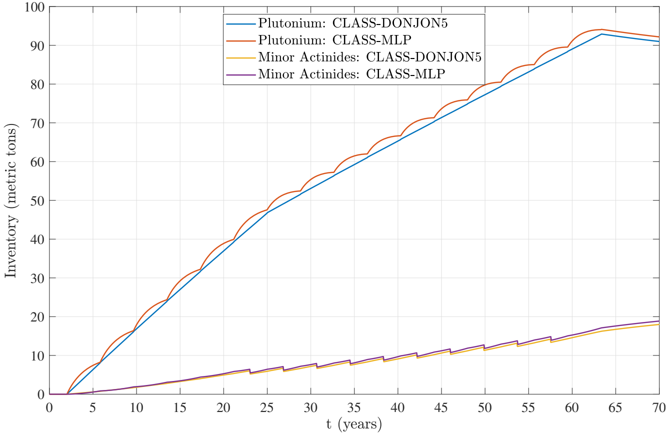


Figure 9: Pu and Minor Actinides in fuel cycle (scenario OneBU)

Databases sampling 1/3

Table 1: MULTICOMPO sampling for boron and burnup

Parameter	Number
Boron concentration (ppm)	0.0, 1375.0 and 2750.0
Burnup (GWd.t_{HM}^{-1})	0 ... 56.2 (23 steps)

Databases sampling 2/3

Table 2: MULTICOMPO (diffusion database) sampling

UOX	
Parameter	Sampling
Enrichment ($\%_{HM}$)	3.00, 4.00 and 5.00
MOX	
Parameter	Sampling
Enrichment ($\%_{HM}$)	4.50, 6.00, 7.50, 9.00, 10.50, 12.00 and 13.50
^{238}Pu ($\%_{Pu}$)	0.50 and 5.50
^{240}Pu ($\%_{Pu}$)	21.50, 26.50 and 31.50
^{241}Pu ($\%_{Pu}$)	1.50, 10.50 and 19.50
^{242}Pu ($\%_{Pu}$)	3.50, 8.00 and 12.50
^{241}Am ($\%_{Pu}$)	0.01 and 1.75
^{239}Pu ($\%_{Pu}$)	100 - ($\sum_{j \neq 239} {}^{j}\text{Pu} + {}^{241}\text{Am}$)

Databases sampling 3/3

Table 3: Neural networks databases sampling

Parameter	Number
UOX random compositions	800
MOX random compositions	5000
Cross-section predictors (by reactor type)	66
Reactivity predictor (by reactor type)	1

Scenario OneBU

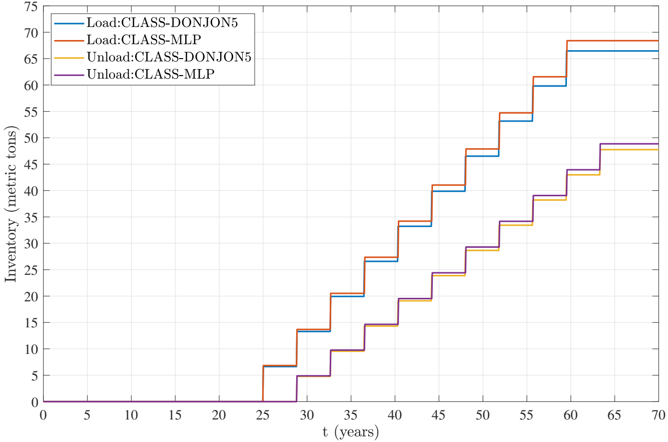


Figure 10: Accumulation of Pu in/out MOX reactor (scenario OneBU)

Scenario OneBU

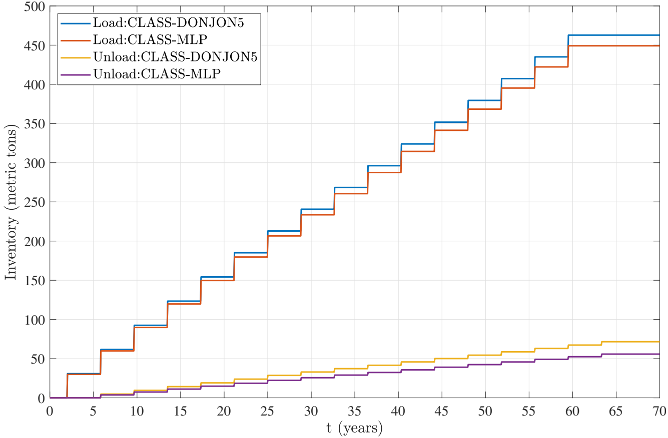


Figure 11: Accumulation of ^{235}U in/out UOX reactors (scenario OneBU)

Scenario OneBU

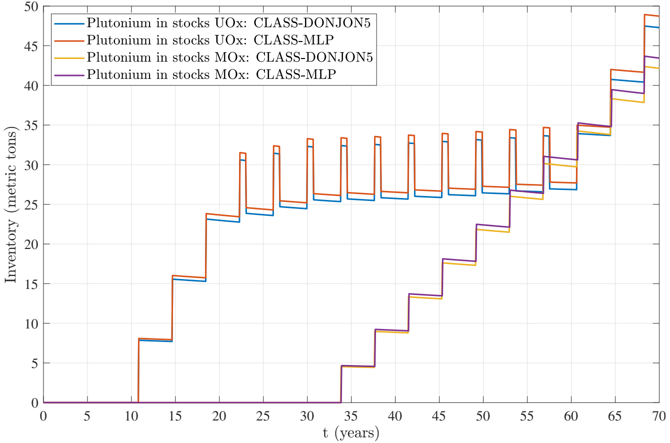


Figure 12: Plutonium in stocks (scenario OneBU)

Scenario OneBU

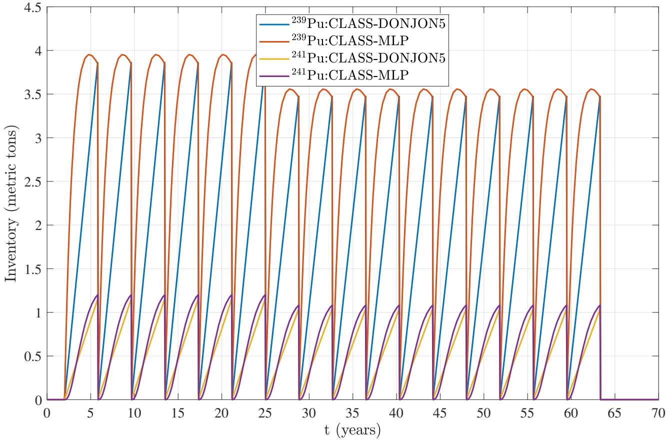


Figure 13: Fissile plutonium in UOX reactors (scenario OneBU)

Scenario OneBU

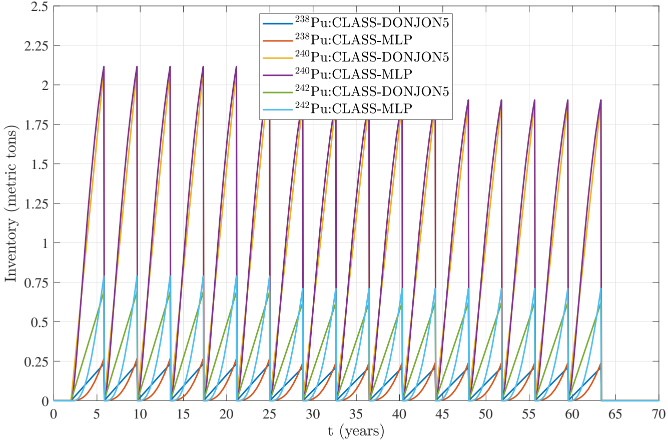


Figure 14: Fertile plutonium in UOX reactors (scenario OneBU)

Scenario OneBU

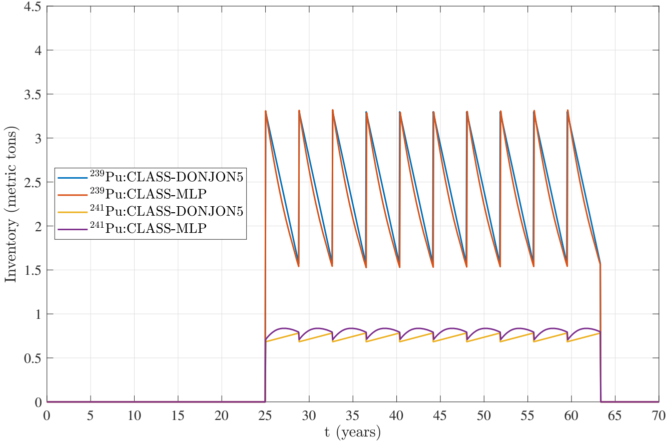


Figure 15: Fissile plutonium in MOX reactor (scenario OneBU)

Scenario OneBU

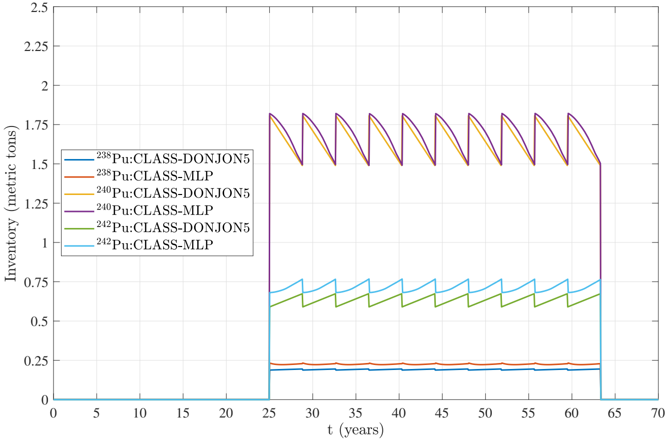


Figure 16: Fertile plutonium in MOX reactor (scenario OneBU)

Scenario TwoBU

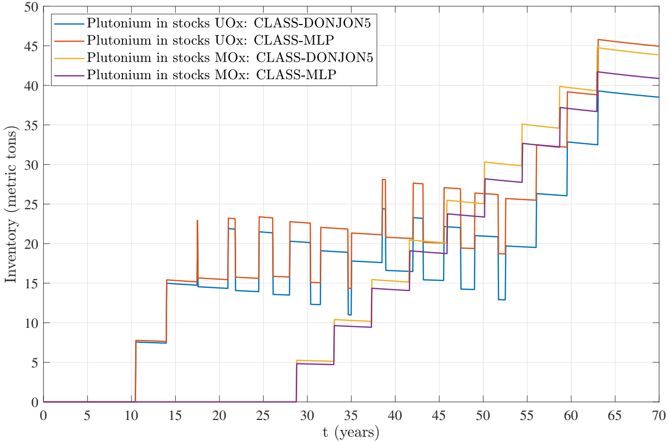


Figure 17: Plutonium in stocks (scenario TwoBU)

Loading plans

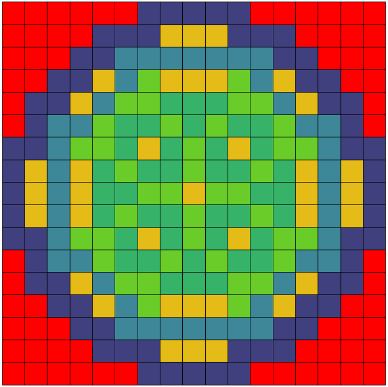


Figure 18: UOX

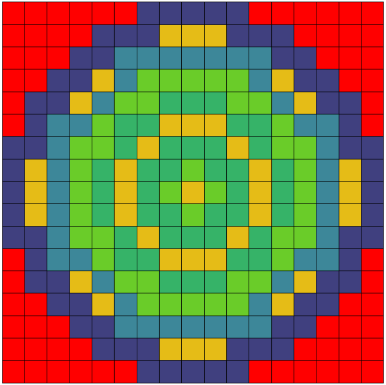


Figure 19: MOX

Flux map for MOX reactors after 50 EFPD

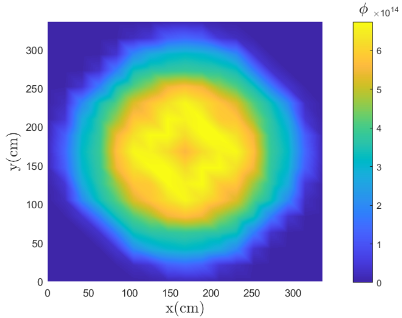


Figure 20: with UOX load plan

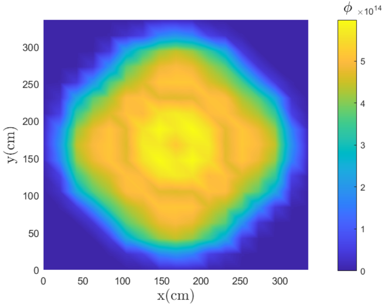


Figure 21: with MOX load plan

Reloading pattern

<table>
<tr><th></th><th>A</th><th>B</th><th>C</th><th>D</th><th>E</th><th>F</th><th>G</th><th>H</th><th>I</th><th>J</th><th>K</th><th>L</th><th>M</th><th>N</th><th>O</th></tr>
<tr><td>01</td><td>|</td><td>|</td><td>|</td><td>|</td><td>|</td><td>|</td><td>E07</td><td>H07</td><td>K07</td><td>|</td><td>|</td><td>|</td><td>|</td><td>|</td><td>|</td></tr>
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<tr><td>07</td><td>G05</td><td>NEW</td><td>F04</td><td>B05</td><td>G04</td><td>B06</td><td>G02</td><td>D08</td><td>I02</td><td>N06</td><td>I04</td><td>N05</td><td>J04</td><td>NEW</td><td>I05</td></tr>
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</table>

Figure 22: UOX

computed geometry data

Parameter	Value (unit)
Number of fuel pins (per assembly)	17x17 - 25
External fuel pin radius	0.40958 (cm)
External clad radius	0.47980 (cm)
Cell pitch (δ)	1.25984 (cm)
Inter assembly water gap (ε)	0.25000 (cm)
Network pitch	$17\delta + 2\varepsilon = 21.92$ (cm)
Number of assemblies (in the core)	157
Number of bundles	4

Table 4: Geometry data

UOX assembly content with irradiation cycles (350 EFPD)

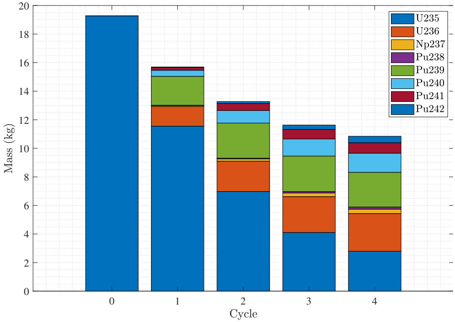

Figure 23: Actinides (w/o uranium 238)

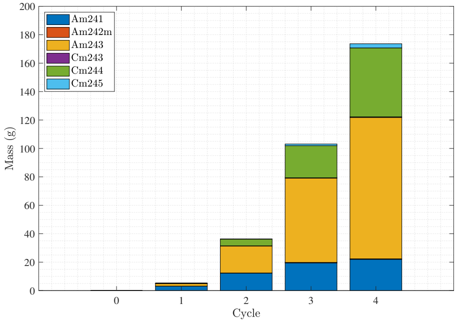

Figure 24: Minor actinides

MOX assembly content with irradiation cycles (350 EFPD)

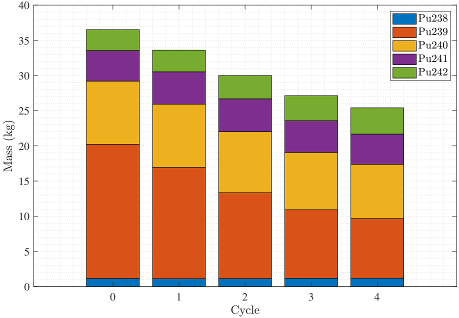

Figure 25: Plutonium

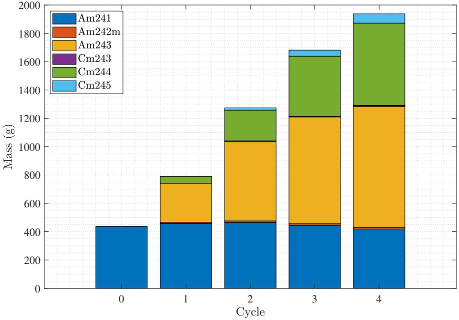

Figure 26: Minor actinides

Reflective materials

1. MoC (Method of Characteristics)
2. One assembly wide
3. One homogeneous mixture

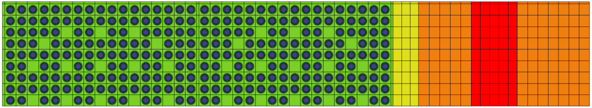

Figure 27: Reflective materials calculation geometry

PWR actinids interactions

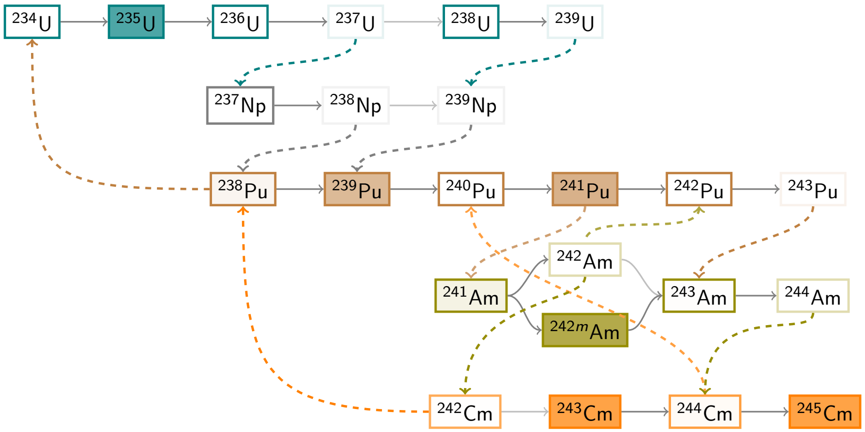

Figure 28: PWR actinides interaction diagram. Dashed line represents natural decay, solid line neutron capture and the more the box is coloured the more the isotope fissions.