Modelling MSRs for fuel cycle simulation studies

Preliminary work on a Pu-Am fueled chloride fast reactor

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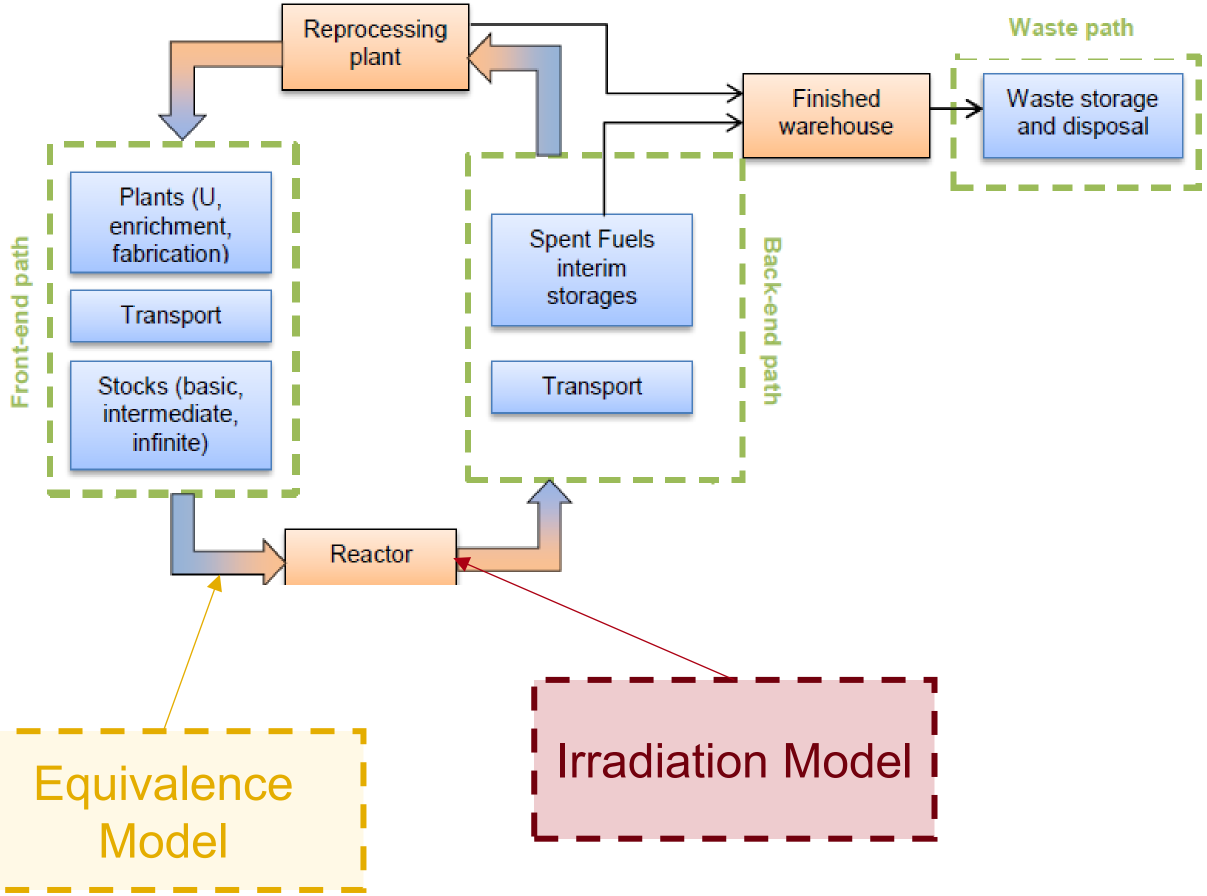
Introduction : COSI simulation code

COSI is a fuel cycle simulation code capable of modelling complex plutonium management strategies and following the isotopic evolutions of the radioactive matter in the cycle



It relies on 3 kind of physical models :

Decay

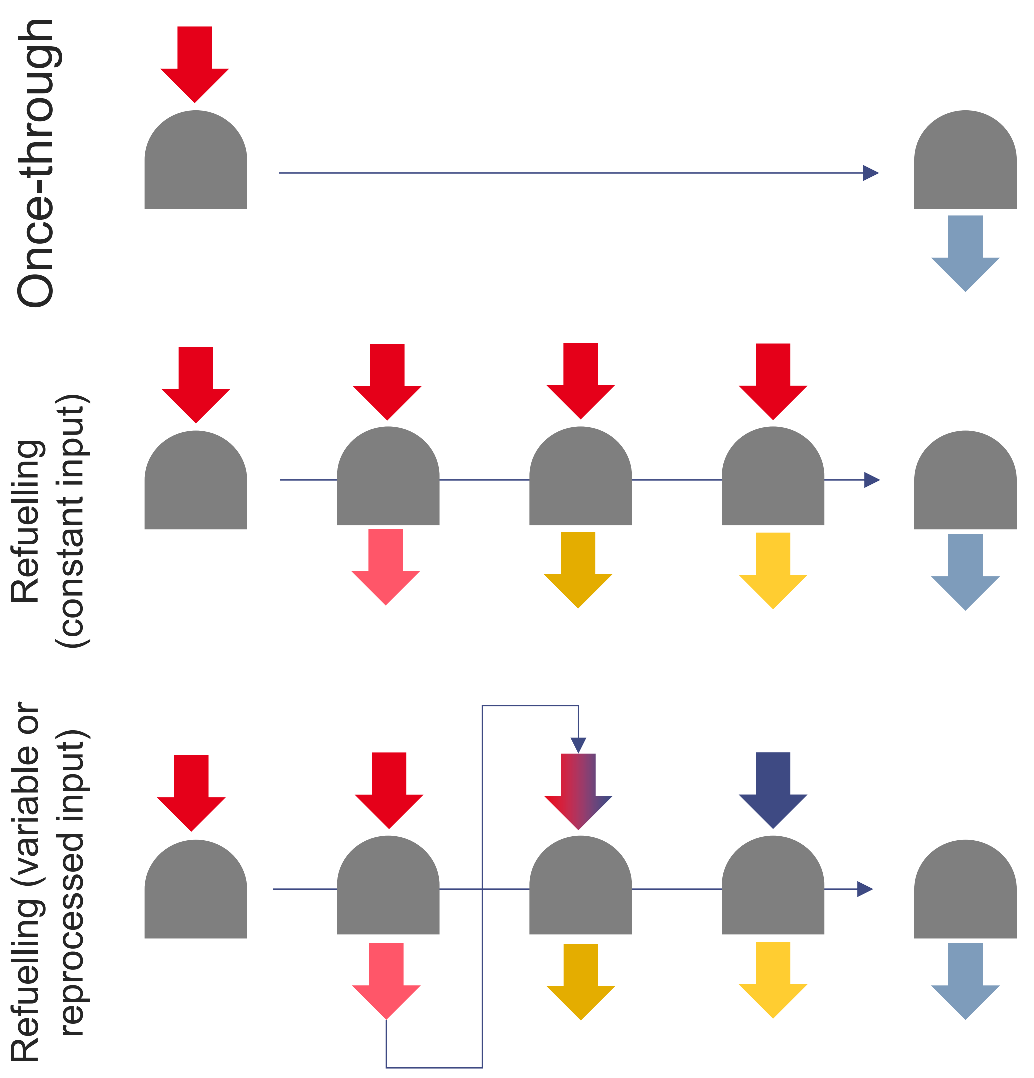
Equivalence Model : Estimate the composition of fresh fuel based on the isotopic composition of the matter available in the stocks

Irradiation Model: Estimates the used fuel composition based on the fresh fuel composition

NB : These models are applied to each fuel batch, with no consideration of the impact of the environment of the batch in the core

How can these models be adapted to modelling MSR ?

Introduction : A variety of MSR designs



Depends on the kind of MSR :
- Refuelling ?
- Input Variation ?
- Reprocessing ?
- Are there any constant values ? In mass or volume ?
- Etc.

- **Once-through**, with constant input : // solid fuel
- With **refuelling** – esp. on-line : need to account for change in the inupt and output, even with constant input isotopy
- With **reprocessing** or variable input : complexity increases

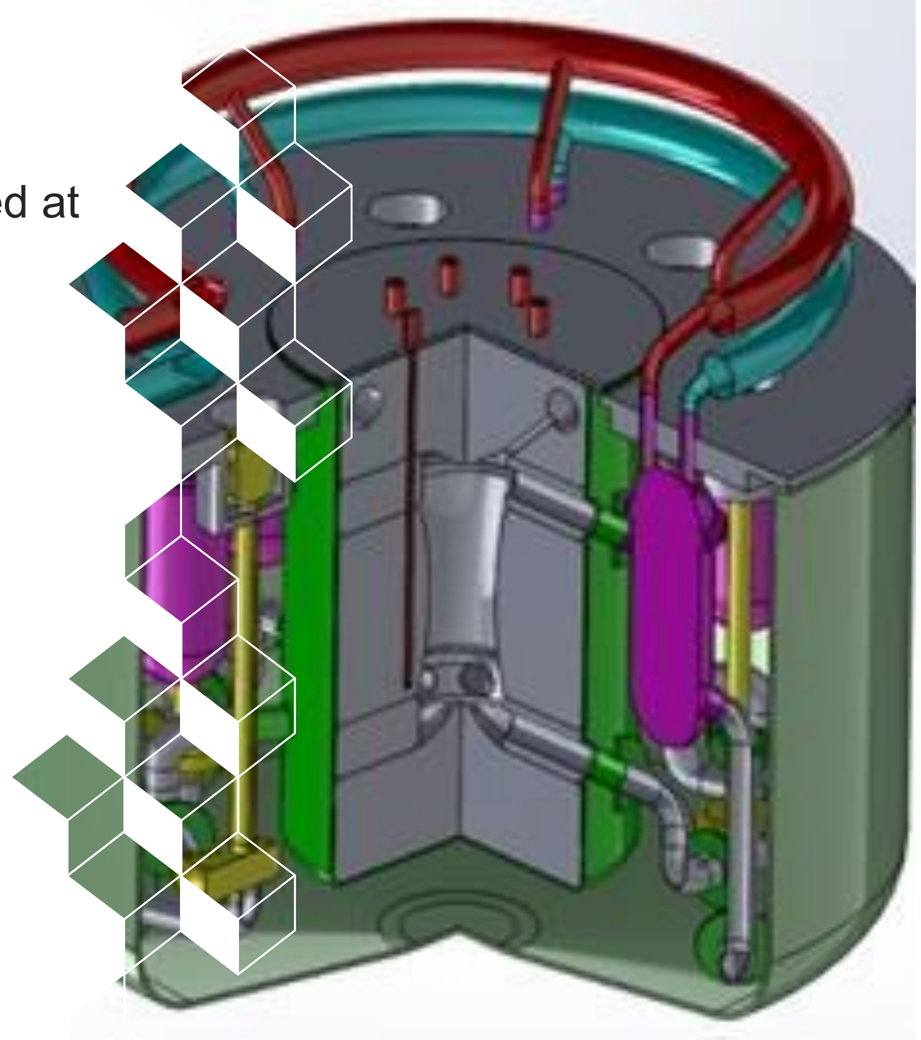
Design choices will determine the difficulties of judiciously modelling MSR in fuel cycle simulation studies

Introduction : ARAMIS-A

<u>Objective :</u> : Transmute Am with a small MSR, using chloride salt in fast spectrum

Neutronic calculation performed with the code « MOSARELA » developped at CEA Cadarache

Caracteristics (v1.0)	Description/Values/Unit
Power	300 MWth
Salt	NaCl-MgCl2-PuCl3-AmCl3
Incineration performances (Np + Am + Cm)	80 kg/TWhe
Initial HN masses (Pu – Am)	2,8 t – 3,4 t (BOL) 2,9 t – 2,6 t (EOL)
Constant Pu – Am ratio in refuelling salt	45 % / 55 %
Refuelling frequency	120 L every 6 months



Ref: *J. Martinet*

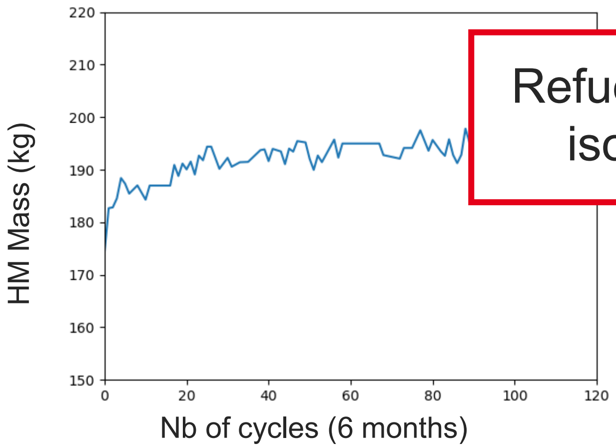
<u>Probable challenge for simulation codes since :</u>

- Core mass changes
- Refuelling vector changes
- Use of 2 differents HN in fuel salt

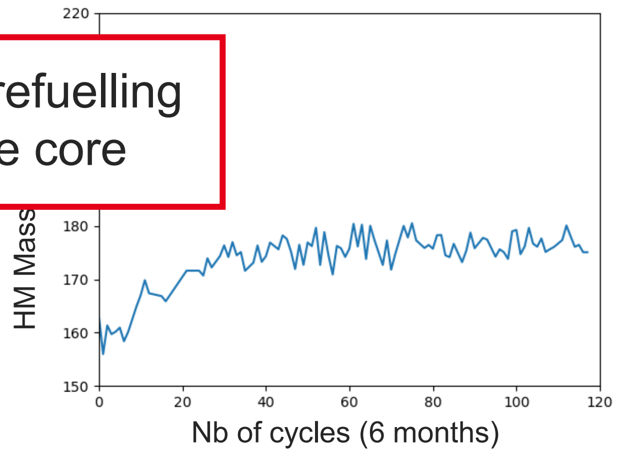
Introduction : ARAMIS A

Alimentation

Isotopy A



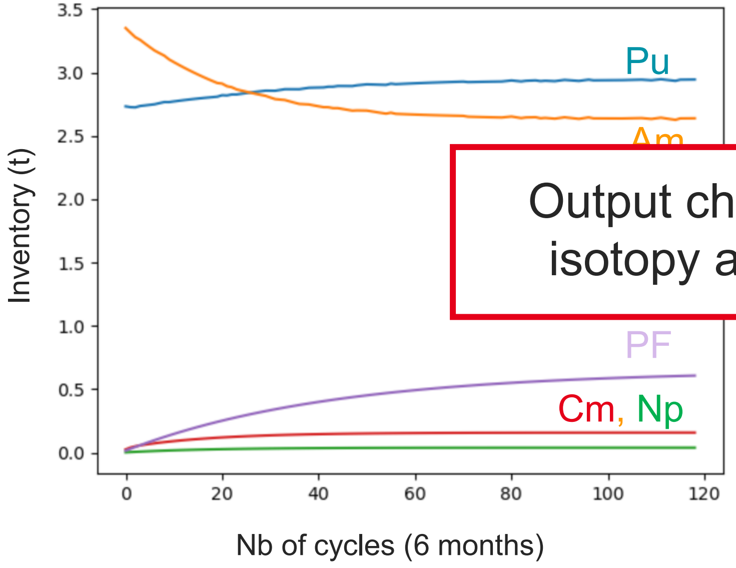
Isotopy D

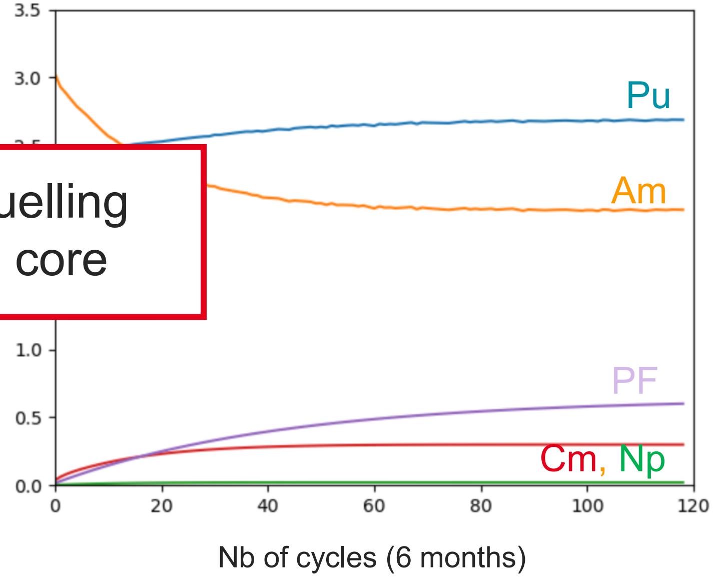


+10 %

Refuelling changes with the refuelling isotopy and the state of the core

In-Core Inventory
(= output composition)





Output changes with the refuelling isotopy and the state of the core

1. Equivalence Model

Equivalence : Usual approach in fast spectrum

Baker & Ross Formula, used to compute fresh solid FR fuel composition

Pu content in fresh fuel

Pu content in fresh fuel if only U238 and Pu239 are used

Mass fraction of isotop i in available stocks

$$\boldsymbol{E} = \frac{\boldsymbol{E_0} - \sum_{i\,\in\,U} \zeta_i * \boldsymbol{W_i}}{\sum_{i\,\in\,Pu+AM} \zeta_i * \boldsymbol{W_i} - \sum_{i\,\in\,U} \zeta_i * \boldsymbol{W_i}}$$

Pu239 equivalent weight of isotop i, calculated for a reference isotopy

$$W_i = \frac{\sigma_i^{+} - \sigma_{238U}^{+}}{\sigma_{239Pu}^{+} - \sigma_{238U}^{+}}$$

$$\sigma_i^{+} = \nu\sigma_i^{f} - \sigma_i^{a}$$

Hypothesis :

- ~~Little variation of [illegible] ection in fast spectrum~~
- ~~Little variation of [illegible] r of heavy nuclei in fresh fuel~~

Does not apply well to ARAMIS A, at least because of variation over the life of the reactor

Need to find another reference than « $\boldsymbol{E_0}$ » to develop an analytical method

Equivalence : Caracterizing a new invariant reference

Need to find another invariant value :

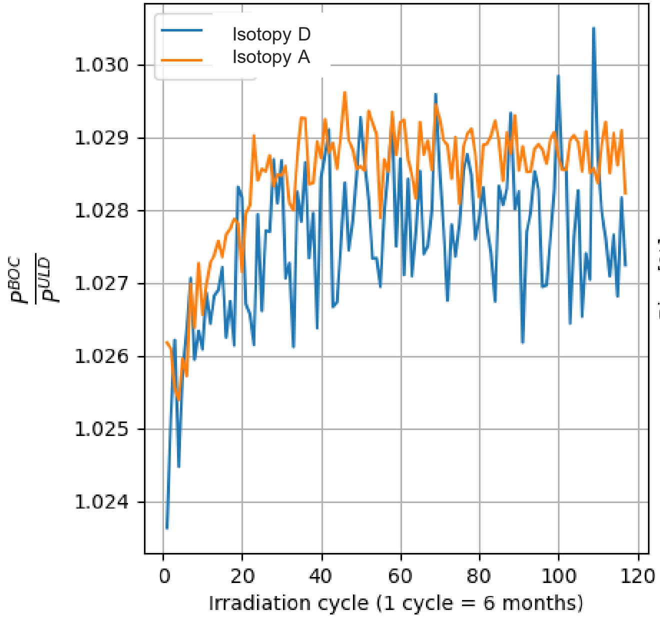
- Associated to the refuelled core
- Time dependant

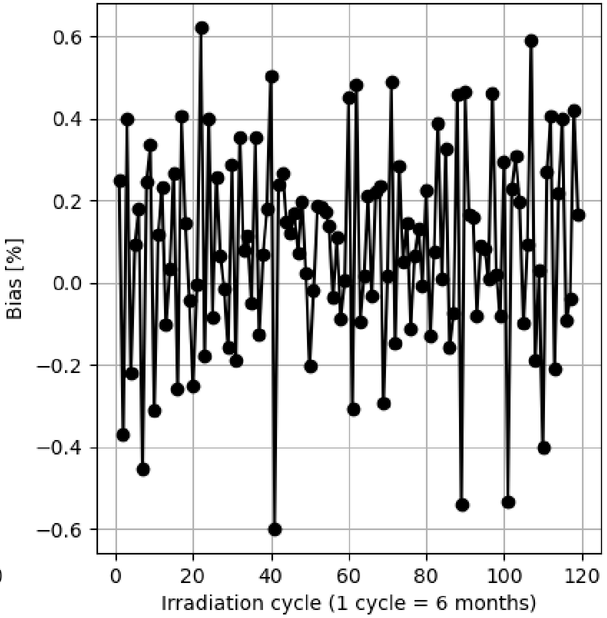
Introduction of estimate P :

$$P = \frac{\sum_{i \in (U, Pu, Am\ Cm\ Np)} m_i * W_i}{M_i}$$

P changes over time but, regardless of isotopy, for a given cycle n :

$$\frac{P_{beginning\ of\ cycle}[n+1]}{P_{unloading}[n]} = cst$$





Possible to predict analytically the HN mass required for refuelling by using a time-tabulated reference for Puld and Pboc, only considering HN weights

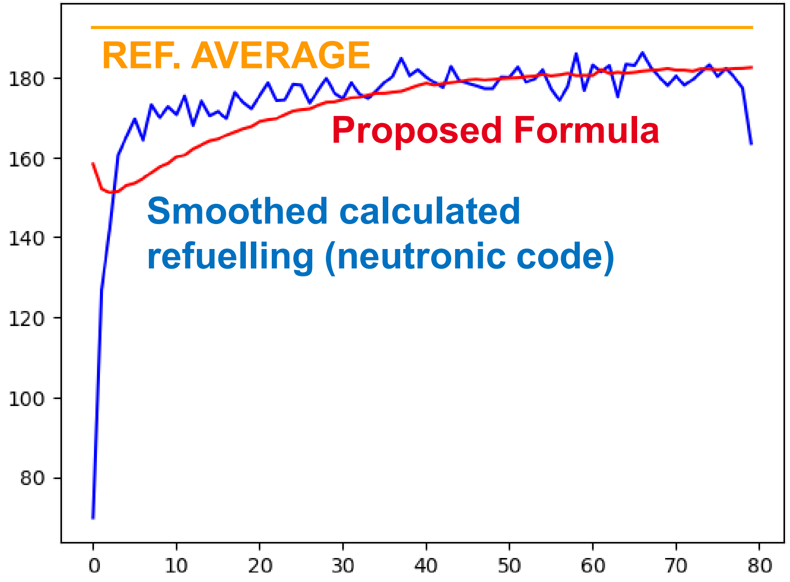
$$m_{HN\ refuelling} = \frac{\frac{P_{unloading}[n]}{P_{unloading}ref[n]} P_{beginning\ of\ cycle}ref[n+1] - P_{unloading}[n]}{P_{alim}[n]}$$

Equivalence : Preliminary verification

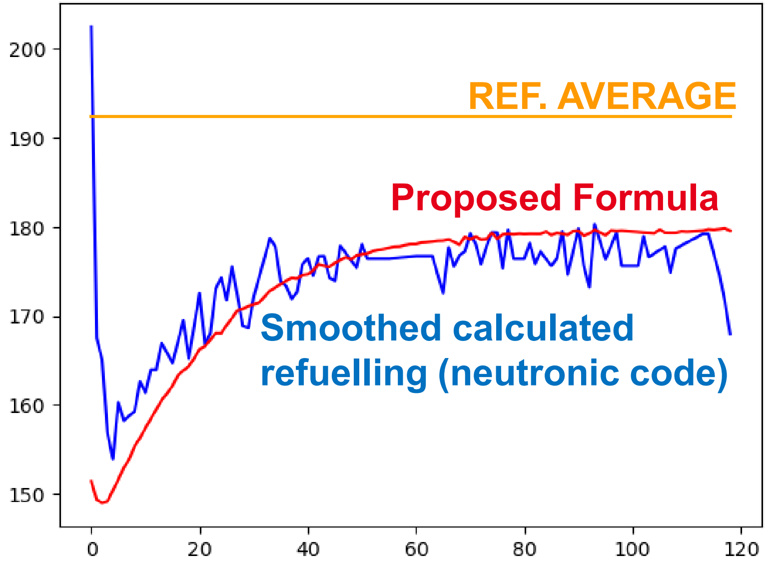
Isotopy closest to A

Isotopy furthest from A

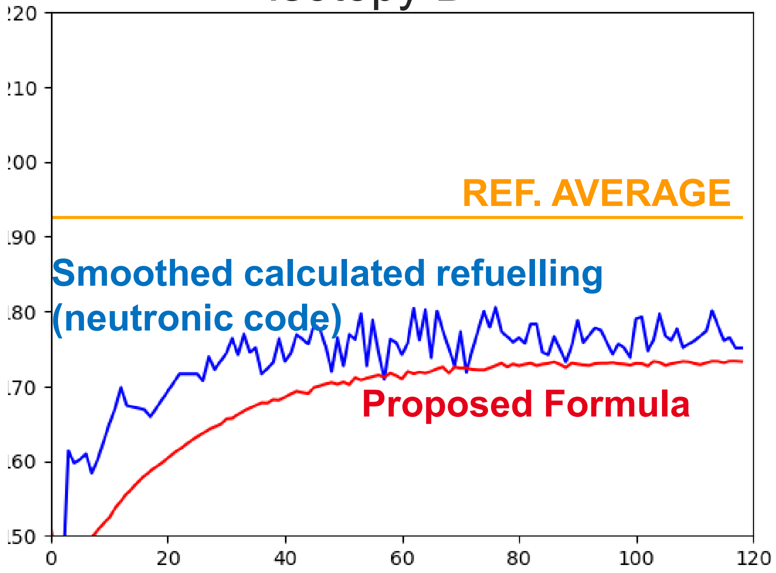
Isotopy B



Isotopy C



Isotopy D



⇒ Follow **time-evolution**

⇒ Changes with **isotopy**

⇒ Current verification done on unloading states calculated by neutronic code : possible « **snowball effect** » not taken into account here, and currently under review

⇒ **Bias** increases when isotopic composition drift from the reference

⇒ Ratio between **complexity of method / actual benefit** in simulation hard to analyse at the moment

2. Irradiation Model

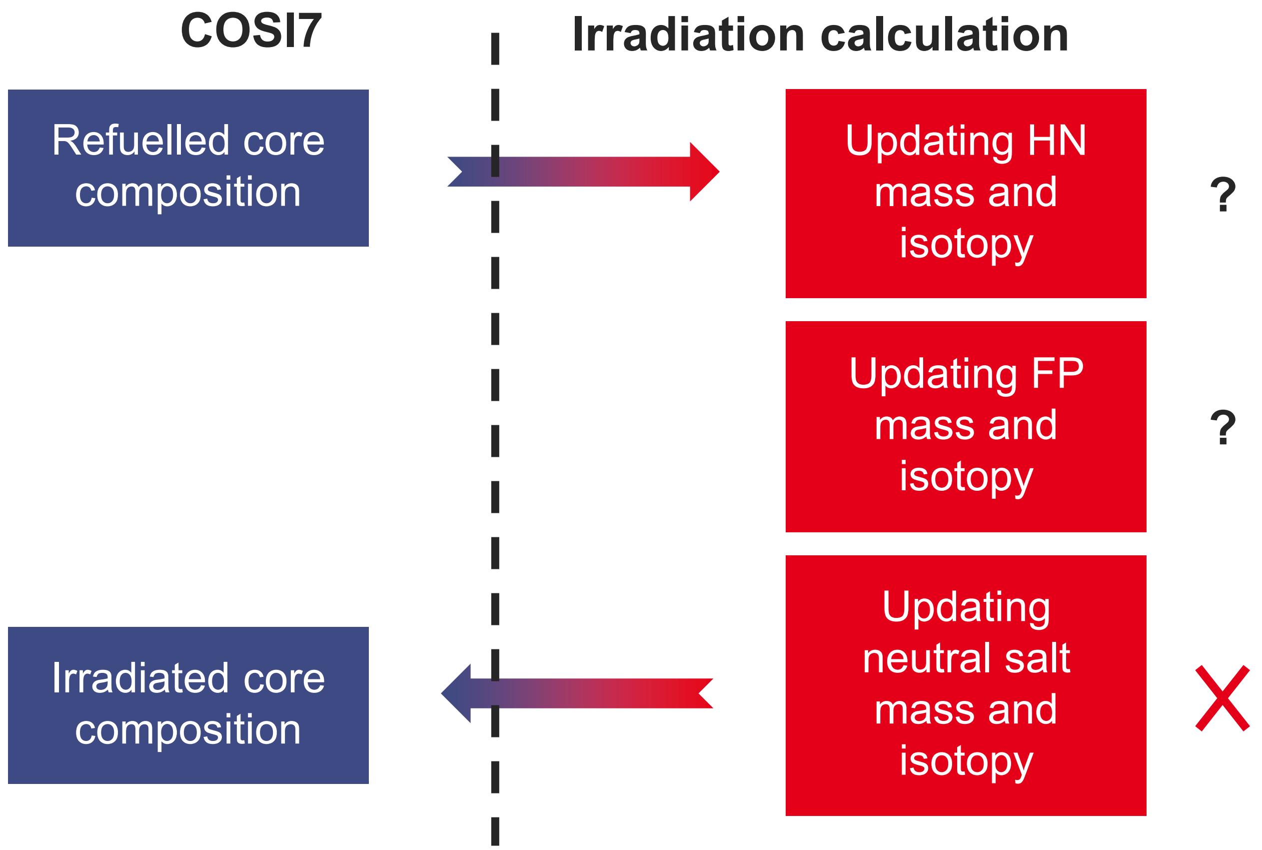
Irradiation : Identified steps

Differences with solid fuel :

- Irradiation models tend to rely on BU > hard to define for refuelled MSRs
- Refuelling salt mixed with the rest of the core > new elements to take into account

In the presented case:

- The equivalence model provides the composition of a refuelled core > need to irradiate the entire core
- COSI can be coupled with any irradiation script or code > possible to avoid defining BU



Question : Which inputs are mandatory to judiciously perform estimations of HN and FP ?

Neutral salt is used as a buffer and out of scope for this study

Irradiation : Heavy nuclei calculation

HN (and FP) mass variation :

During irradiation HN either fissionate or transmute to other HN

- $HN\ mass_{after\ irradiation} = HN\ mass_{in\ refueled\ core} - FP\ production$
- Pth = cst > FP production = cst, independent of time and isotopy
- Analytical update of the total mass of HN after irradiation

HN composition evolution

Neural network, using only HN as inputs

Trained on 6-months cycles, for a variety of starting dates, representative of refuelled cores compositions

Isotop	Average deviation to testing DB [%]	Standard deviation to testing DB [%]
U234	-0,00113	0,45951
U235	-0,00116	0,85189
U236	-0,00221	0,69119
U238	-0,03992	0,74061
Np237	0,02688	1,04492
Pu238	0,00792	0,70789
Pu239	-0,03937	0,78802
Pu240	-0,0108	1,0191
Pu241	0,00415	1,17542
Pu242	0,00445	0,60511
Am241	0,00243	0,10774
Am242m	0,00491	0,5264
Am243	-0,01223	**2,63912**
Cm242	-0,02509	0,52164
Cm243	-0,02981	0,67647
Cm244	-0,01635	0,69458
Cm245	-0,06687	1,18422
Cm246	**-0,12928**	1,48192

Irradiation : Fission products calculation

FP mass variation :

As stated before, FP production = cst

Tested for different refuelling isotopy and different cycles

- Analytical update of the total mass of FP after irradiation

FP composition evolution :

Isotopy of the added FP is considered constant through time and independant from the refuelling isotopy

- True of most FP
- Possible amelioration path, but need to assess wether the concerned FP are of interest (rest of the cycle, chemistry issues, significant enough content, etc.)

Neutral salt :

- Acts as a « buffer », reduced through time to assess the evolution of FP and HN in a code requiring a fixed core mass

3. Conclusions & Perspectives

Conclusions

1. **MSR modeling** in fuel cycle simulation studies is strongly **dependant of the refuelling / unloading strategies**

2. **Existing equivalence models** are **not easily applied** to MSR behaving like ARAMIS-A:
   - Require new invariant references, that might need to be tabulated in time
   - Proposed analytical method in need of further validation

3. **Irradiation** can be applied to the entirety of the core with **less difficulties**
   - HN and FP **mass variation** are **independent of time and refuelling isotopy**
   - **HN composition variation** can be modelled with **ANN** with acceptable bias + training ressources
   - **FP composition variation** can be **neglected**

Limitations and perspectives

1. **Modelling the entire core** instead of batches makes the **handling of reprocessed batches harder** > conflict with the **downstream** of the cycle (cooling time, etc.)

2. Need of further **validation and critical analysis** of the presented model
   - Possible **“Snowball effect”** of the interaction between the equivalence and irradiation models currently under review
   - Need to assess the **actual benefits** of implementing complex modelling of MSR – neutronic codes not mature enough at the time this work began + possibility to neglect the transitionary phase (*P.E. Dufour ongoing PHD studies*)

3. No consideration of **neutral salt**
   - Considered **out of scope** for COSI
   - Might be of interest for **chemistry or life cycle assessment studies**, especially for **Cl37**