



GLOBAL 2019

International Nuclear
Fuel Cycle Conference



TOP FUEL | 2019

Light Water Reactor Fuel Performance Conference



ANS Meetings

Analysis of transition scenarios from a PWR to a SFR fleet simulated with the CLASS code

Lea Tillard

Ph.D student



IRSN

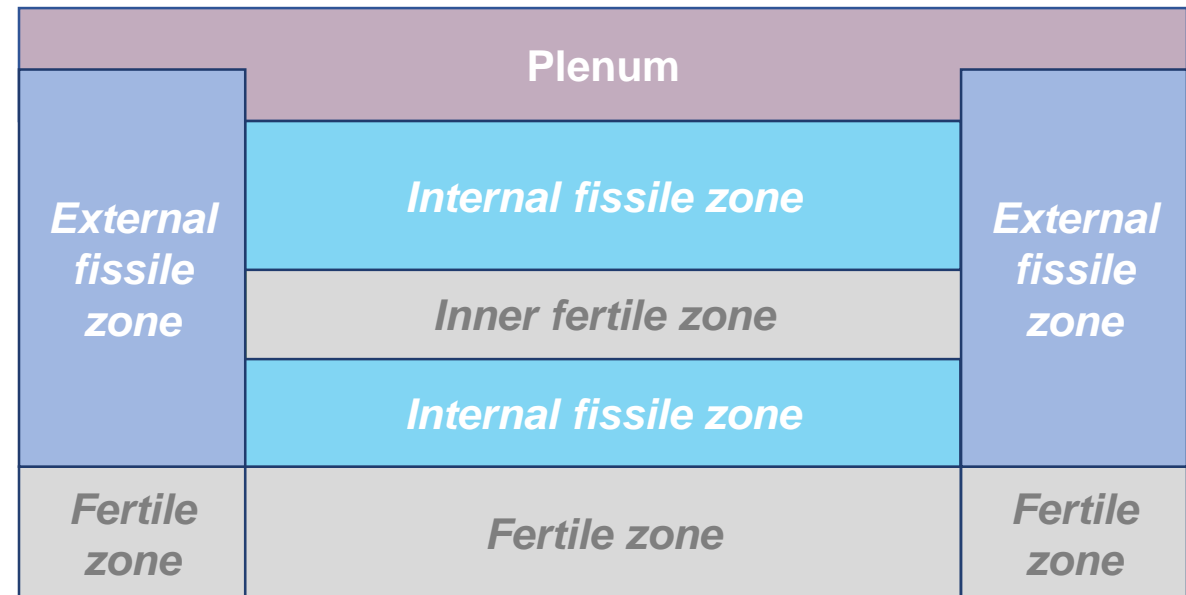
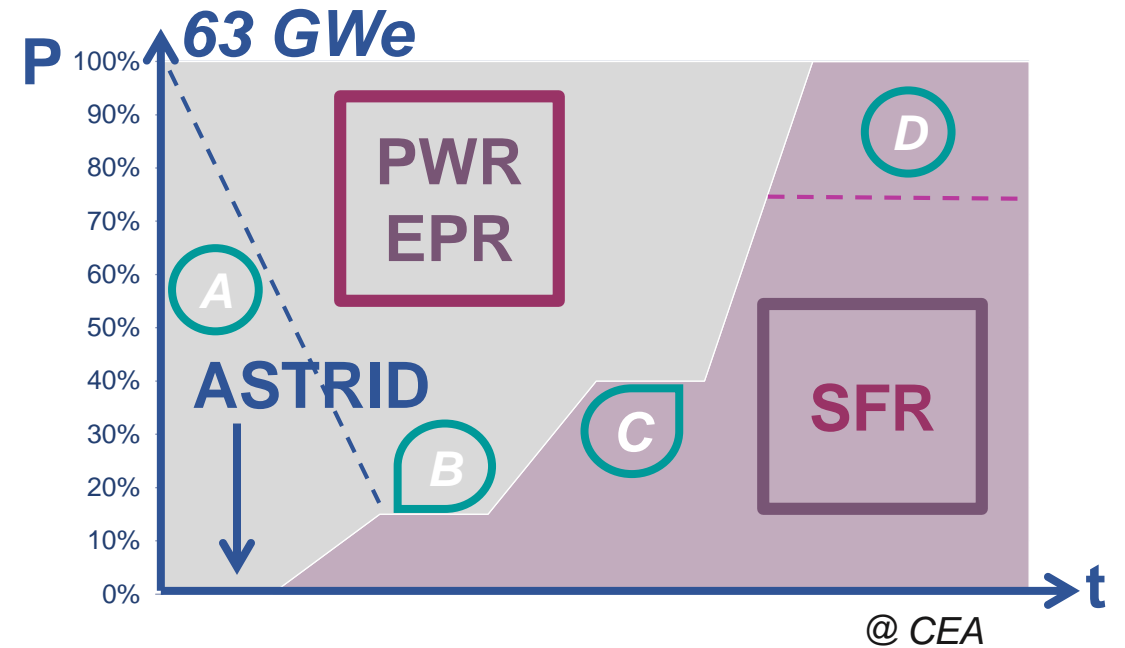


Outline

- Context
- New SFR modelling in the CLASS code
- Methods and study cases
- Fuel management strategies
- Impact of SFRs on the fuel cycle
- Conclusion and perspectives

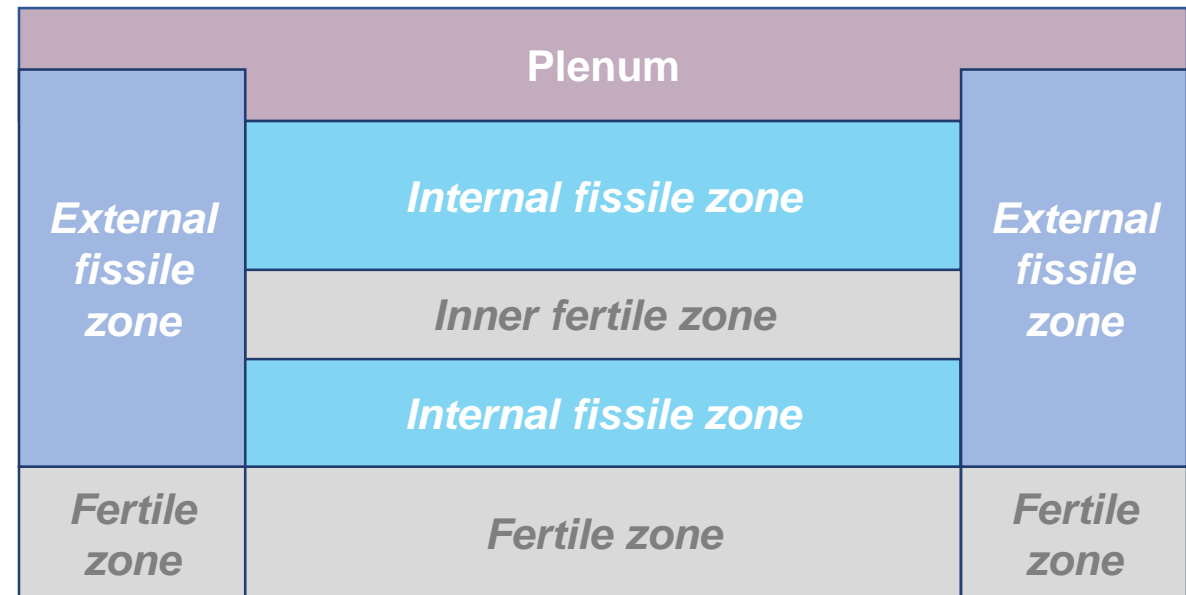
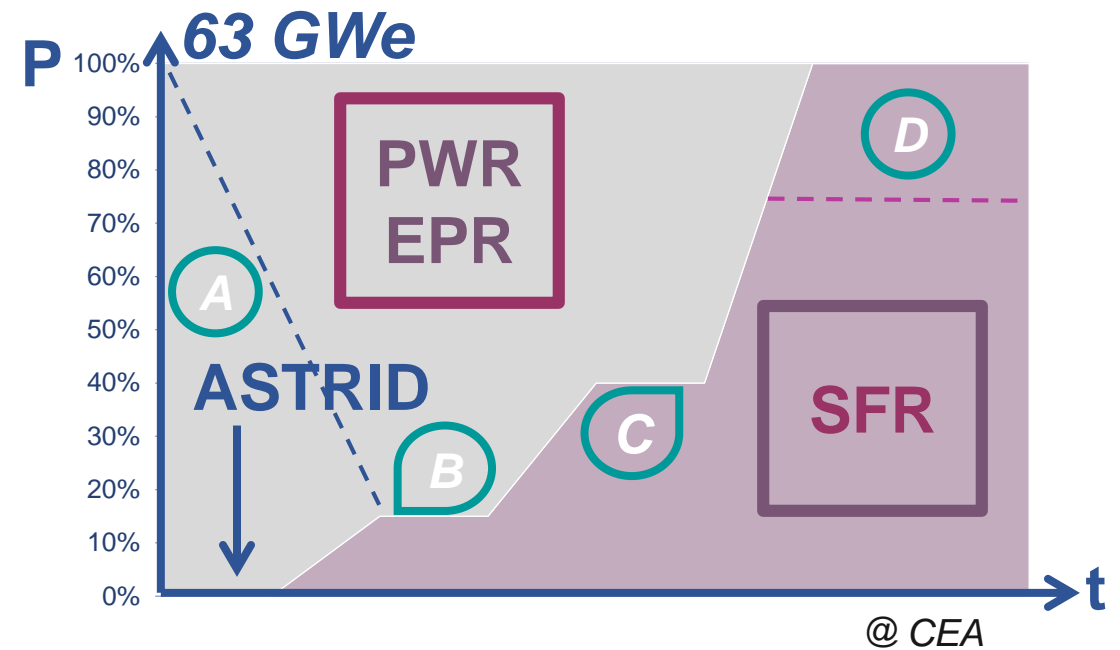
Introduction and motivations

- One of the French strategy
 - Transition towards a 100% SFR fleet
 - Development of innovative SFR-CFV
→ ASTRID design



Introduction and motivations

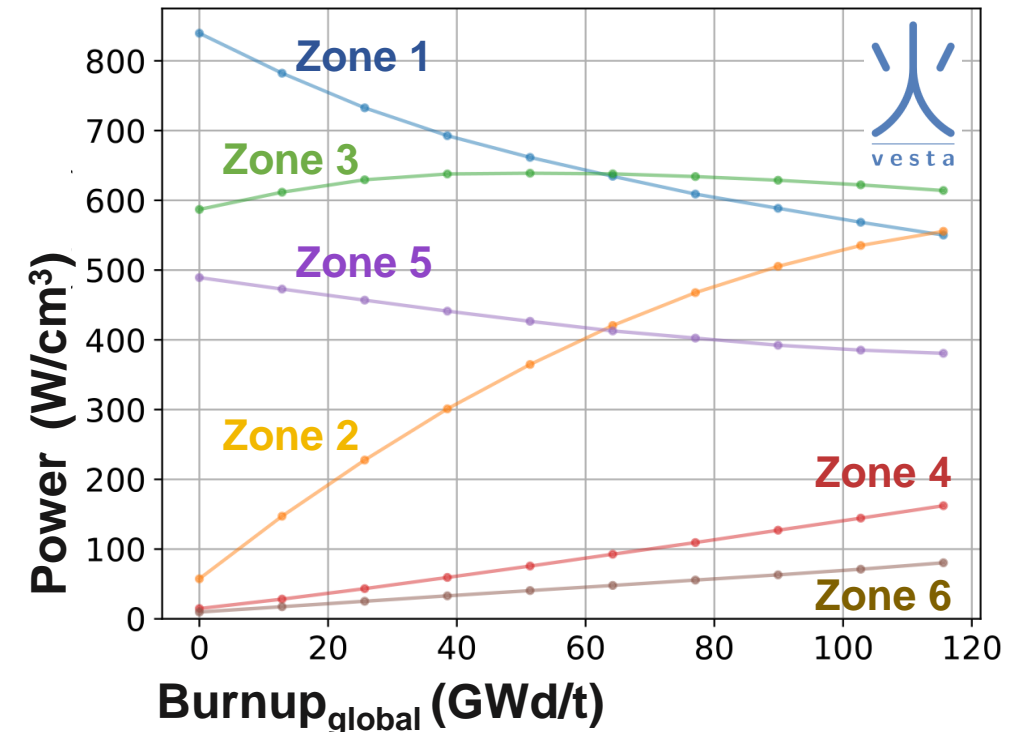
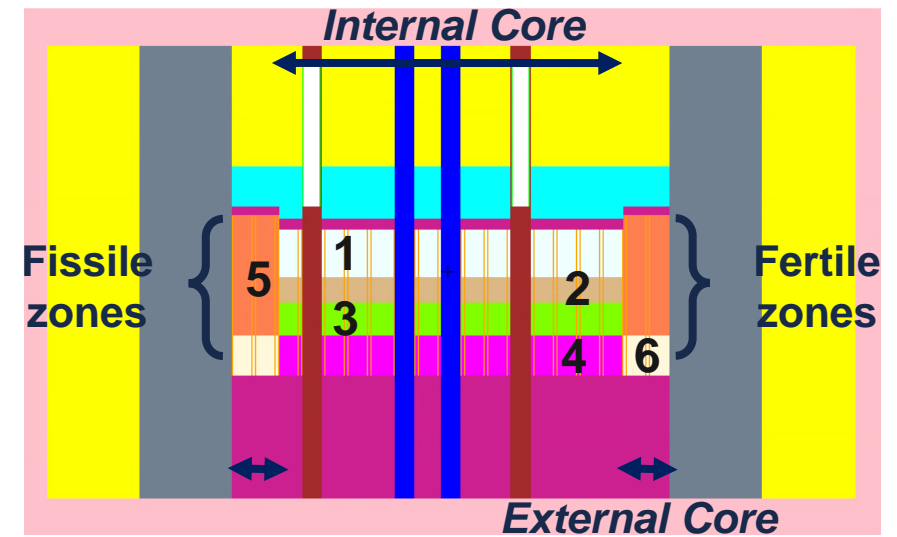
- One of the French strategy
 - Transition towards a 100% SFR fleet
 - Development of innovative SFR-CFV → ASTRID design
- Uncertain time frame
 - Deployment of SFRs after 2050?
- Questions raised
 - Plutonium status for the next decades?
 - Dynamic plutonium management with ASTRID-like reactors?



ASTRID-like reactor models

- 600 MW_e break-even design
O. Fabbris Ph.D. Thesis, CEA, 2014
- Heterogeneous core for low void effect
 - Geometrical characteristics → favor neutron leakage
 - 2 Pu contents for inner and outer zones

- Challenges: maintain the core heterogeneity & zone interactions
- Need: new multizone models in the CLASS code



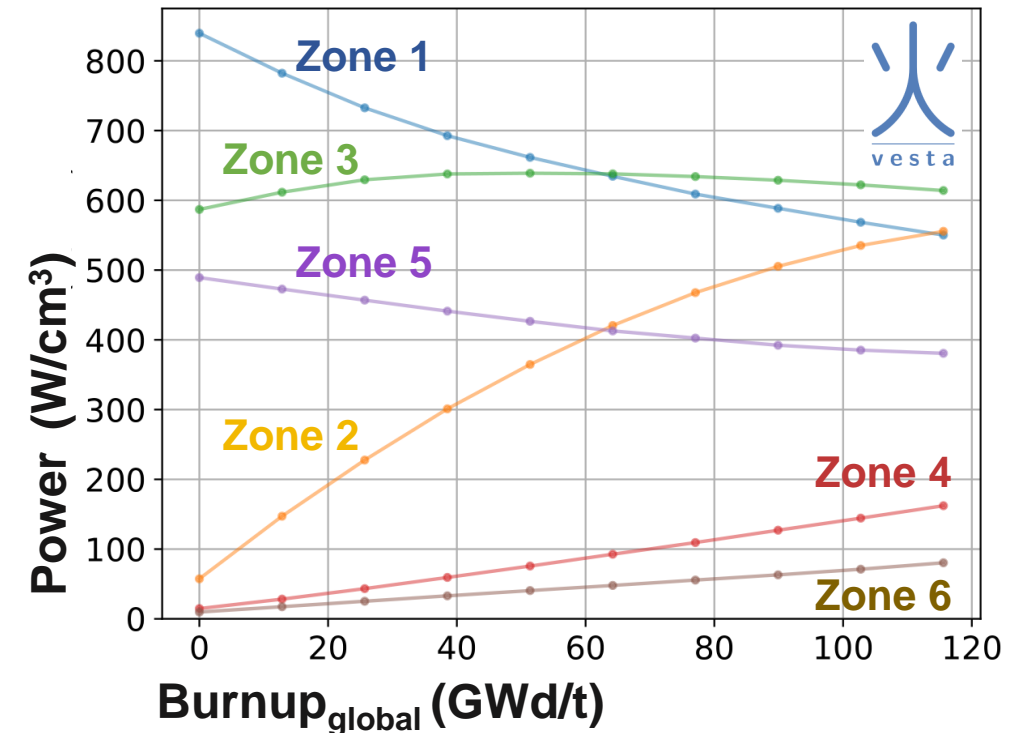
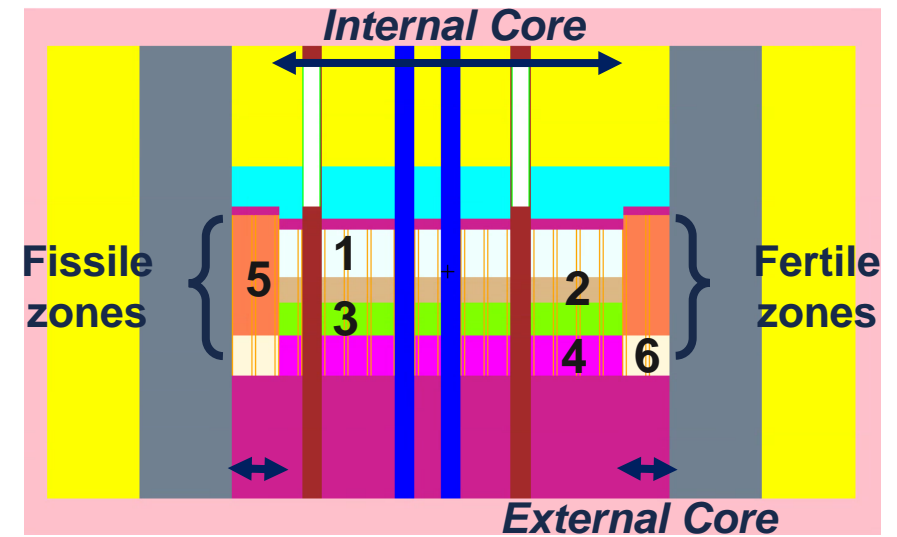
ASTRID-like reactor models

- Challenges in dynamic fuel cycle calculations

- *A priori* unknown fuels
- Fuel evolution maintaining the heterogeneity of the core

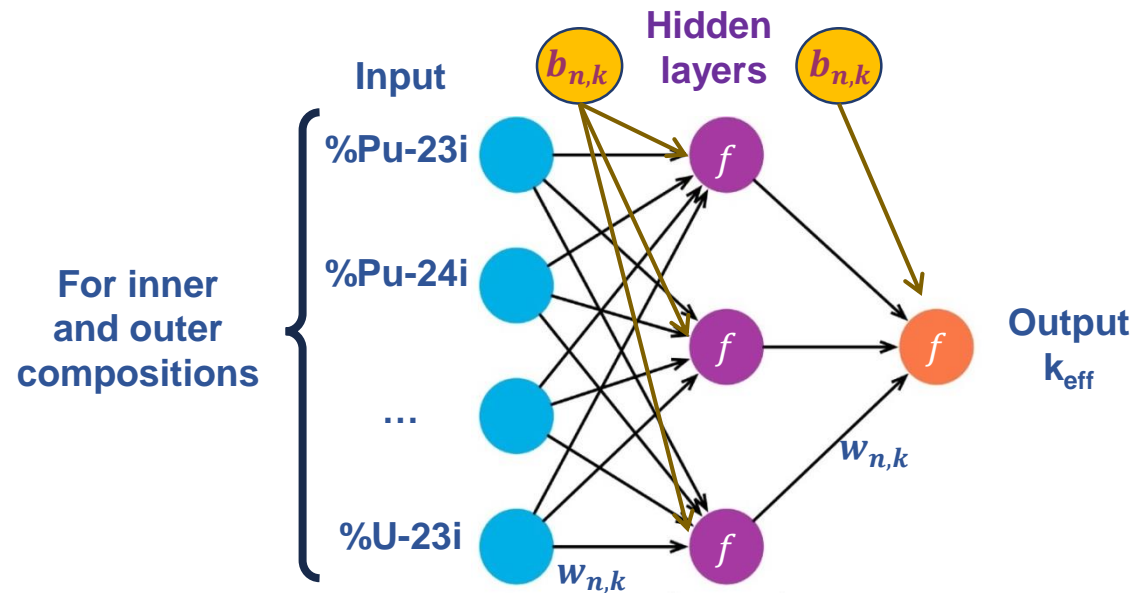
L. Tillard et al., ICAPP 2019

- Fuel evolution as a function of fresh fuel
 - EOC composition for each zone
- Fresh fuel fabrication adapted to available materials, considering 2 criteria
 - BOC criticality
 - Initial power distribution

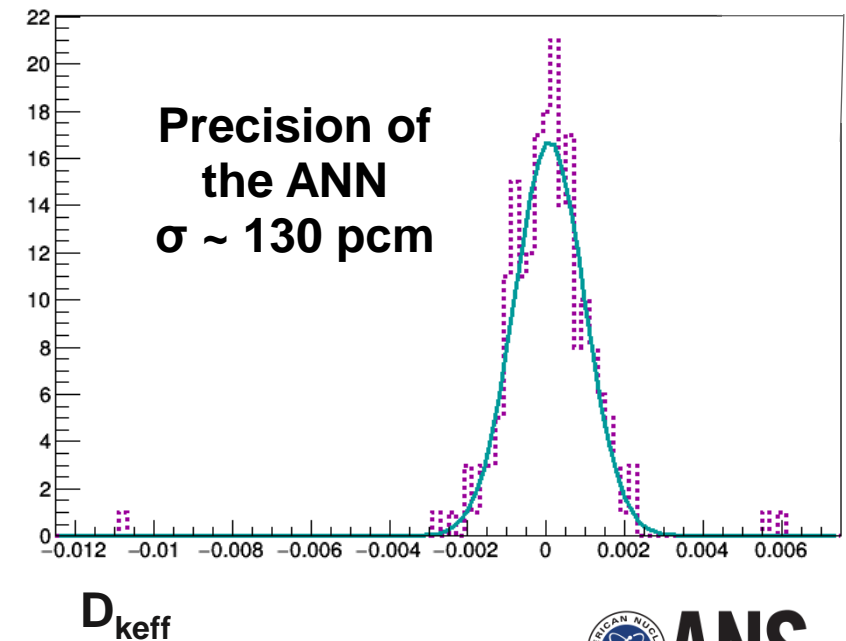
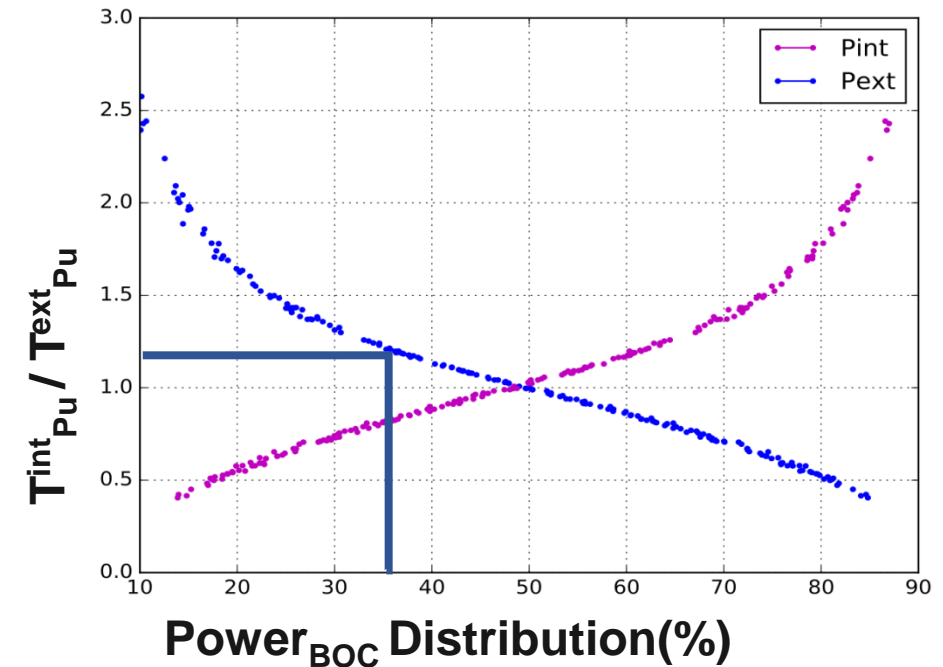


Multizone fuel fabrication model

- Pu enrichment ratio sets the power distribution in the reactor & *vice versa*
- k_{eff} prediction using Artificial Neural Networks based on fresh fuel compositions

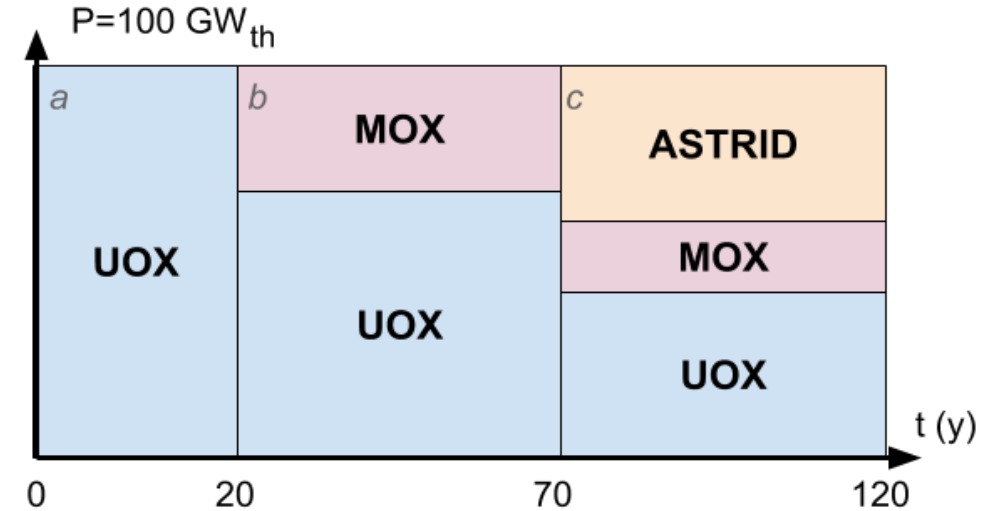


→ Accuracy close to Monte-Carlo simulations



Scenario definitions: goals and methods

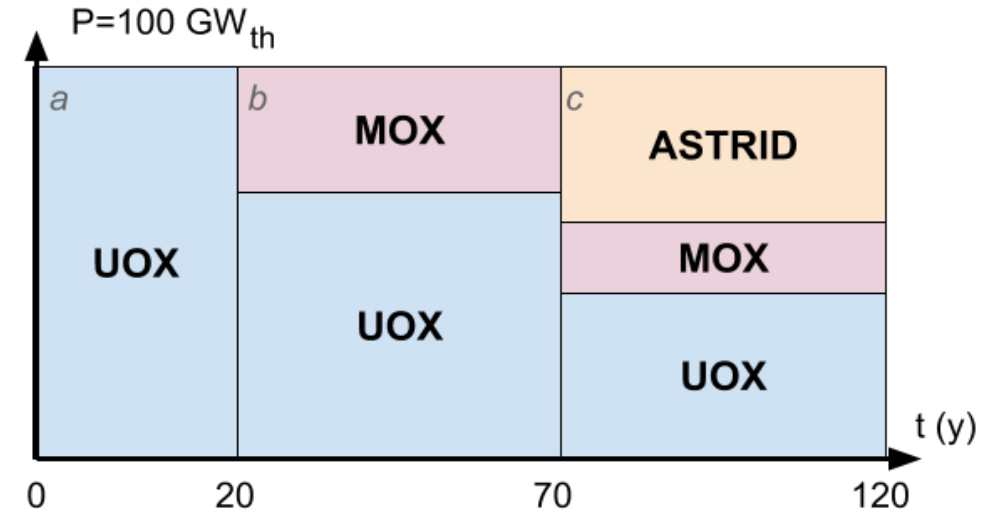
- Goals
 - *Observe* strategy impact on SFRs
 - *Understand* interactions between the reactors
 - *Identify* possible Pu shortage or other issues



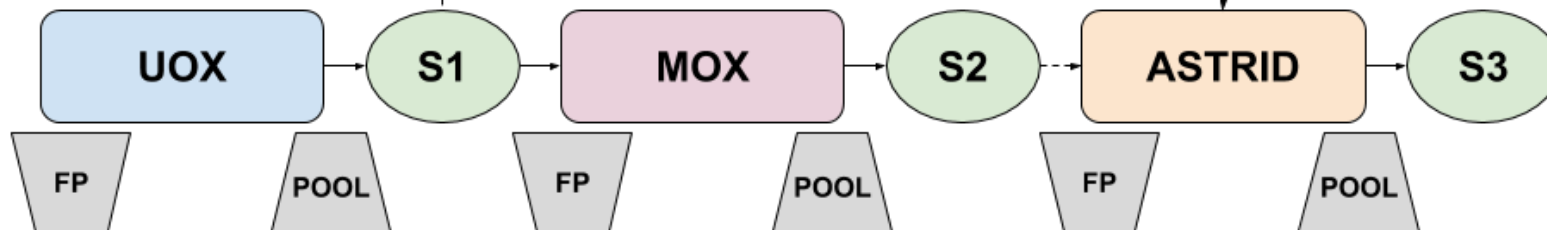
Scenario definitions: goals and methods

- Methods

- Wide parameter **sweeping methodology**
 - Identify parameters that may impact our evaluation criteria
 - Sample those parameters to quantify their mutual impacts
- Phase a&b with PWRs for an initial Pu inventory



Case A



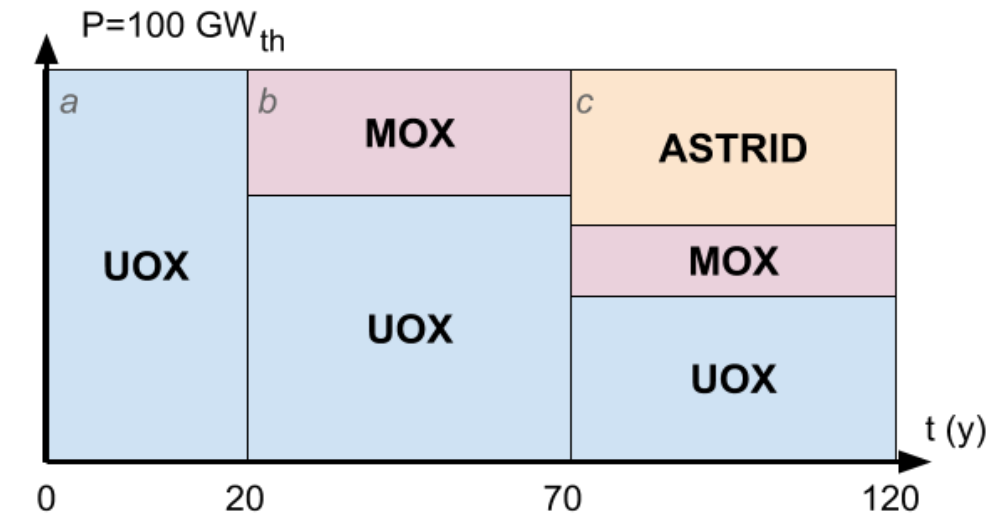
Sampling parameters:

- Number of ASTRID-like reactors
- PWR-UOX burnup
- MOX fraction for PWR
- Stock management (LIFO/FIFO)
- SFR cooling time
- Material flows

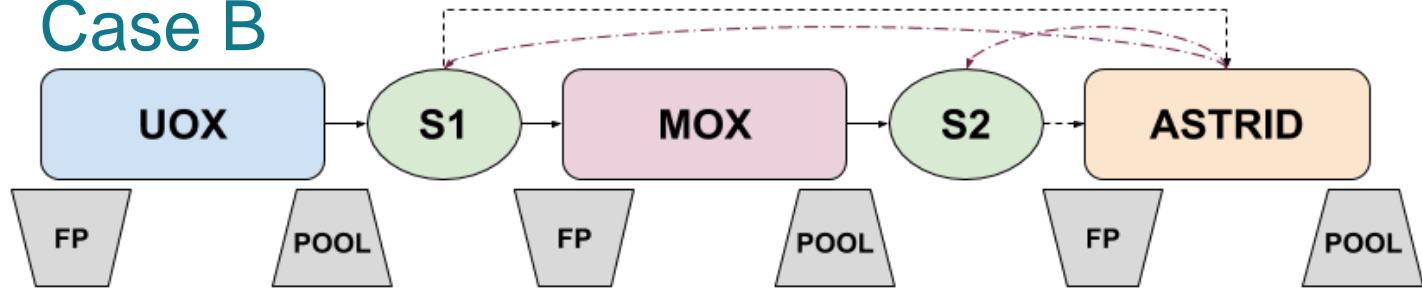
Scenario definitions: goals and methods

- Methods

- Wide parameter **sweeping methodology**
 - Identify parameters that may impact our evaluation criteria
 - Sample those parameters to quantify their mutual impacts
- Phase a&b with PWRs for an initial Pu inventory



Case B

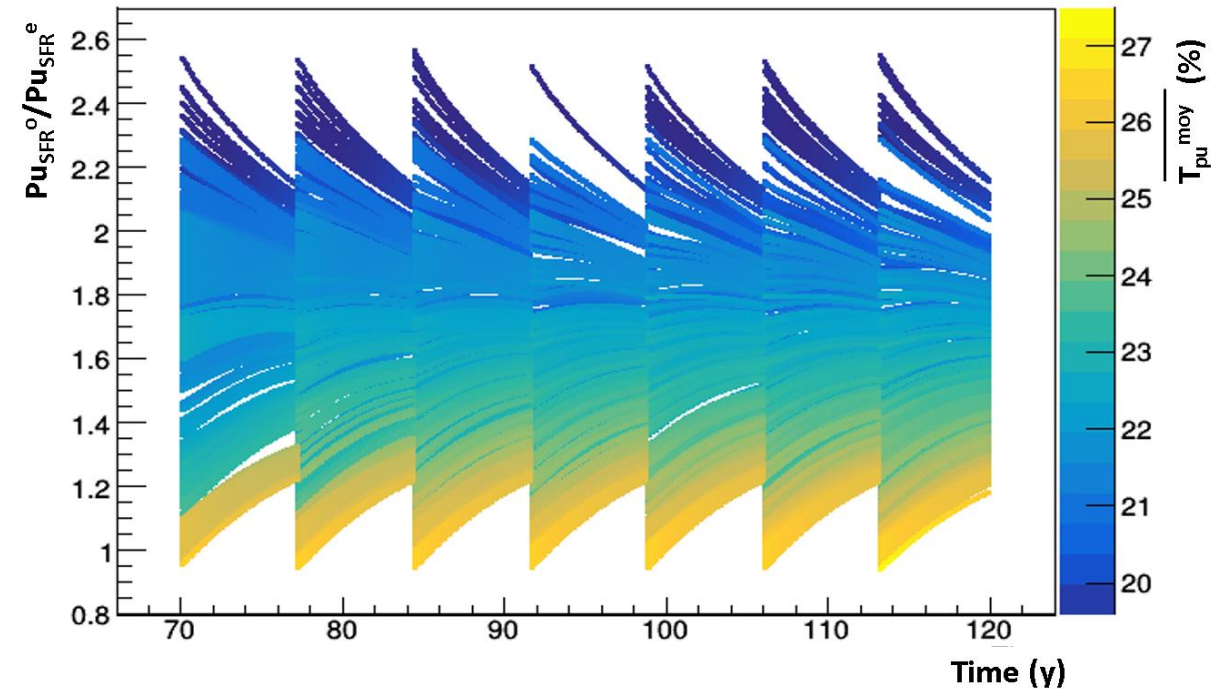
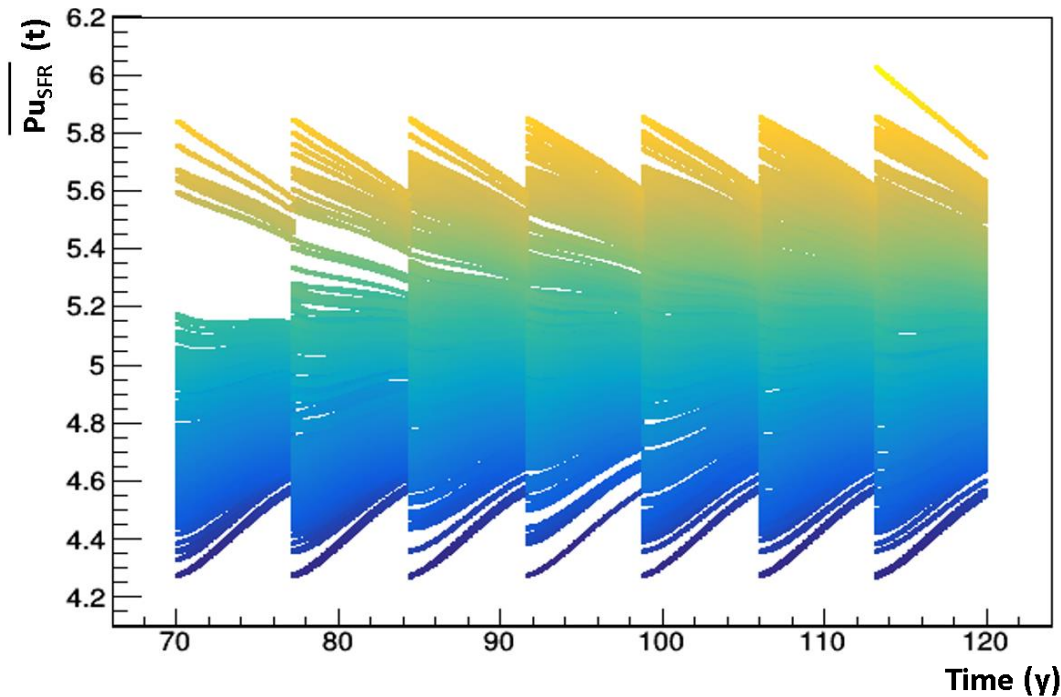


Sampling parameters:

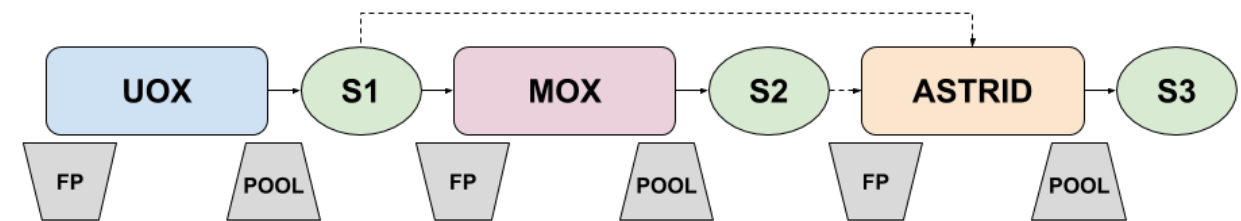
- Number of ASTRID-like reactors
- PWR-UOX burnup
- MOX fraction for PWR
- Stock management (LIFO/FIFO)
- SFR cooling time
- Material flows

Plutonium quantity and isotopic quality in SFRs

- Case A: SFR spent fuels are not reprocessed

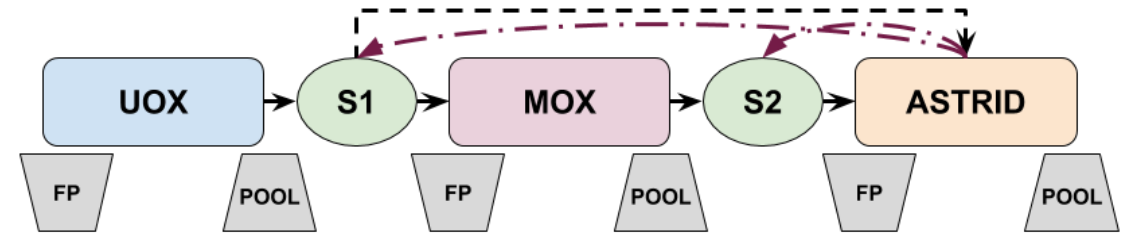
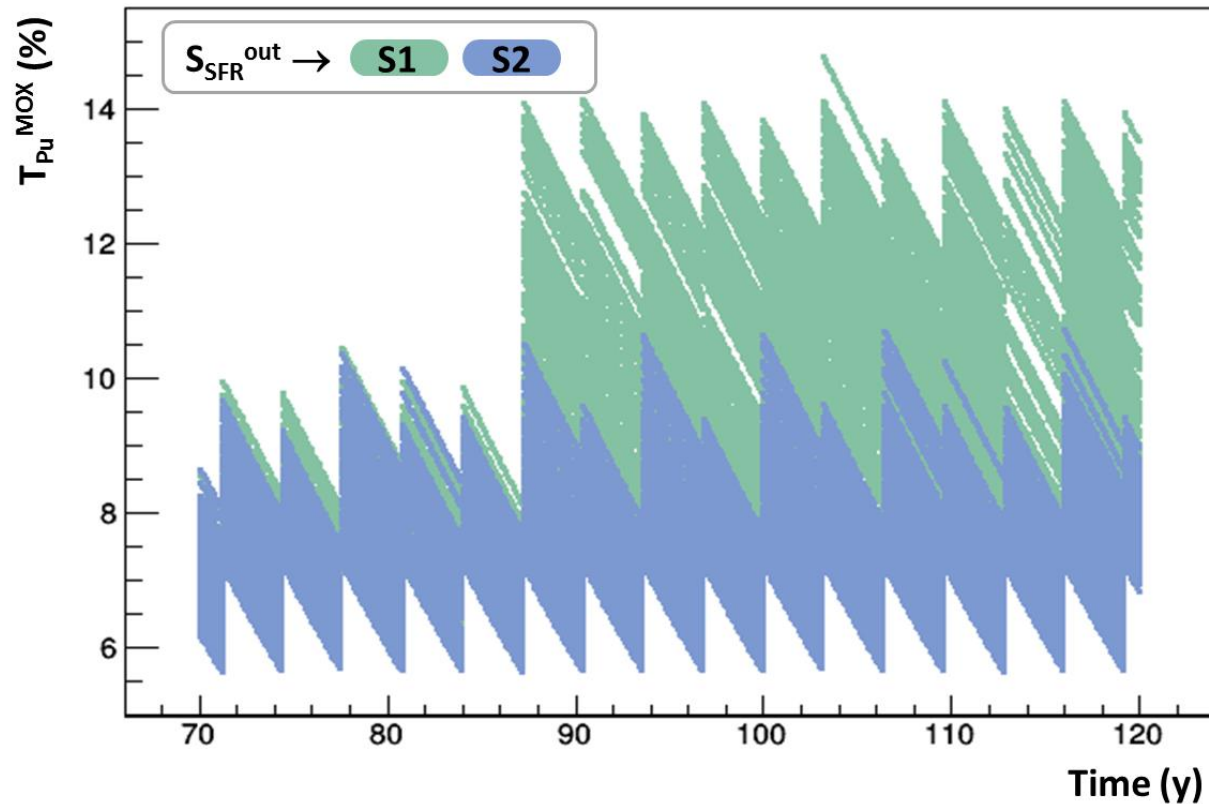


- SFR: Breeder or Burner depending on the Pu quality
- Isotopic quality & quantity in SFR tend to a steady-state value



Impact of SFR reprocessing on PWR fresh fuels

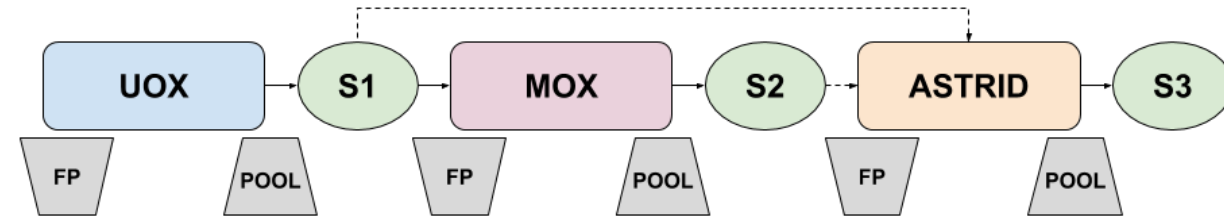
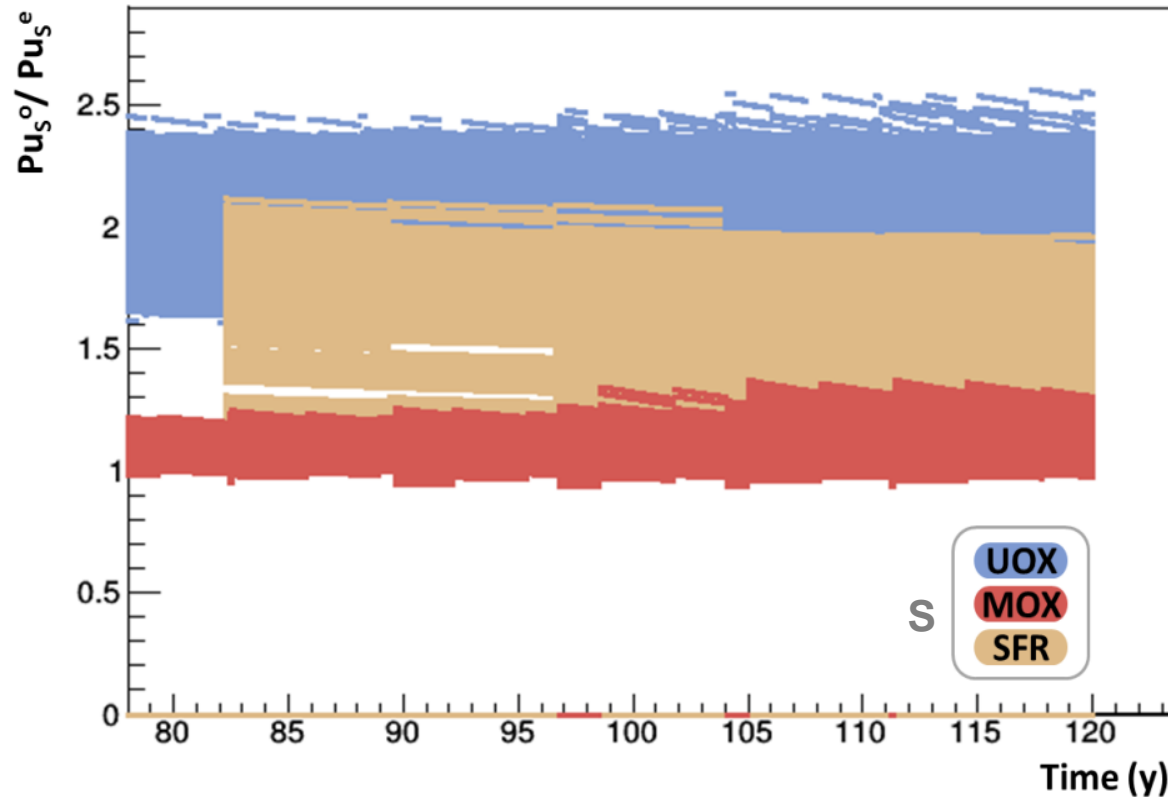
- Case B: SFR spent fuels are reprocessed for SFR or PWR-MOX fresh fuel



- Possible high plutonium enrichment in PWR-MOX fuel (> 12%)
- Due to Pu quality in SFR spent fuels?

Impact of SFR reprocessing on PWR fresh fuels

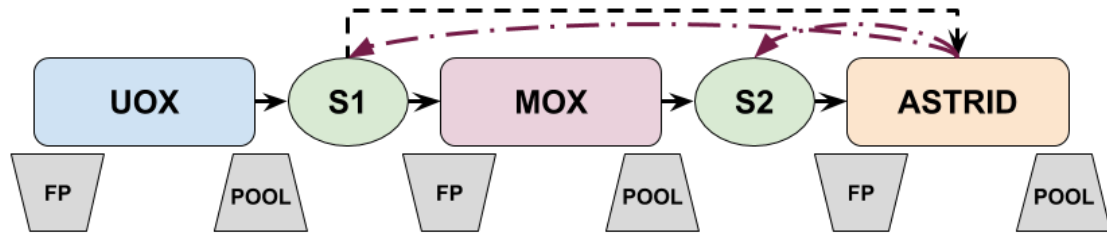
- Case A: SFR spent fuels are not reprocessed



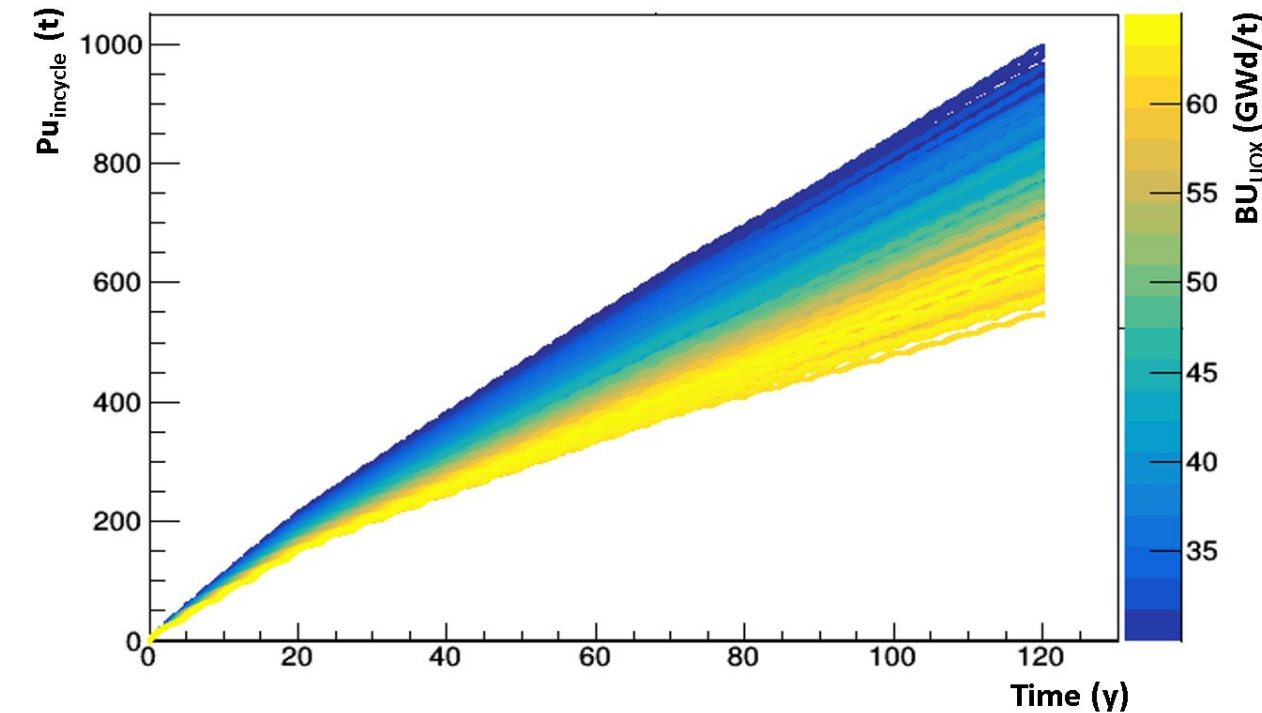
→ Pu from SFR spent fuels has often a lower quality than Pu from PWR-UOX spent fuels

Global in-cycle plutonium inventory

- Case B: SFR spent fuels are reprocessed for SFR or PWR-MOX fresh fuel



- Limited number of ASTRID-like reactors deployed (up to 20)
- No Pu stabilization



- PWR fleet are mainly **Pu breeder** and the introduction of some ASTRID-like reactors does not change the main behavior of the fleet
- A mixed fleet with such ASTRID-like reactors imposes a **high fraction of SFRs** to reach Pu stabilization

Conclusions and perspectives

- New models for ASTRID-like reactors have been implemented in the CLASS code → maintaining core heterogeneity & zone interactions
 - Fresh fuel construction
 - Fuel evolution modelling

Conclusions and perspectives

- New models for ASTRID-like reactors have been implemented in the CLASS code → maintaining core heterogeneity & zone interactions
 - Fresh fuel construction
 - Fuel evolution modelling
- Models have been used for scenario studies
 - Using the Wide Parameter Sweeping Methodology
 - The introduction of some ASTRID-like SFRs in the fleet does not allow to reach Pu stabilization
 - It involves some constraints on the reprocessing strategies for Pu multi-recycling

Conclusions and perspectives

- New models for ASTRID-like reactors have been implemented in the CLASS code → maintaining core heterogeneity & zone interactions
 - Fresh fuel construction
 - Fuel evolution modelling
- Models have been used for scenario studies
 - Using the Wide Parameter Sweeping Methodology
 - The introduction of some ASTRID-like SFRs in the fleet does not allow to reach Pu stabilization
 - It involves some constraints on the reprocessing strategies for Pu multi-recycling
- New models for a SFR burner design has been developed to study their potentialities for Pu management in mixed fleets



GLOBAL 2019

International Nuclear
Fuel Cycle Conference



TOP FUEL | 2019

Light Water Reactor Fuel Performance Conference



ANS Meetings



Thank you for your attention!

Sincere thanks to J.Clavel¹, X.Doligez², E.Dumonteil¹, M.Ernoult², J.Liang², N.Thiollière³

1. IRSN – Neutronics Laboratory

2. CNRS/IN2P3/Univ. Paris Sud – IPNO

3. CNRS/IN2P3/Univ. de Nantes – Subatech Laboratory

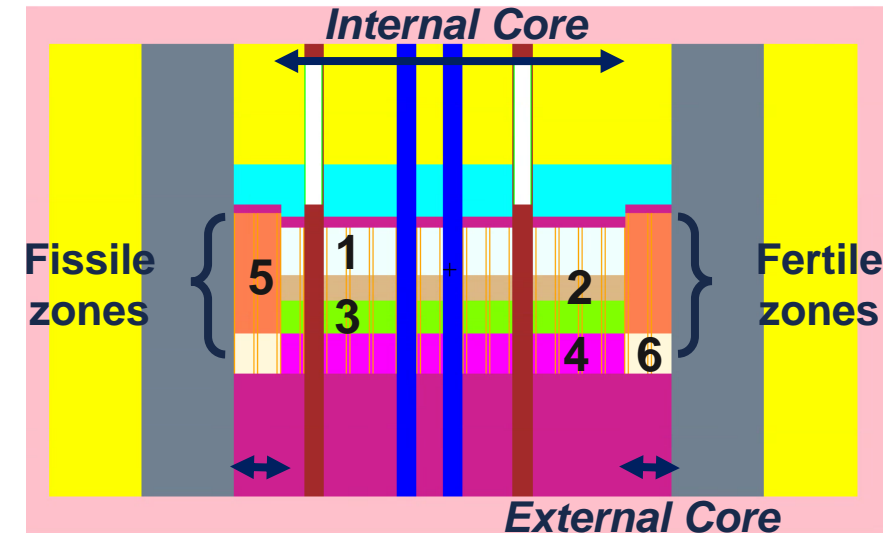


ASTRID-like modelling hypothesis

- Simulation hypothesis → for reactors studies and CLASS development



- VESTA-MCNP full core depletion calculations
- Full core loaded with fresh fuel
- 6 depletion zones: 3 fissile & 3 fertile zones
- 2 Pu enrichments for inner and outer zones
- Control assembly extracted



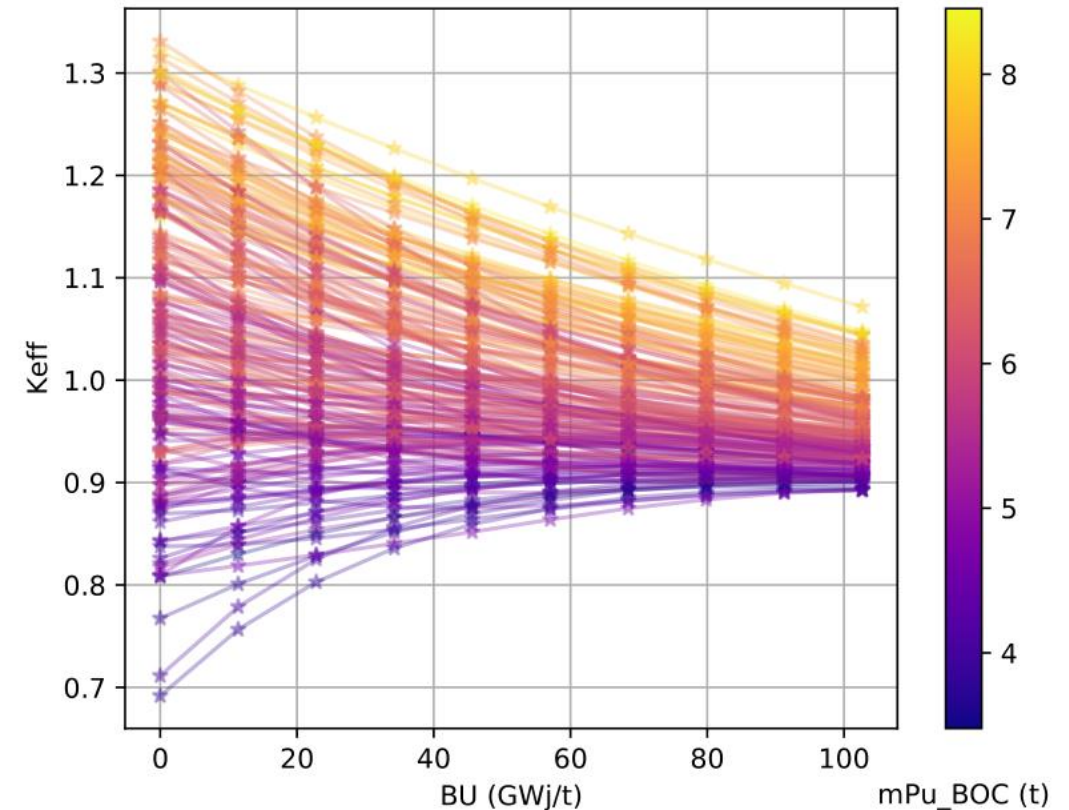
- Challenge: to maintain the core heterogeneity & zone interactions
- New physics models development in CLASS code

ASTRID-like data base

- 1000 depletion simulations with different fresh fuel compositions
 - VESTA-MCNP full core depletion calculations
 - Fuel choice: UOX & MOX fuel recycling → LHS sampling
 - Parameters: ^{238}Pu , ^{240}Pu , ^{241}Pu , ^{242}Pu , ^{241}Am , $T_{\text{Pu}_{\text{int}}}$ & $T_{\text{Pu}_{\text{ext}}}$

	Min	Max
T_Puint	15	40
T_Puext	15	40
B_Pu238	1	8
B_Pu240	20	40
B_Pu241	0	17
B_Pu242	5	17
B_Am241	0	15

Fuel i
 $k_{\text{eff}}(0), \dots, k_{\text{eff}}(T)$
 $\sigma(0), \sigma(1), \dots, \sigma(T)$
 $P(0), P(1), \dots, P(T)$
 $\phi(0), \phi(1), \dots, \phi(T)$
 $N(0), \dots, N(T)$

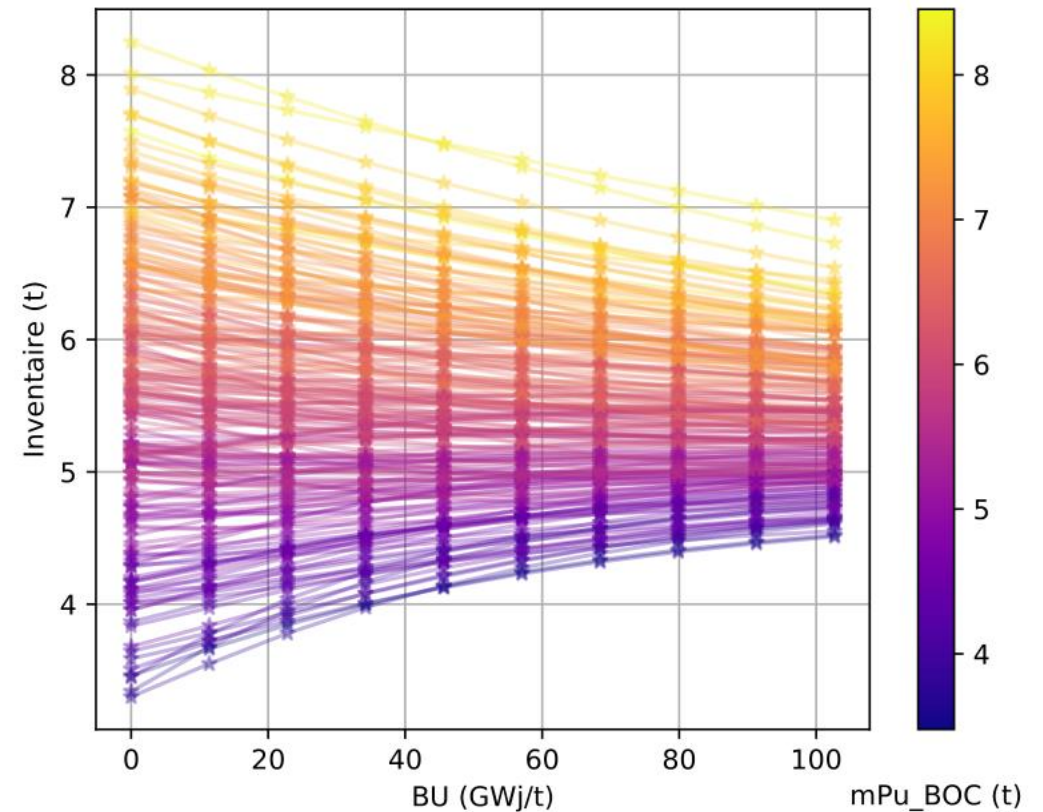


ASTRID-like data base

- 1000 depletion simulations with different fresh fuel compositions
 - VESTA-MCNP full core depletion calculations
 - Fuel choice: UOX & MOX fuel recycling
→ LHS sampling
 - Parameters: ^{238}Pu , ^{240}Pu , ^{241}Pu , ^{242}Pu , ^{241}Am , $T_{\text{Pu}_{\text{int}}}$ & $T_{\text{Pu}_{\text{ext}}}$

	Min	Max
T_Puint	15	40
T_Puext	15	40
B_Pu238	1	8
B_Pu240	20	40
B_Pu241	0	17
B_Pu242	5	17
B_Am241	0	15

Fuel i
 $k_{\text{eff}}(0), \dots, k_{\text{eff}}(T)$
 $\sigma(0), \sigma(1), \dots, \sigma(T)$
 $P(0), P(1), \dots, P(T)$
 $\phi(0), \phi(1), \dots, \phi(T)$
 $N(0), \dots, N(T)$



Multizone Fuel Irradiation Model

- **Input data:** Cycle time, initial fuel composition / depletion zone
- Bateman equations resolution **for each zone**

$$\frac{dN_{i,z}}{dt} = \underbrace{-\left(\lambda_i + \sigma_{i,r,z}\varphi_z\right)N_{i,z}}_{\text{Loss}} + \underbrace{\sum_{j \neq i} \left(\lambda_{j \rightarrow i} + \sigma_{j \rightarrow i,r,z}\varphi_z\right) N_{j,z}}_{\text{Production}}$$

*i Isotope
j Parent Isotope
r Reaction
z Zone*

- Decay constants (λ)
- Local cross-sections (σ) → **Cross-section predictor**
- Local flux (φ) → **Flux or Power predictor**
 - With

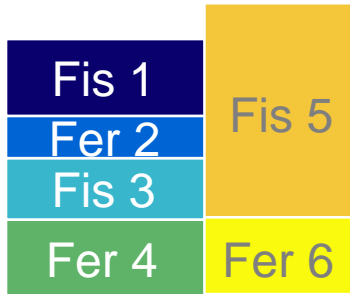
$$\varphi_z(t) = \sum_i \frac{P_z(t)}{\varepsilon_i^{fis} \times \sigma_{i,z}^{fis}(t) \times N_{i,z}(t)}$$

$$P_{tot} = \sum_z P_z(t)$$

- Predictors: ANN generation
 - Generation database: 1000 depletion calculations
 - Parameters: time, zone number, fissile fresh fuel compositions

Multizone Fuel Irradiation Model

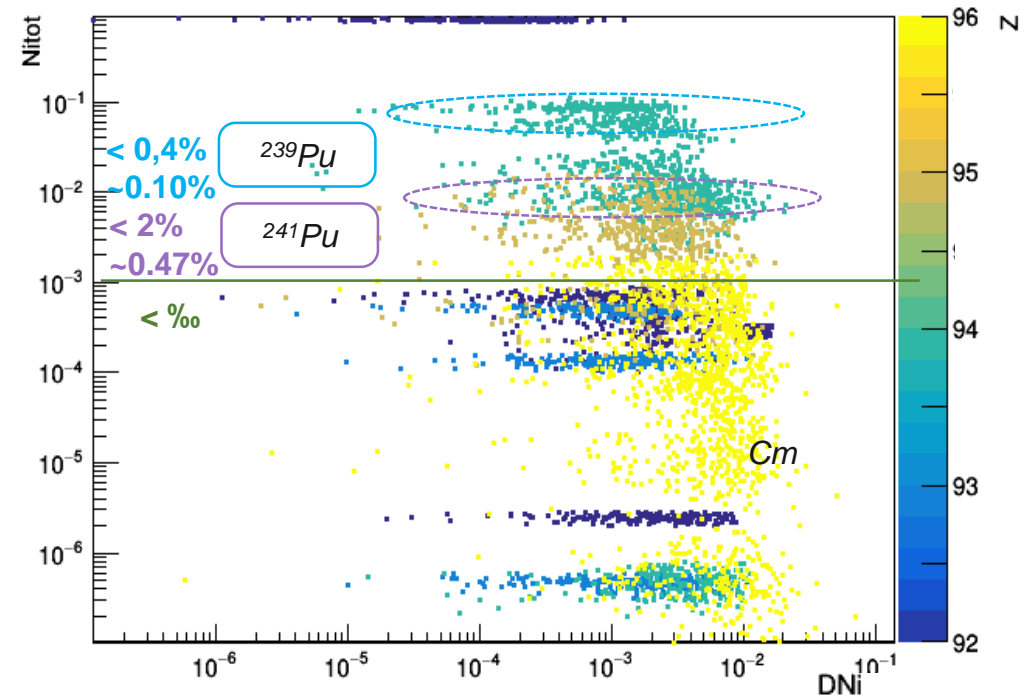
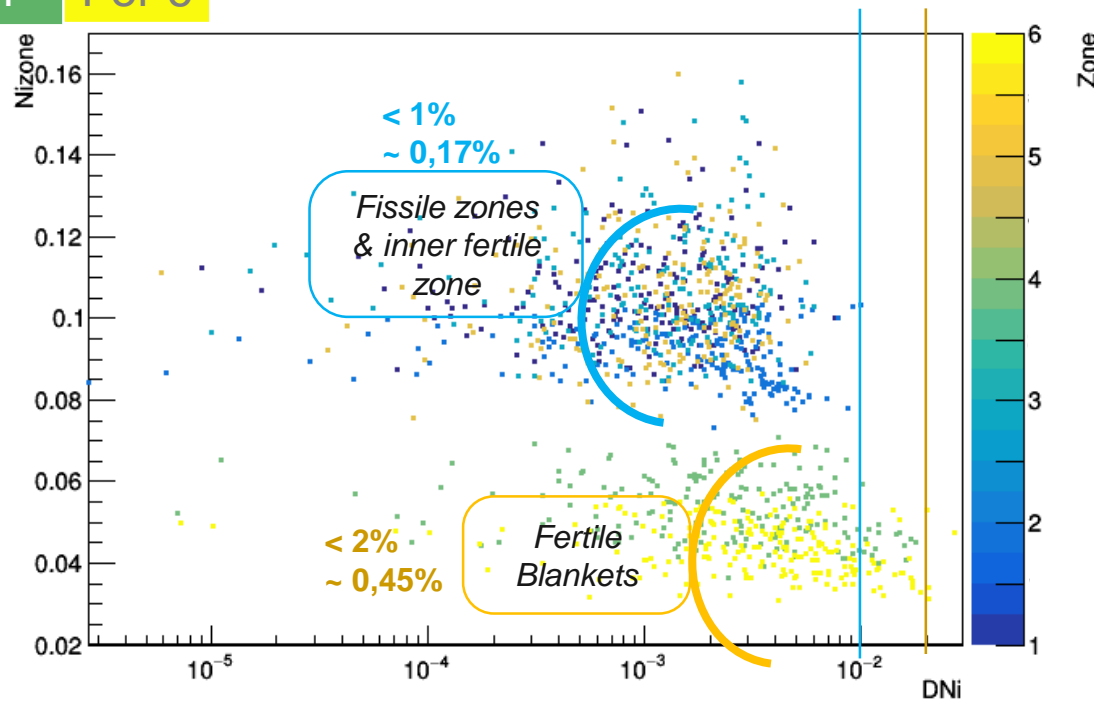
- Deviation induced on inventory estimation at EOC



$$DN_i = \left| \frac{N_i^{VESTA} - N_i^{CLASS}}{N_i^{VESTA}} \right|$$

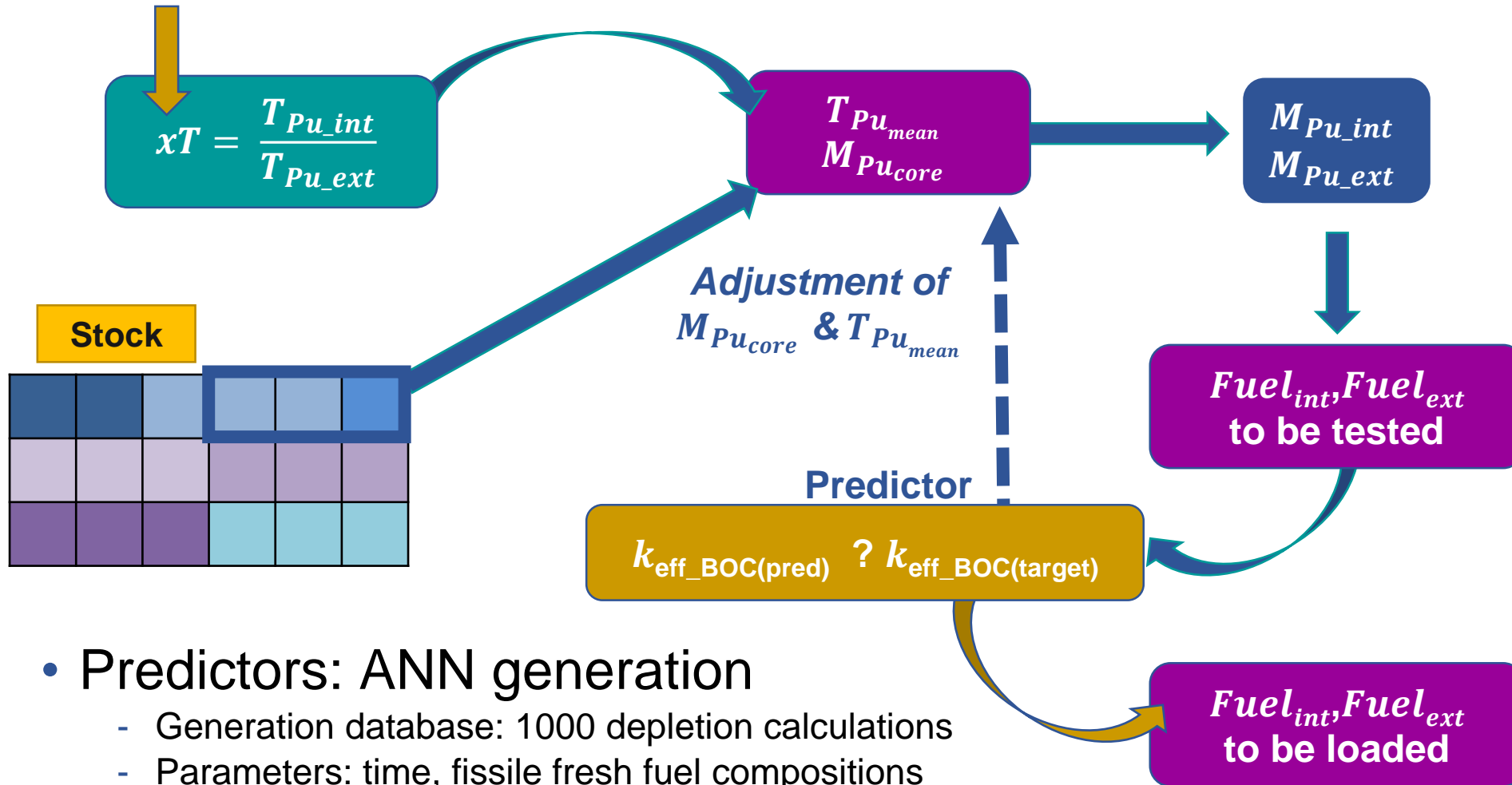
- Local inventory: ^{239}Pu

- Global inventory: Minor actinides



Multizone Fuel Fabrication Model

- $P_{z(\text{target})}$ & $k_{\text{eff_BOC}(\text{target})}$ → User choice



- Predictors: ANN generation
 - Generation database: 1000 depletion calculations
 - Parameters: time, fissile fresh fuel compositions

Multizone Fuel Fabrication Model

$$x_T = \frac{T_{Pu_int}}{T_{Pu_ext}}$$

$$x_M = \frac{M_{int}}{M_{ext}}$$

$$T_{Pu_mean} = \frac{T_{Pu_int}M_{int} + T_{Pu_ext}M_{ext}}{M_{int} + M_{ext}}$$

$$T_{Pu_ext} = T_{Pu_mean} \times \frac{M_{int} + M_{ext}}{x_T M_{int} + M_{ext}}$$

$$T_{Pu_int} = x_T \times T_{Pu_ext}$$

$$M_{Pu_core} = T_{Pu_mean} \times M_{core}$$

$$M_{Pu_int} = M_{Pu_core} \times \frac{x_M x_T}{1 + x_M x_T}$$

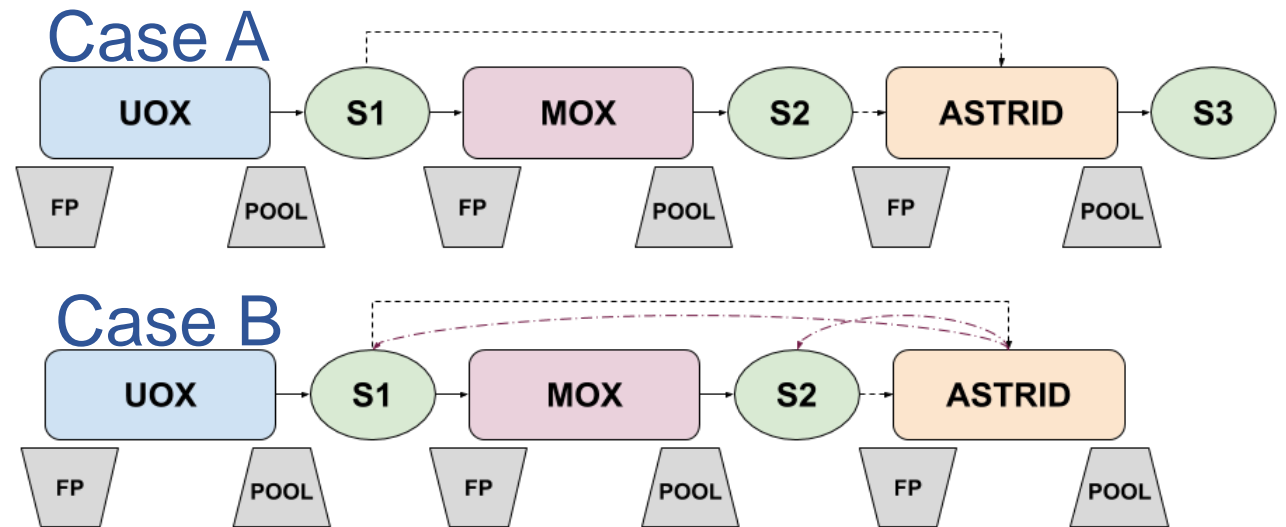
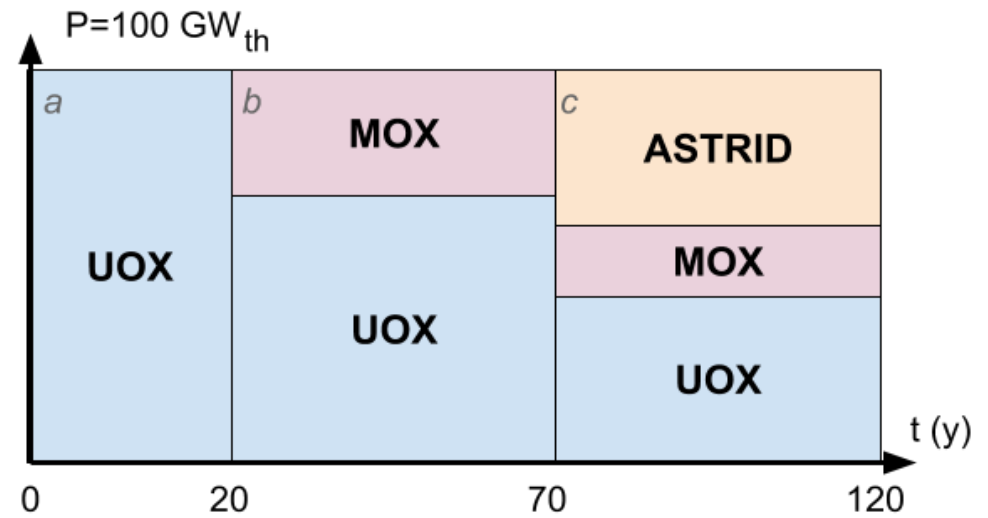
$$M_{Pu_ext} = M_{Pu_core} \times \frac{1}{1 + x_M x_T}$$

Scenario definitions

- Fixed parameters
 - Constant power
 - 3 phases: 20y, 50y, 50y
 - Ratio F_{MOX}/F_{UOX} constant (phase b&c)
 - BU_{SFR} 100GWd/t, BU_{MOX} 42GWd/t
 - SM_{MOX} LIFO ...

- Sample parameters
 - BU_{UOX} [30;60] GWd/t
 - F_{MOX} [5;15] %
 - N_{SFR} [0;20]
 - SM [LIFO;FIFO]
 - TC_{SFR} [5;10] y
 - Material flows

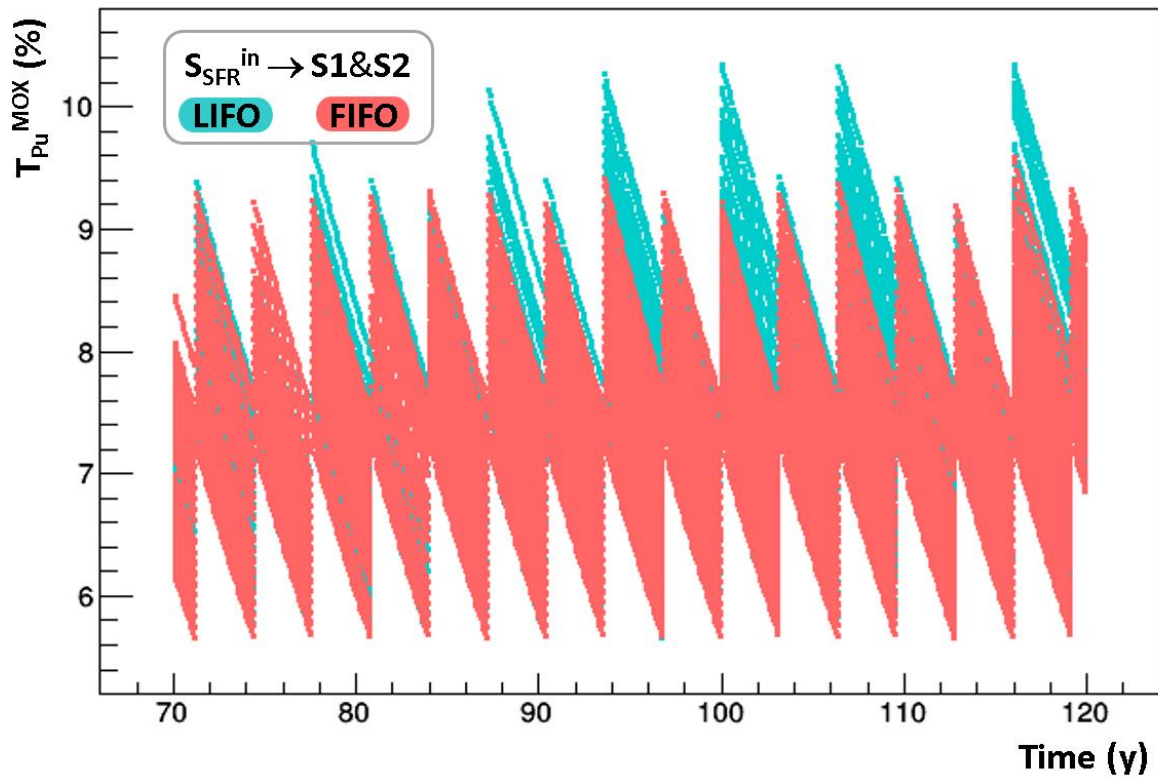
- Main output
 - Plutonium quality
 - Plutonium quantity
 - Plutonium contents ...



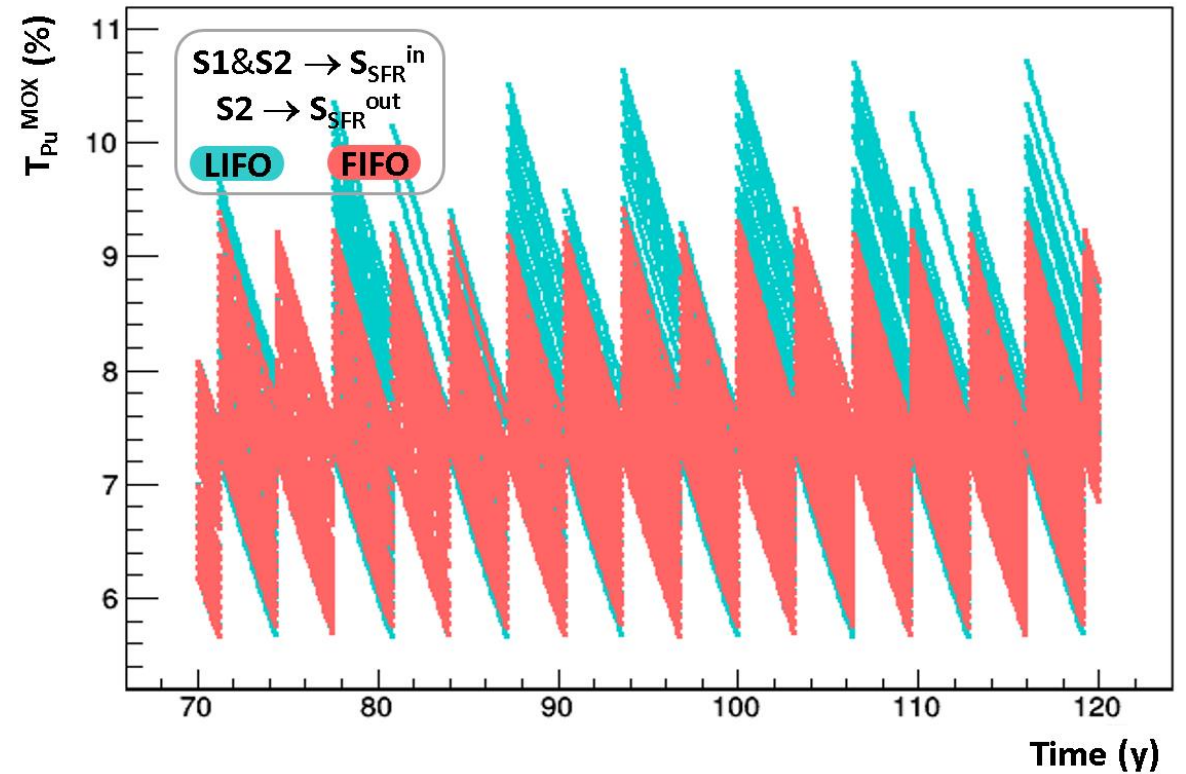
$$Q = \frac{N_{239Pu} + N_{241Pu}}{N_{238Pu} + N_{240Pu} + N_{242Pu}}$$

Impact of stock feeding SFR fab. plant on PWR fresh fuels

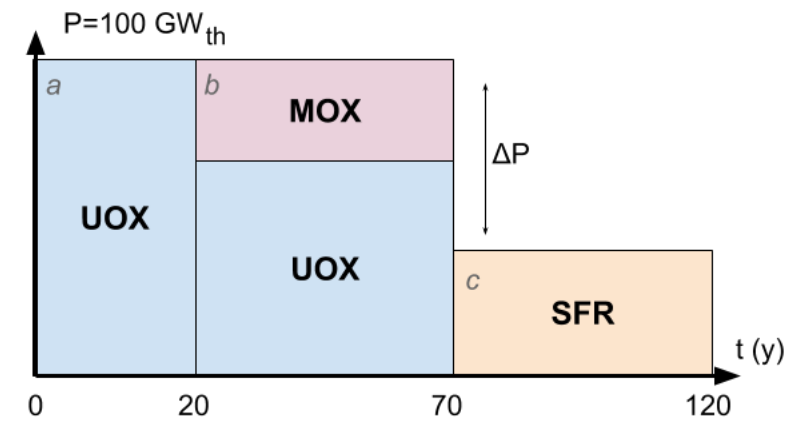
- Case A



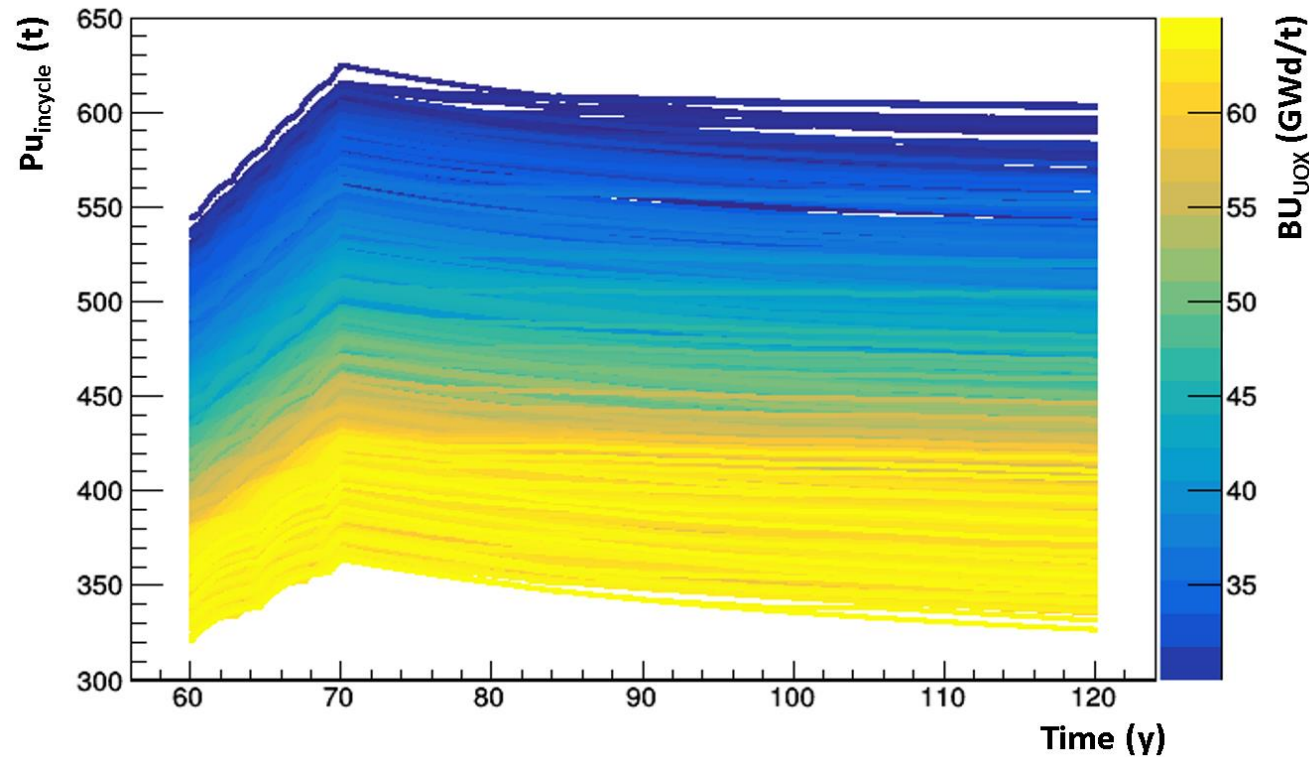
- Case B



Pu stabilization with a 100% SFR fleet



- In-cycle Plutonium



- Plutonium outside reactors

