IRSN
INSTITUT
DE RADIOPROTECTION
ET DE SÛRETÉ NUCLÉAIRE

Faire avancer la sûreté nucléaire

Multi-zone fuel irradiation model for ASTRID-like SFR with the CLASS code

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on Fuel Cycle Simulation

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Léa Tillard, Ph.D. Student
lea.tillard@irsn.fr
Dr. Jean-Baptiste Clavel
Dr. Eric Dumonteil

Outline

Context & Objectives of the study

Multi-zone Fuel Irradiation Model

Multi-zone cross-sections Predictor

Impact of using a Power Predictor or a Flux Predictor on fuel composition estimation

Conclusion & Perspectives

Context

- Uncertain placement of nuclear power in the future french energy mix
    - Energy Transition Act, political & scientific discussions

- Uncertain strategy of reactor fleet renewal
    - Extension of the PWR fleet
    - Deployment of new SFR-CFV *(low void effect)*
      (Reference Strategy, CEA Report, 2015)

- Uncertain Pu status: waste or valuable fuel for a future SFR fleet
    - *One waiting strategy*: stabilization of Pu inventory in cycle thanks to **Pu multi-recycling**
        - PWR (e.g. with MOXEUS fuel[1], ...)
        - **ASTRID-like reactors**: breeder, isogenerator, burner

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1. Study of plutonium incineration in PWR loaded with MOX on enriched uranium support with the fuel cycle simulator CLASS by Fanny COURTIN (Ph.D. Thesis)

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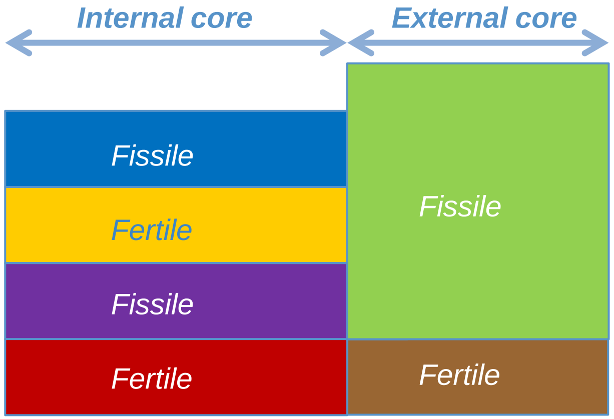
➚ Possibilities for Pu in cycle dynamic management with SFR-CFV?

[1] *Study of plutonium incineration in PWR loaded with MOX on enriched uranium support with the fuel cycle simulator CLASS by Fanny COURTIN (Ph.D. Thesis)*

Objectives

- Pu isogenerator ASTRID-like SFR-CFV **heterogeneous core** design
  (shape, fissile & fertile fuel zones)

- For one Cycle time & one fresh fuel composition: each zone as a really **different behavior**
  - E.g. at EOC: the inner fertile zone acts like an inner fissile zone



Sectional view of ASTRID-like reactor

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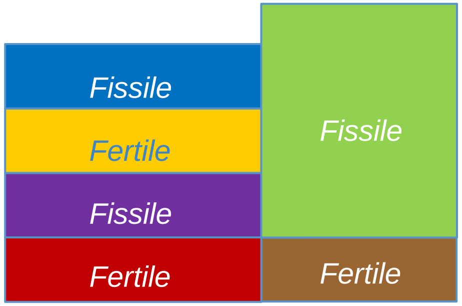

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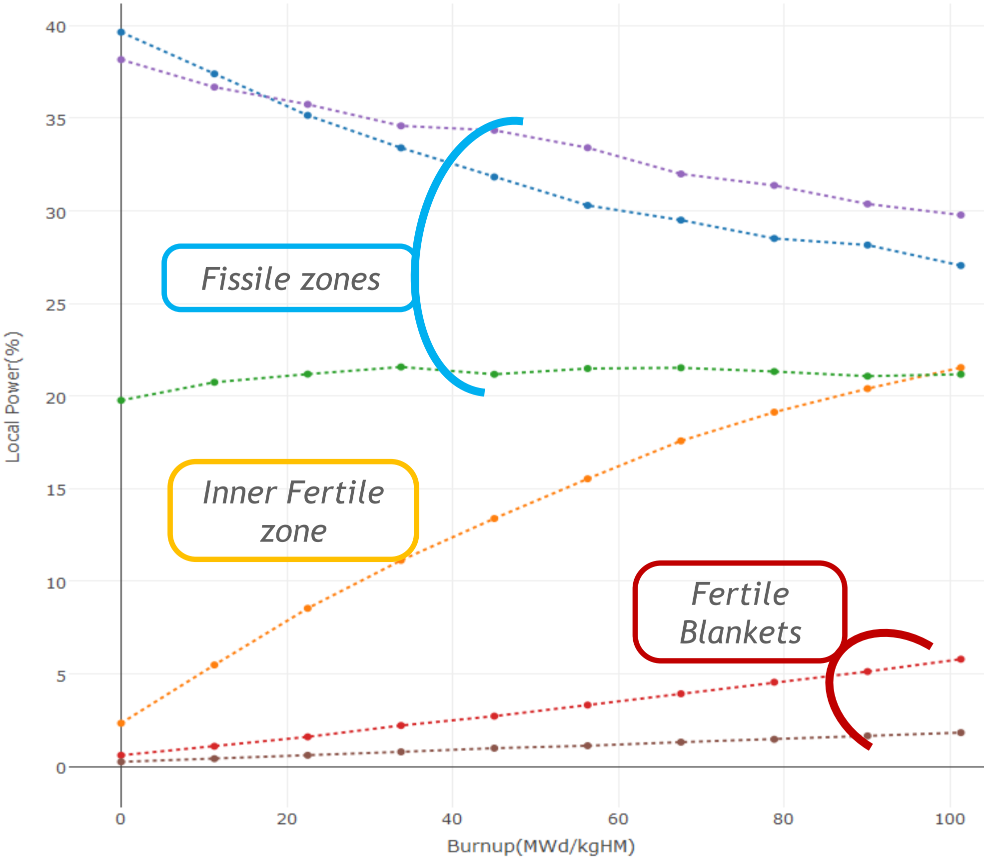

Evolution of Local Powers during irradiation

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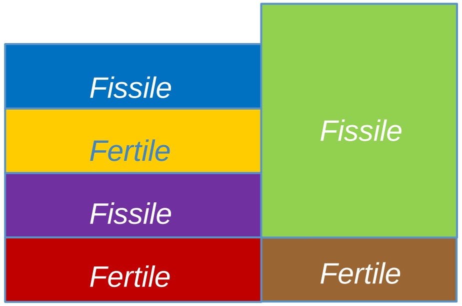

Sectional view of ASTRID-like reactor

- For one Cycle time & one fresh fuel composition: each zone as a really **different behavior**
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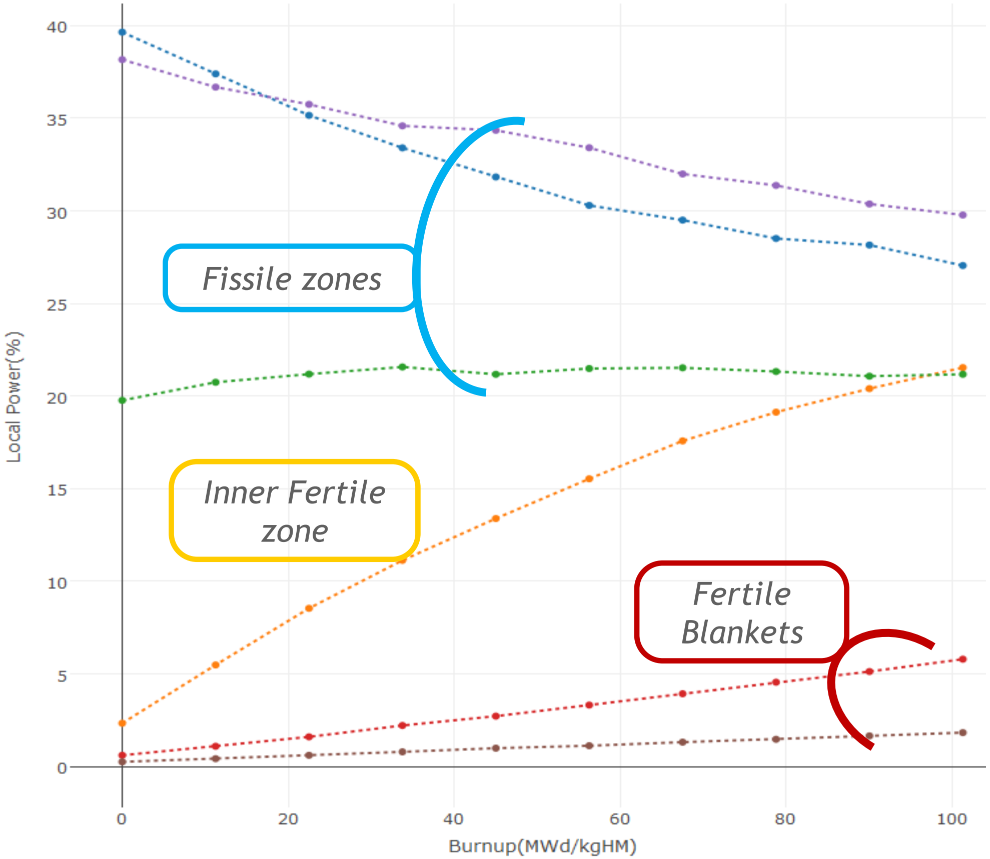
↗ **How to maintain the reactor heterogeneity during the fuel irradiation while keeping interactions between the fuel zones?**



Evolution of Local Powers during irradiation

Multi-zone Fuel Irradiation Model

- Cycle time, initial fuel composition of each evolutive zone
  → ***input data***
- Bateman equations resolution **for each zone**

$$\frac{dN_i}{dt} = \underbrace{-(\lambda_i + \sigma_i \varphi)N_i}_{\text{Loss}} + \underbrace{\sum_{j \neq i} \left(\lambda_{j \to i} + \sigma_{j \to i}\varphi\right) N_j}_{\text{Production}}$$

i Isotope
j Parent Isotope
k zone

  - Decay constants (λ)
  - Local cross-sections (σ) calculations → ***a XS Model***
  - Local flux (φ): **from a specific power calculation** → ***a Power Model***
    - With $P_{tot} = \sum_k P_k(t)$ $\qquad$ $\varphi_k(t) = \sum_i \frac{P_k(t)}{\varepsilon_i{}^{fis} \times \sigma_{i,k}{}^{fis}(t) \times N_{i,k}(t)}$

Multi-zone Fuel Irradiation Model

- Cycle time, initial fuel composition of each evolutive zone
  → ***input data***

- Bateman equations resolution **for each zone**

$$\frac{dN_i}{dt} = -(\lambda_i + \sigma_i \varphi) N_i + \sum_{j \neq i} \left(\lambda_{j \to i} + \sigma_{j \to i} \varphi\right) N_j$$

i Isotope
j Parent Isotope
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- Scenario simulation with the code CLASS
  - New dedicated model for **fuel irradiation in multi-zone reactors**
    - Generally: homogeneous fuel ↝ approximation
    - 6 independant fresh fuel compositions: depletion over time and per zone
    - 2 predictive models based on Artificial Neural Networks *(ANN)*

Core Library for Advanced Scenario Simulation

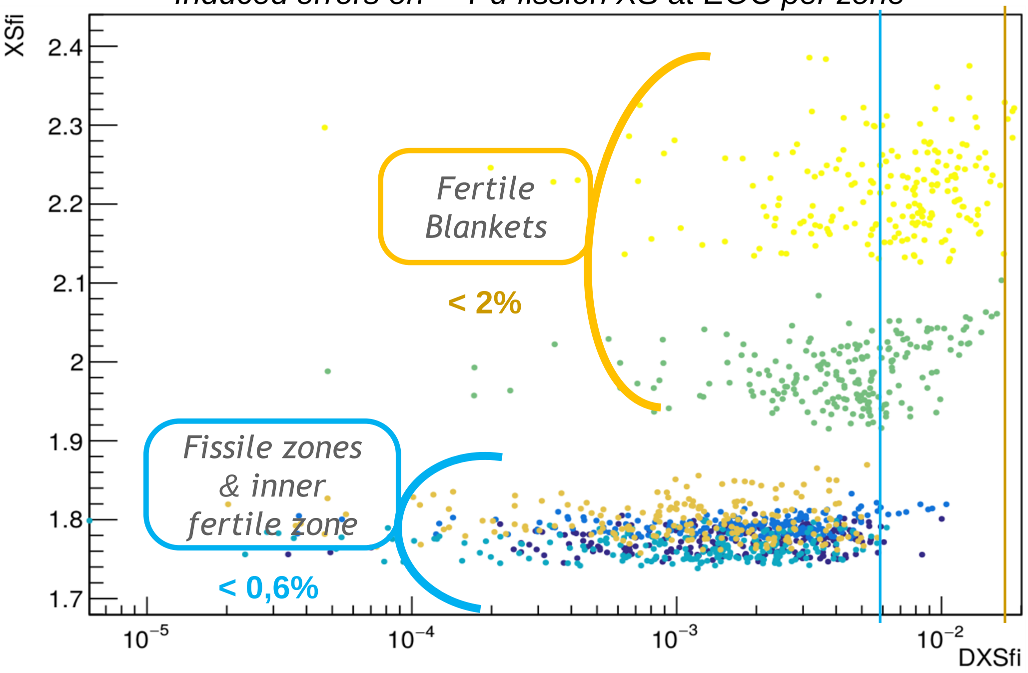
Multi-zone cross-sections predictor

- XS Model: training on **full core** depletion simulations
  - Zone number is an ANN new input parameter: ***space discretization***

- Predictor accuracy verification
  - Example of $XS_{fission}$ (barn) ^{239}Pu per zone
  - $DXS_{fi} = \left|\frac{XS_{fi}^{VESTA} - XS_{fi}^{CLASS}}{XS_{fi}^{VESTA}}\right|$ at ~100 GWd/t

- **$Errors_{fertiles}$ > $Errors_{fissiles}$**
- **Induced errors by multi-zone XS_f predictors < 2%**
- **Direct impact of XS_f on flux calculation**

Induced errors on ^{239}Pu fission XS at EOC per zone



Fertile Blankets

< 2%

Fissile zones & inner fertile zone

< 0,6%

Local power predictor

- <u>Local power Model</u>: training on **full core** depletion simulations
  - Zone number is an ANN new input parameter: ***space discretization***
  - ***Constraint on local power:*** $P_{tot} = \sum_k P_k(t)$

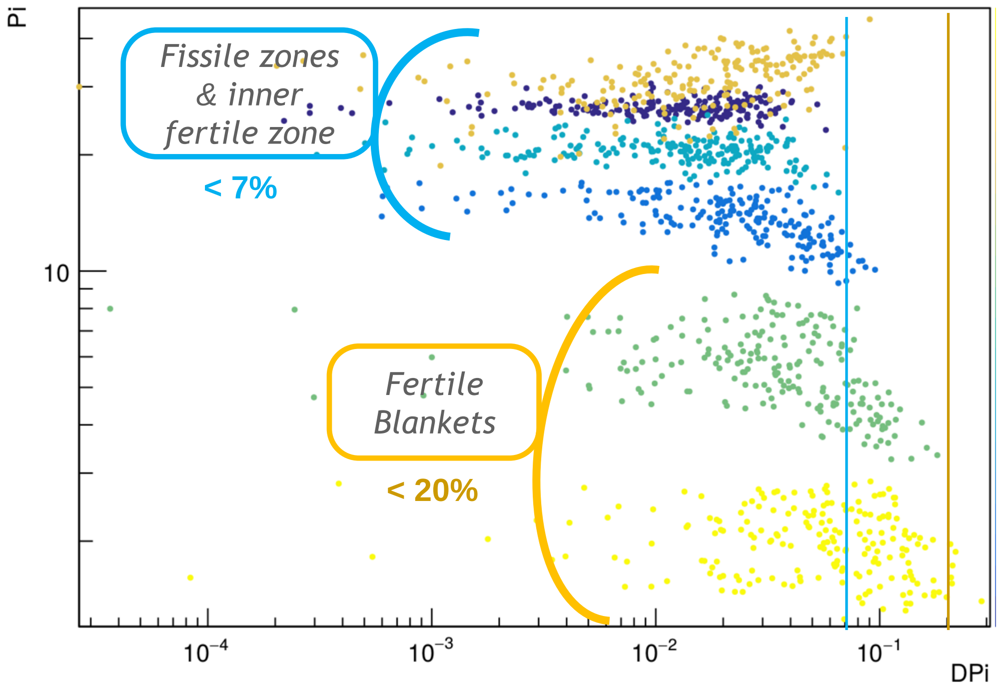
- Predictor accuracy verification
  - Pi: %power per zone
  - $DP_i = \left| \frac{P_i^{VESTA} - P_i^{CLASS}}{P_i^{VESTA}} \right|$ at ~100 GWd/t

↗ **Induced error < 20%**

↗ **Direct impact on flux & composition per zone**

↗ **Important errors in fertile blankets but lower %power so lower impact on global inventories** *(<10% for Pu_i)*

Induced errors on local power at EOC per zone



Fuel composition estimation with a Power Model

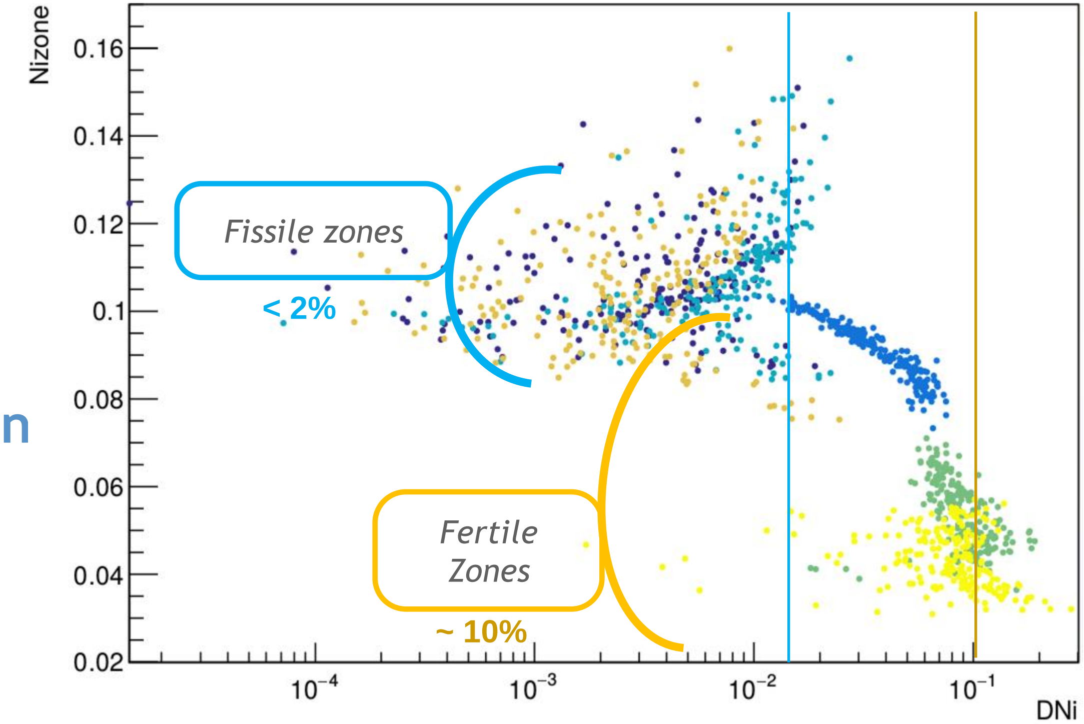
- Example of ^{239}Pu composition **per zone**
  - ○ Ni_{zone}: ^{239}Pu atomic proportion
  - ○ $DN_i = \left|\frac{N_i^{VESTA} - N_i^{CLASS}}{N_i^{VESTA}}\right|$ at ~100 GWd/t

↗ **Errors on ^{239}Pu estimation in fertile zones ~10%**

- Too many uncertainty ?

$$\varphi_k(t) = \sum_i \frac{P_k(t)}{\varepsilon_i{}^{fis} \times \sigma_{i,k}{}^{fis}(t) \times N_{i,k}(t)}$$

Induced errors on ^{239}Pu inventory at EOC per zone

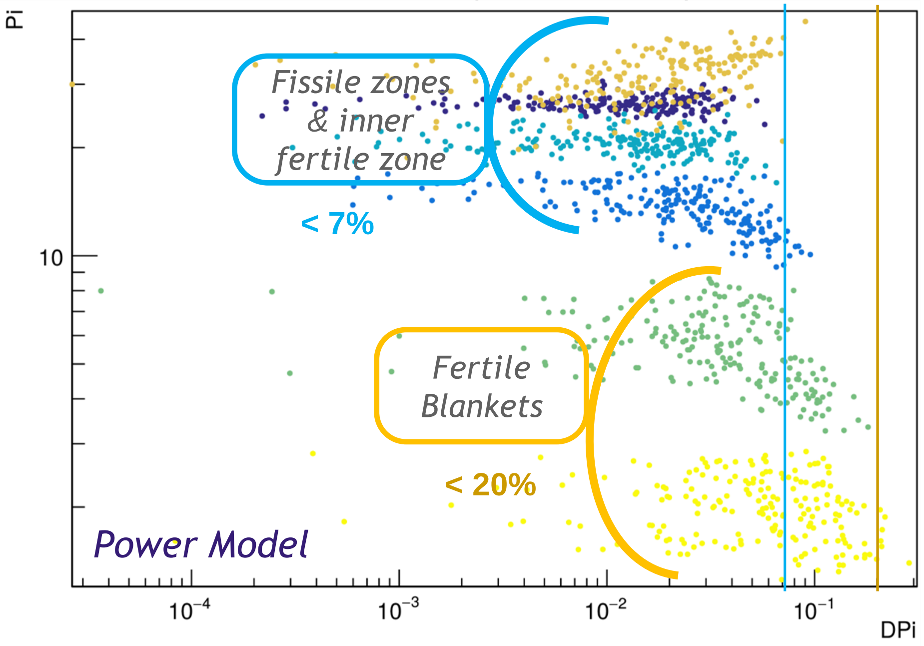


- **Less constraint** if direct prediction of local flux: **a Flux Model**
  - ○ **But size & reactor power modulations** get more challenging

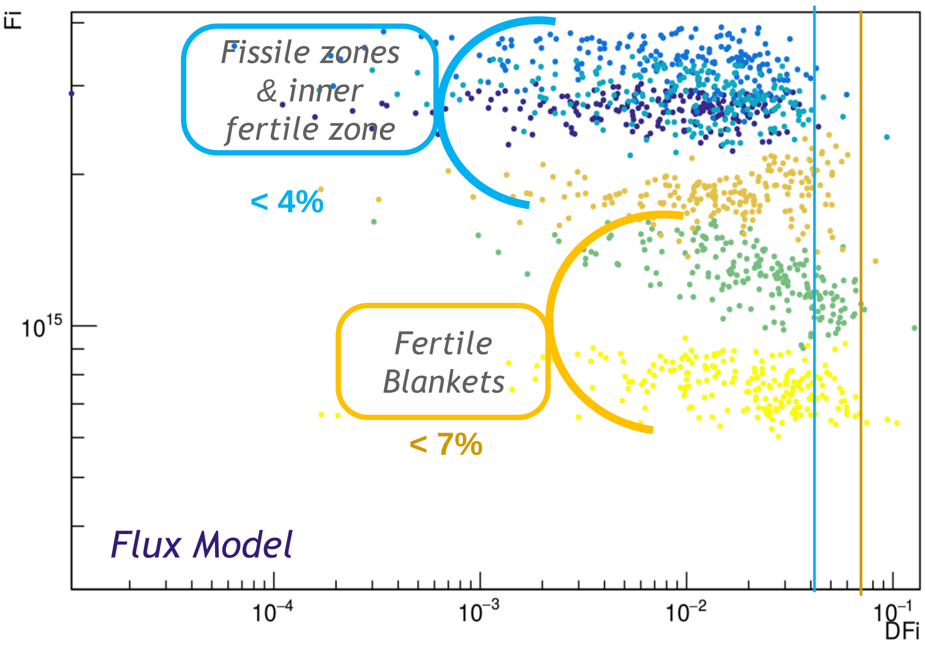
Local power predictor or local flux predictor

- Predictors accuracy verification: **Power Model VS Flux Model**
  - Pi: %power per zone & Fi: local flux ($1/cm^2/s$)

Induced errors on local power at EOC per zone



Induced errors on local flux at EOC per zone

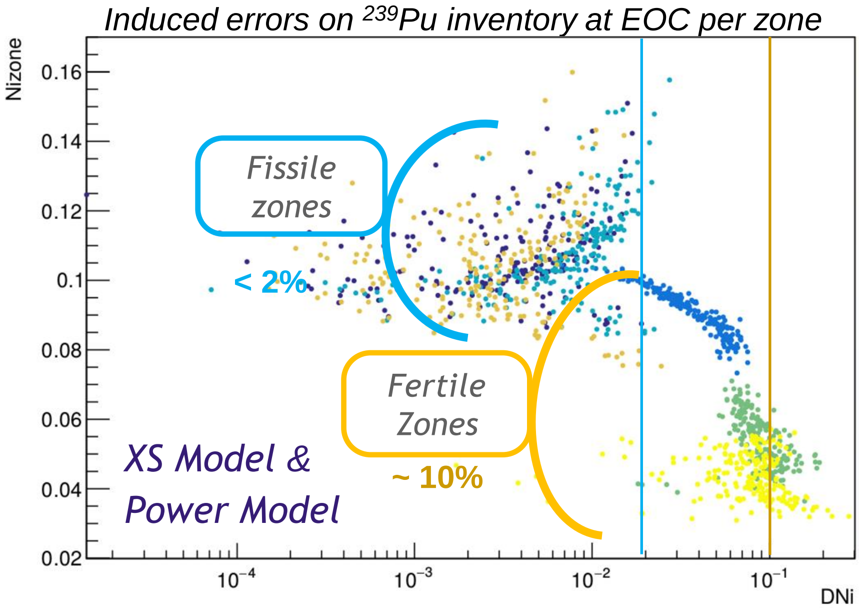


- Induced errors by multi-zone local flux predictors < 7%
- Improvement by predicting directly local flux
- Still an impact on the CLASS compositions estimation per zone

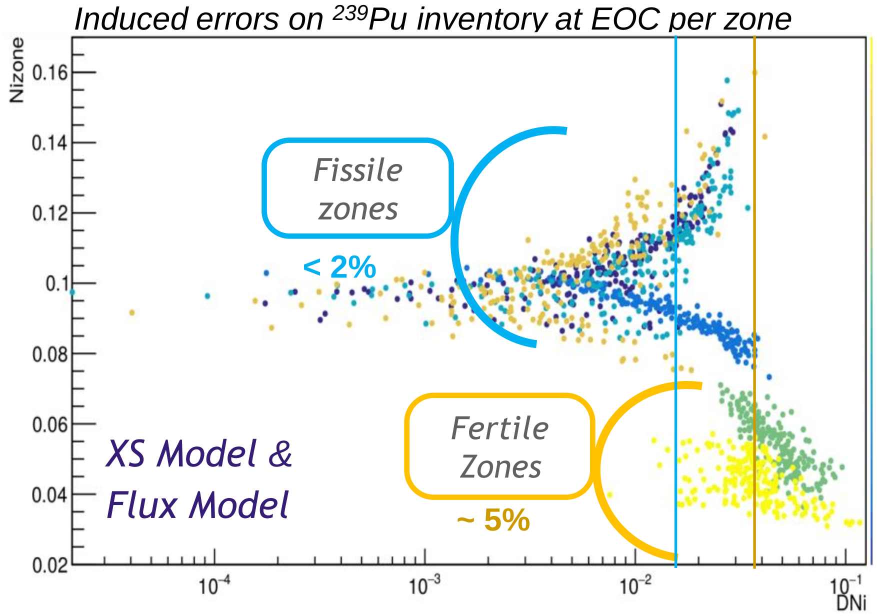
Impact of the model on fuel composition estimation

- Impact of both predictors on fuel composition estimation

- Example of ^{239}Pu composition **per zone**
  - Ni_{zone}: ^{239}Pu atomic proportion
  - $DN_i = \left|\frac{N_i^{VESTA} - N_i^{CLASS}}{N_i^{VESTA}}\right|$ at ~100 GWd/t



Induced errors on ^{239}Pu inventory at EOC per zone



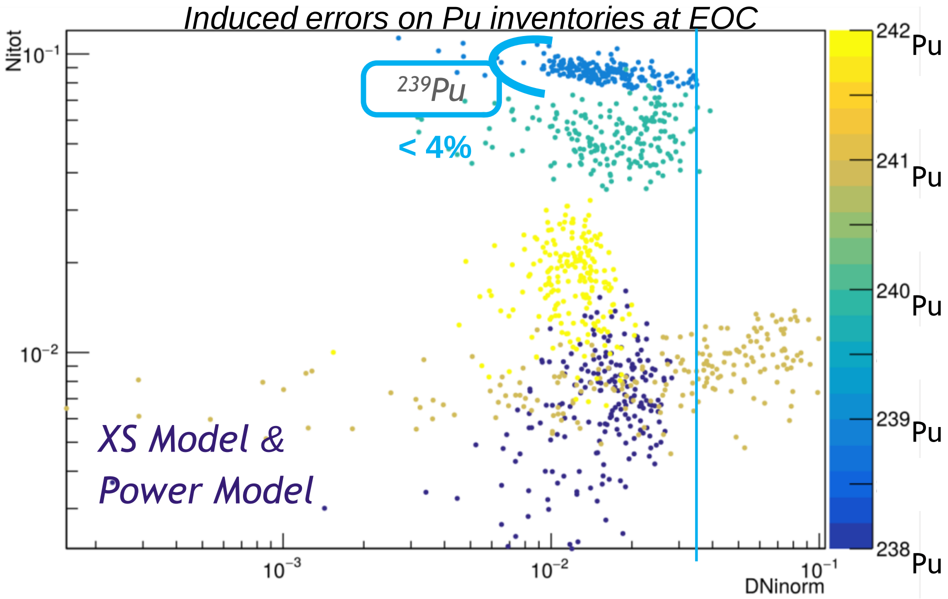
Induced errors on ^{239}Pu inventory at EOC per zone

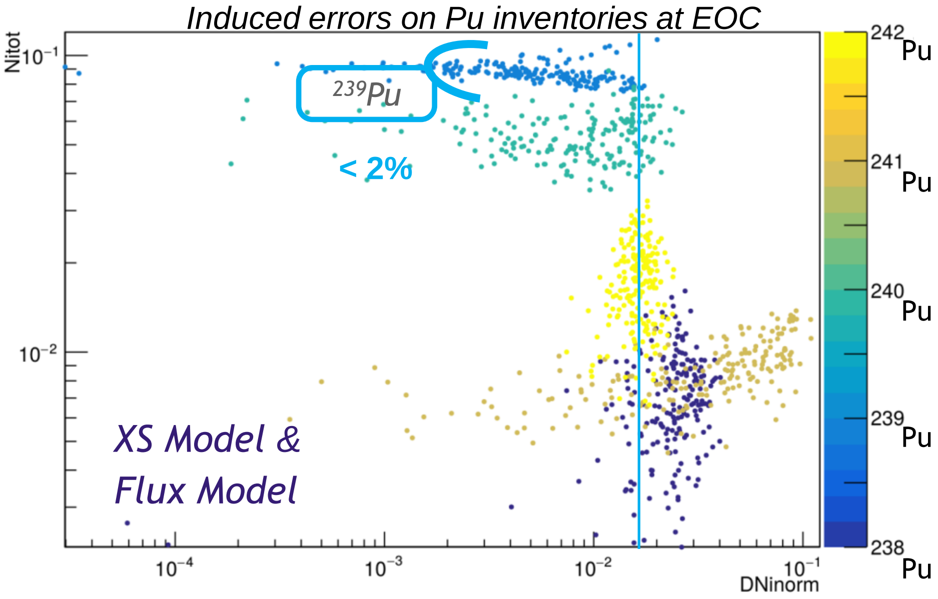
➚ Gain of a factor 2 on the ^{239}Pu composition estimation

Impact of the model on fuel composition estimation

- Impact of both predictors on fuel composition estimation

- Example of Pu composition ➞ **global inventory: homogenization**
  - Ni_{tot}: **total** Pu atomic proportion
  - $DN_{inorm} = \left|\frac{N_i^{VESTA} - N_i^{CLASS}}{N_i^{VESTA}}\right|$ at ~100 GWd/t


Induced errors on Pu inventories at EOC


Induced errors on Pu inventories at EOC

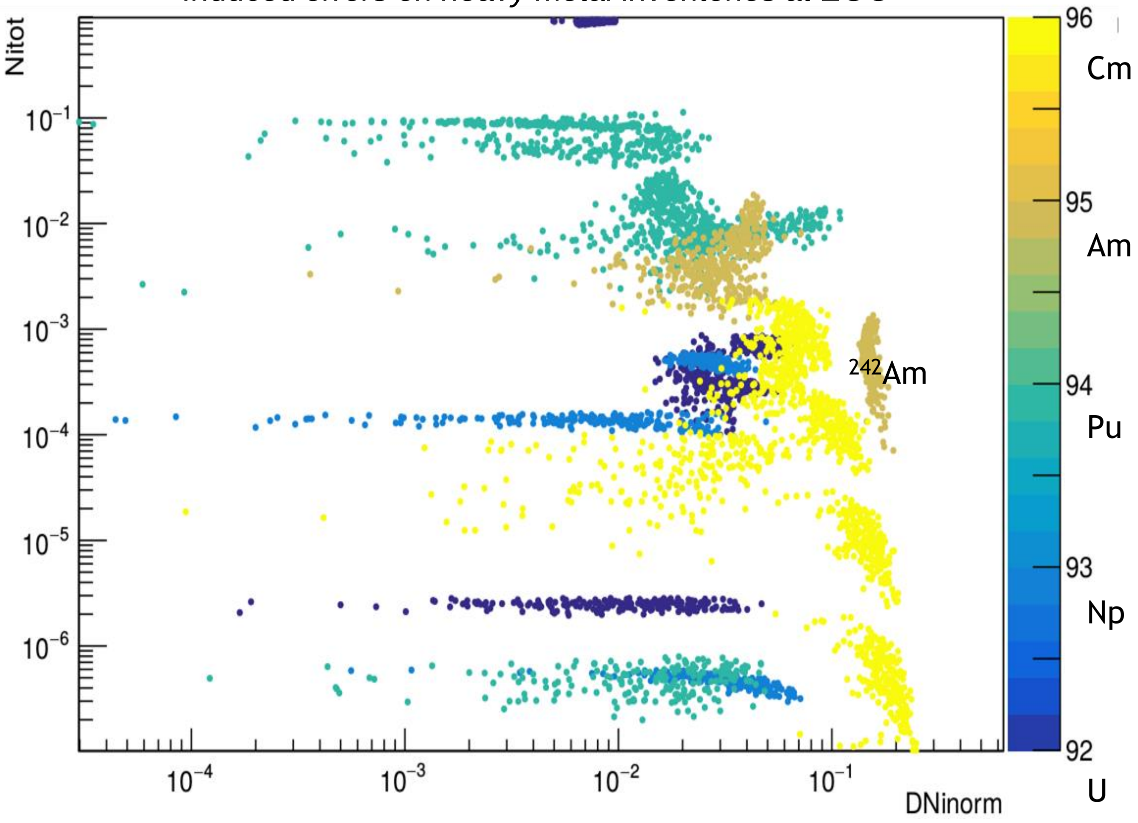
➚ **Errors in fertile zones > Errors on a global reactor scale**

➚ **Fertile separation ?**

Fuel composition estimation with a Flux Model

- Isotopic composition → **global inventory: homogenization**
  - ○ Ni_{tot}: **total** Heavy Metal atomic proportion
  - ○ $DN_{inorm} = \left|\frac{N_i^{VESTA} - N_i^{CLASS}}{N_i^{VESTA}}\right|$ at ~100 GWd/t

Induced errors on heavy metal inventories at EOC



- ↗ **Good Pu estimation: new irradiation model appropriate for Pu stabilization in cycle**
- ↗ **Model not appropriate for MA recycling**

Conclusion & Perspectives

- To study the capability of ASTRID-like reactors to stabilize the Pu in cycle while keeping its heterogeneity
  → **A new multi-zone fuel irradiation model**

- Good multi-zone cross-sections predictions → **errors induced < 2%**
- Compromise between model accuracy & flexibility
  - Better prediction of local flux than local power → **errors induced < 7%**

    → **better composition estimations**

    → **but no direct control of the reactor power**
- Impact of multi-zone irradiation on the electronuclear fuel cycle
  - Irradiation model accuracy very related with the zone number
  - Uncertainty balanced on the reactor scale

    → **no fissile & fertile separation management with the Power Model**

- Impact of the multi-zone fuel irradiation model at a scenario scale ?
- Homogeneous irradiation model / Multi-zone fuel irradiation model ?
- Application with other type of reactor

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Thank you for your attention !

Special thanks to Marc Ernoult, Xavier Doligez, Abdoul-Aziz Zakari-Issoufoub

Databank generation

Learning and training database

- Draw of t_{Pu} (2 cores), initial isotopic vector (5 isotopes) : 7 parameters
  - LHS method *(Latin HyperSquare)*
- Buffer ^{239}Pu
- U isotopic vector (^{238}U 99.2% - ^{235}U 0.8%)
- 1000 initial fuel compositions

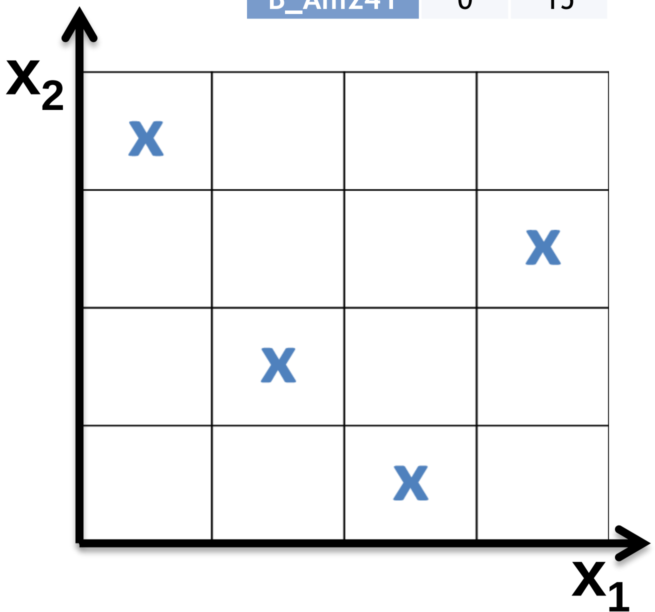
	Min	Max
T_Puint	15	40
T_Puext	15	40
B_Pu238	1	8
B_Pu240	20	40
B_Pu241	0	17
B_Pu242	5	17
B_Am241	0	15

↗ **1000 Monte-Carlo depletion calculations**

Testing database

- Same methodology
- 200 initial fuel compositions

↗ **200 Monte-Carlo depletion calculations**



Depletion calculations: 10 timesteps

Relative error due to the random seed with one composition

- Error EOC

Isotope	*^{239}Pu fission XS*	*Flux*	*^{239}Pu Composition*
Upper Fissile	0.13%	1.29%	0.12%
Lower Fissile	0.12 %	1.10%	0.09%
External Fissile	0.12%	2.92%	0.1%
Inner fertile	0.12%	0.64%	0.09%
Fertile Blanket internal	0.27%	1.37%	2.44%
Fertile Blanket external	0.75%	2.30%	1.15%