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Analysis of the Reactivity Loss of the Phenix Core Cycles for the Experimental Validation of the DARWIN-FR Code Package

Mr. Victor Viallon

CEA/IRESNE, France

28 February 2024

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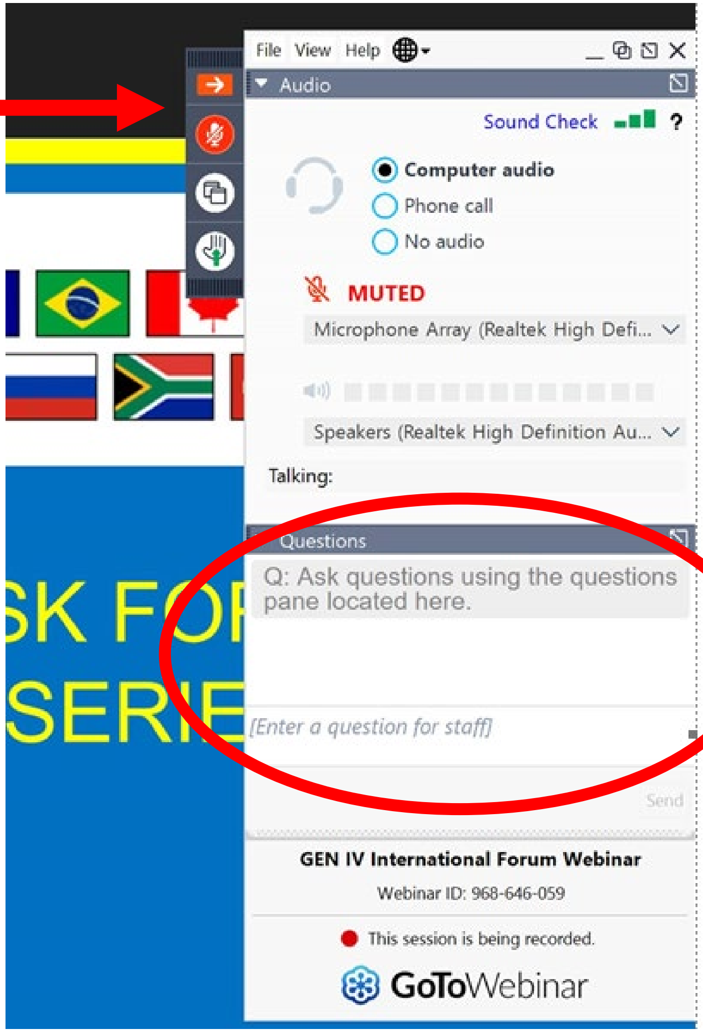

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Analysis of the Reactivity Loss of the Phenix Core Cycles for the Experimental Validation of the DARWIN-FR Code Package

Mr. Victor Viallon

PhD work supervised and directed by **Elias-Yammir Garcia-Cervantes** and **Laurent Buiron**

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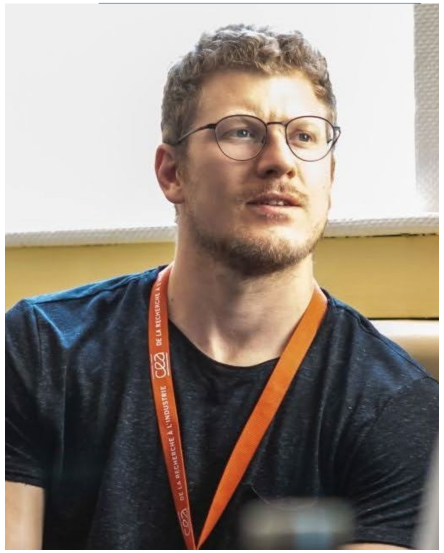
Meet the Presenter

Mr. Victor Viallon



- 3rd year PhD Student in the Research Institute for Nuclear Systems for low-carbon Energy Production (IRESNE) at CEA Cadarache, France
- Master degree in mechanics and industrial risk control engineering degree from the Centre-Val de Loire National Institute of Applied Sciences (INSA CVL)
- Advanced graduate degree in nuclear Engineering from the French Institute for Energy and Health Technologies (INSTN)

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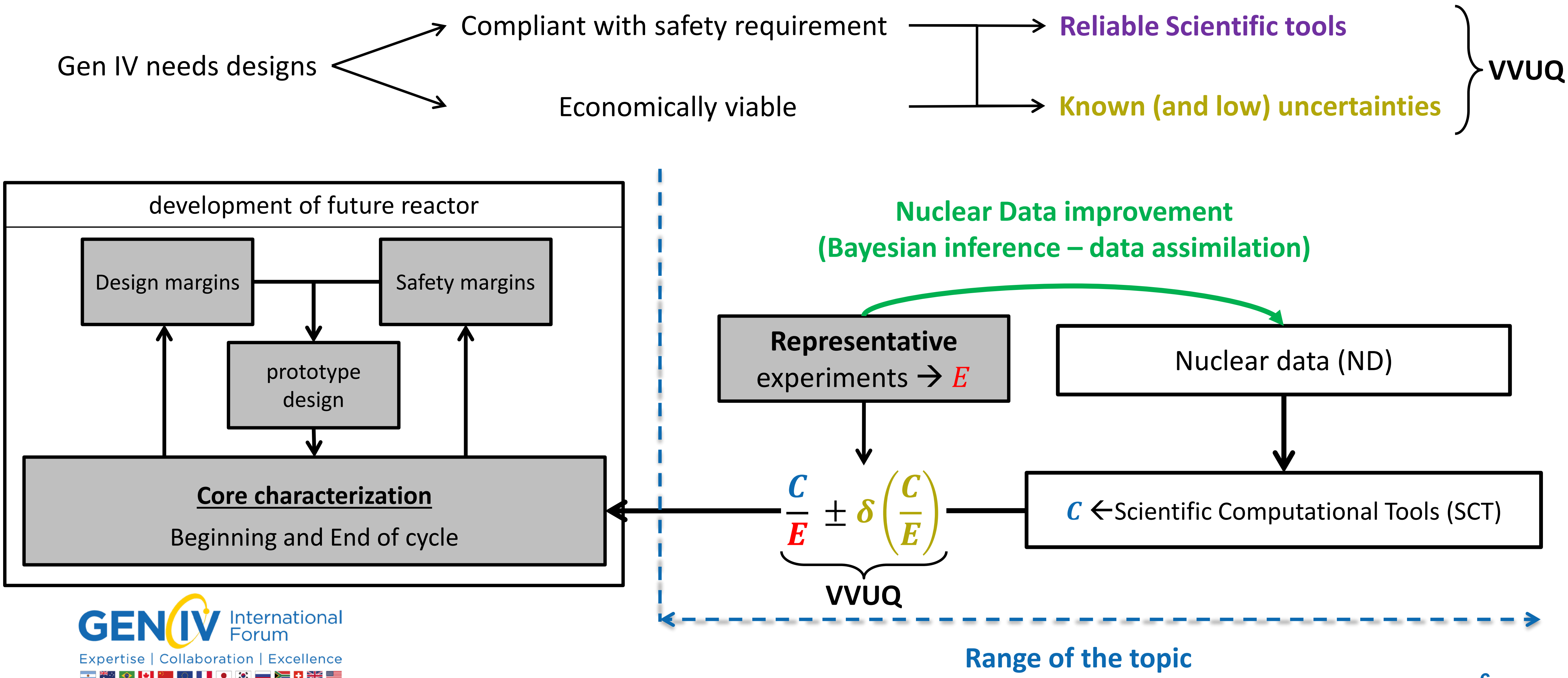
Email: victor.viallon@cea.fr

Context

Analysis of the Reactivity Loss of the Phenix Core Cycles for the Experimental Validation of the DARWIN-FR Code Package



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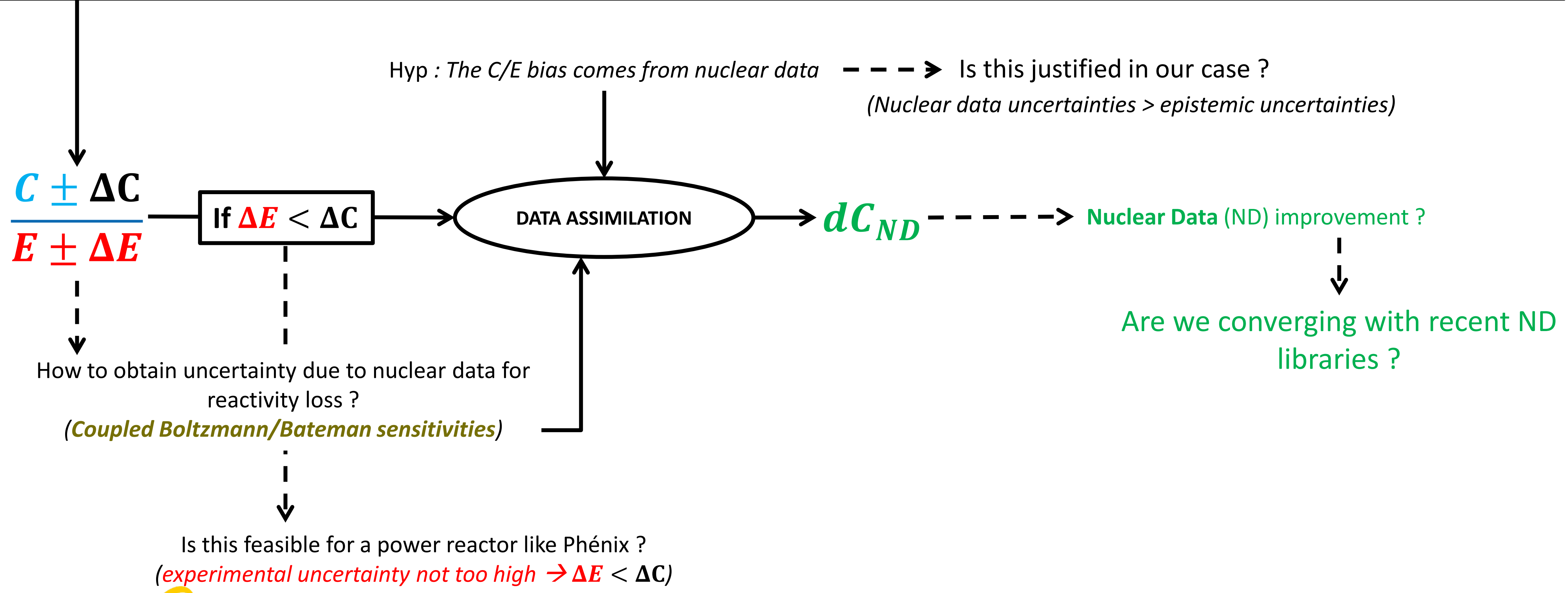
Context

Reactivity loss : Fuel wear speed / Time cycle → Core economics
Related to End of cycle core characterization → Safety
Can provide information for fast Fission Yield → Science

Analysis of the **Reactivity Loss** of the **Phenix** Core Cycles for the **Experimental Validation** of the **DARWIN-FR Code Package**



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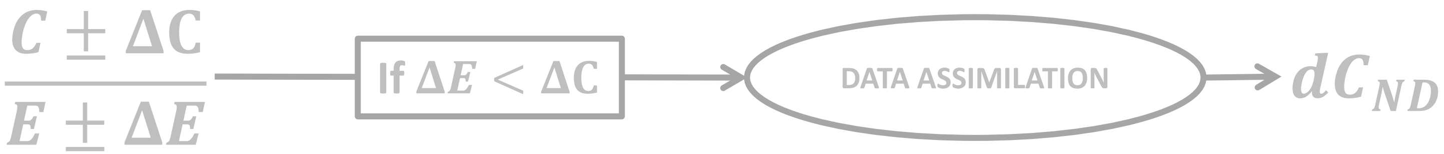
Context



$\frac{C \pm \Delta C}{E \pm \Delta E}$
If $\Delta E < \Delta C$
DATA ASSIMILATION
dC_{ND}

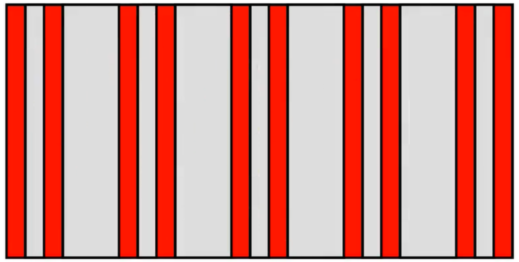
1. Phenix cycle simulation with DARWIN-FR package

Simulation of Phenix cycles with the DARWIN-FR code package

What is reactivity loss ?

Multiplication factor : $k_{eff} = \frac{\text{Number of neutron produced by fission}}{\text{Number of neutron absorbed and leaked}}$ **Reactivity** : $\rho = \frac{k_{eff} - 1}{k_{eff} \cdot \beta_{eff}}$ [$] **Criticality** : $k_{eff} = 1 \mid \rho = 0$

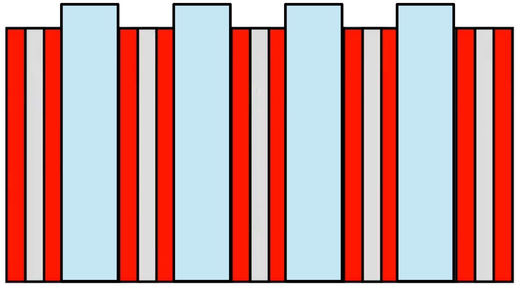
hypothetical **Supercritical**
(forbidden to have $\rho > 50¢$)



Reactivity excess

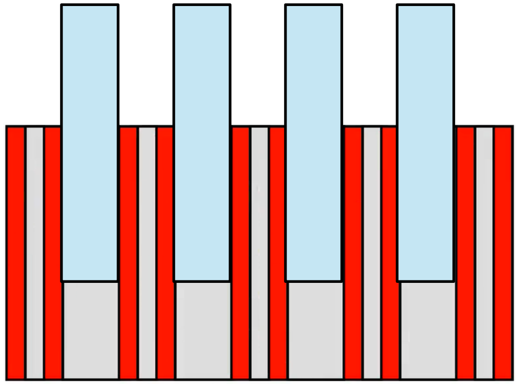
$\rho = 10\ \$$

Subcritical



$\rho = 10\$ - 20\$ = -10\$$

Critical



$\rho = 10\$ - 10\$ = 0\$$

Control rods to temper the reactivity excess and **pilot the reactor reactivity**

ρ = **Reactivity excess** − **Control rods worth**

Neutronics for reactor physics = How and how much is the **reactivity affected**

by self-induced physical phenomena on the reactivity excess (fuel depletion, sodium void, T, …)
by operator induced phenomenon on the control rod worth

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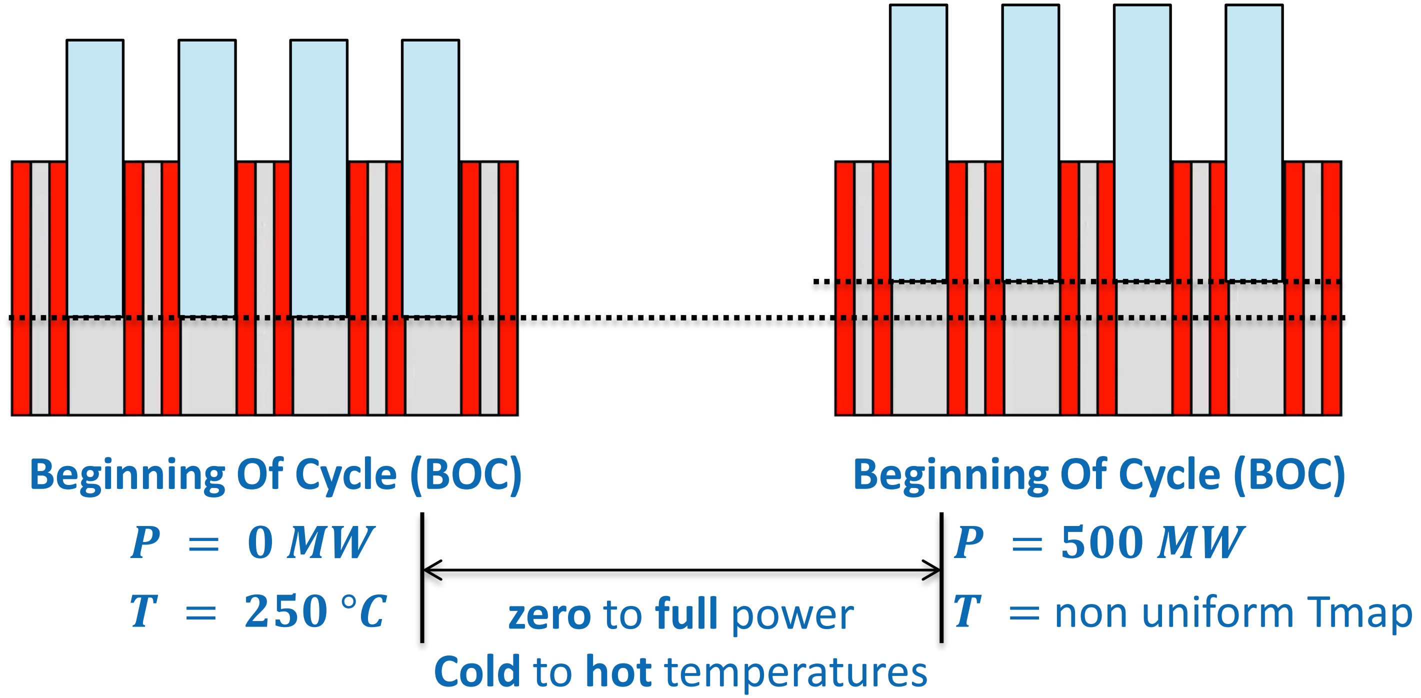
Simulation of Phenix cycles with the DARWIN-FR code package

What is reactivity loss ?

in normal operation → $\rho = \text{Reactivity excess} - \text{Control rods worth} = 0$



Control rod worth ↘

↓ Reactivity insertion by control rod extraction

Power ↗

↓

Temperatures ↗

↓ Physical phenomenon (**feedback**)

Reactivity Excess ↘

Simulation of Phenix cycles with the DARWIN-FR code package

What is reactivity loss ?

in normal operation → $\rho = \text{Reactivity excess} - \text{Control rods worth} = 0$

$$\rho = \rho_{RE} - \rho_{CRW} = 0$$

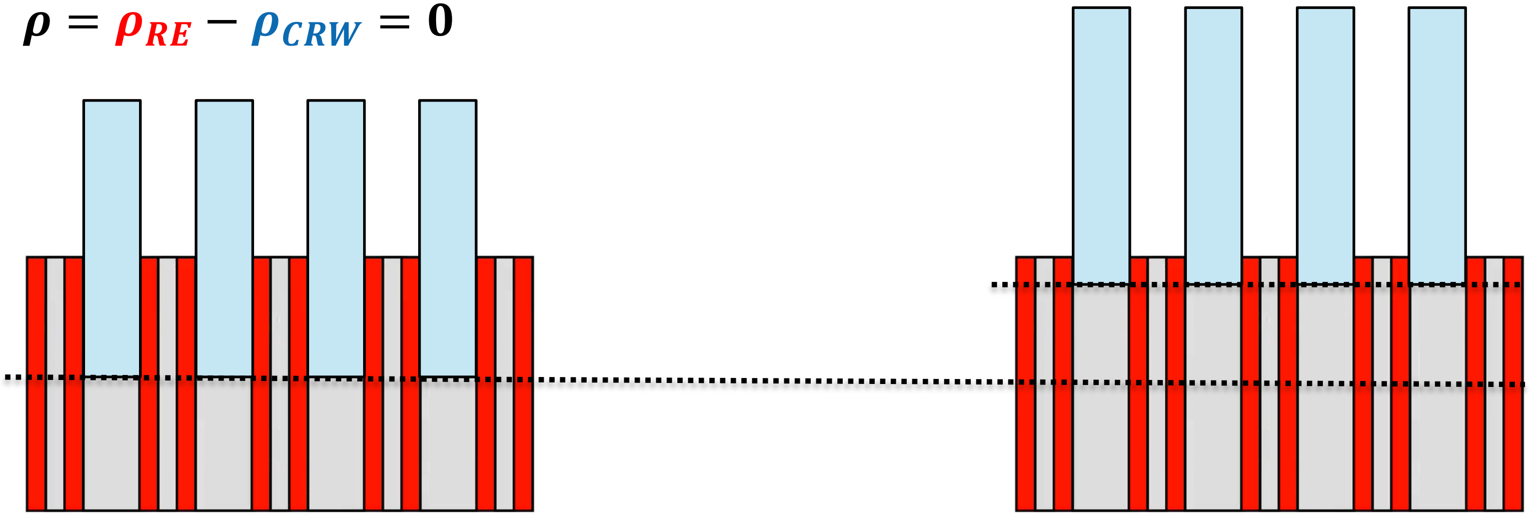
Fuel depletion
(isotopic composition evolution)

Reactivity loss

Reactivity Excess ↘
(depending on the reactor)

To maintain criticality
Control rods ↗

Control rod worth ↘



Beginning Of Cycle (BOC)

End Of Cycle (EOC)

Fuel depletion

what's the new **isotopic composition** ?

Does the total feedback change ?

…

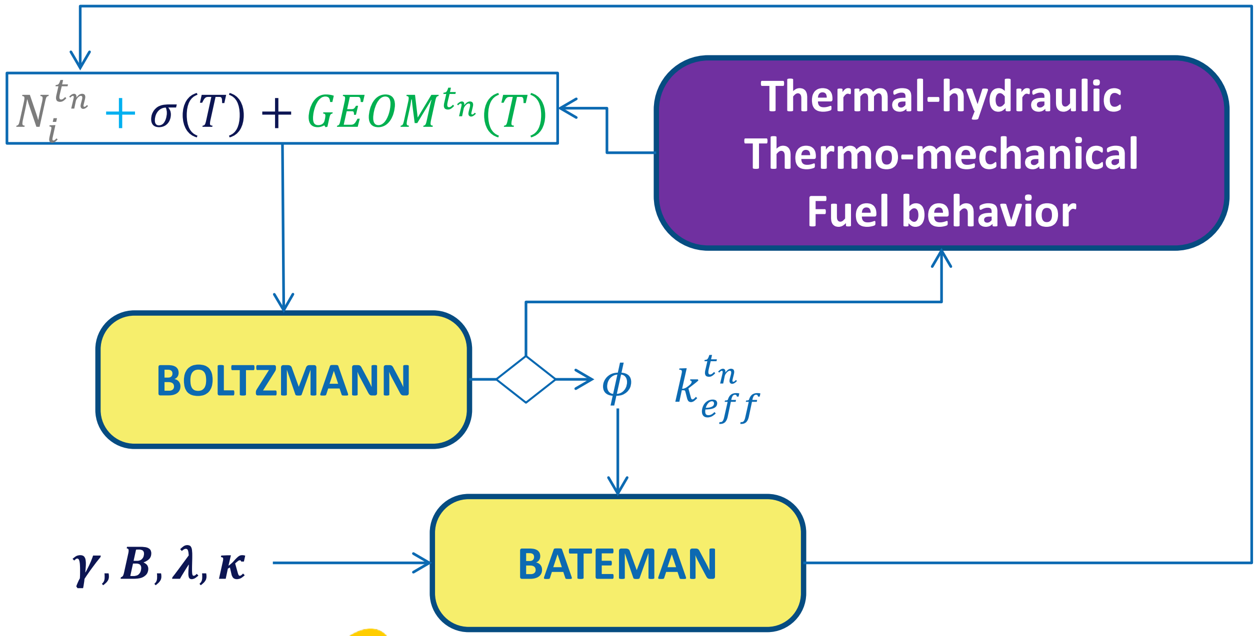
Simulation of Phenix cycles with the DARWIN-FR code package

How to compute reactivity loss ?

BATEMAN → $N_i(\vec{r},t) = g\left(\boldsymbol{\tau}\left(\vec{\boldsymbol{r}}, \boldsymbol{\phi}(\vec{\boldsymbol{r}}, \boldsymbol{E}, \boldsymbol{\Omega}, \mathbf{t})\right), \boldsymbol{\kappa}, \boldsymbol{\sigma}(\boldsymbol{E}, \boldsymbol{T})\right), \boldsymbol{\gamma}_{\boldsymbol{I}}, \boldsymbol{B}, \boldsymbol{\lambda})$

BOLTZMANN → $\boldsymbol{\phi}(\vec{\boldsymbol{r}}, \boldsymbol{E}, \boldsymbol{\Omega}, \mathbf{t}) = f\left(N_i(\vec{r},t,T), \boldsymbol{\sigma}(\boldsymbol{E}, \boldsymbol{T}), \boldsymbol{\partial\omega}(\boldsymbol{T})\right)$

Coupled equations - - - - - → Quasi-static hypothesis
(Boltzmann stationary + Constant flux depletion)



Reactivity loss coefficient : $\alpha_{BU} = \frac{\mathrm{d}\rho_{RE}}{\mathrm{d}t}$

- Boltzmann → Monte-Carlo
- Bateman → Monte-Carlo
- Thermal-hydraulic → CFD
- Fuel behavior → FEM
- Thermo-mechanical → FEM

} High-Fidelity → **Not reachable now**

We need to add **assumptions** and use **deterministic** methods

Simulation of Phenix cycles with the DARWIN-FR code package

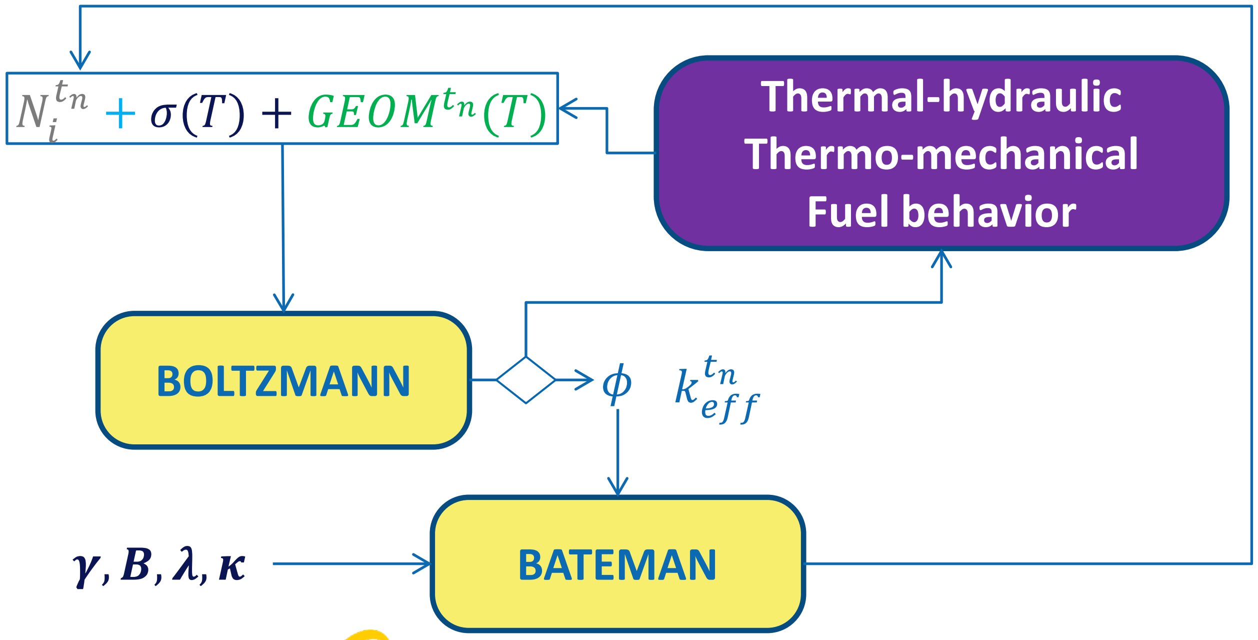
How to compute reactivity loss ?

BATEMAN → $N_i(\vec{r},t) = g\big(\boldsymbol{\tau}(\vec{r}, \boldsymbol{\phi}(\vec{r},E,\Omega,t)), \boldsymbol{\kappa}, \boldsymbol{\sigma}(E,T)\big), \boldsymbol{\gamma_I}, \boldsymbol{B}, \boldsymbol{\lambda}\big)$

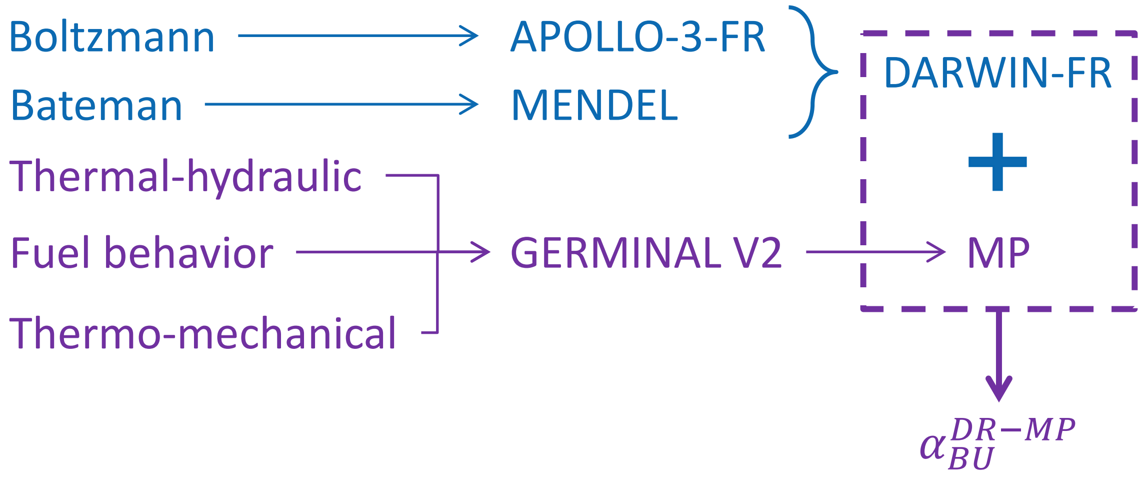
BOLTZMANN → $\boldsymbol{\phi}(\vec{r},E,\Omega,t) = f\big(N_i(\vec{r},t,T), \boldsymbol{\sigma}(E,T), \boldsymbol{\partial\omega}(T)\big)$

Coupled equations - - - - - → Quasi-static hypothesis

(Boltzmann stationary + Constant flux depletion)



Reactivity loss coefficient : $\alpha_{BU} = \frac{d\rho_{RE}}{dt}$



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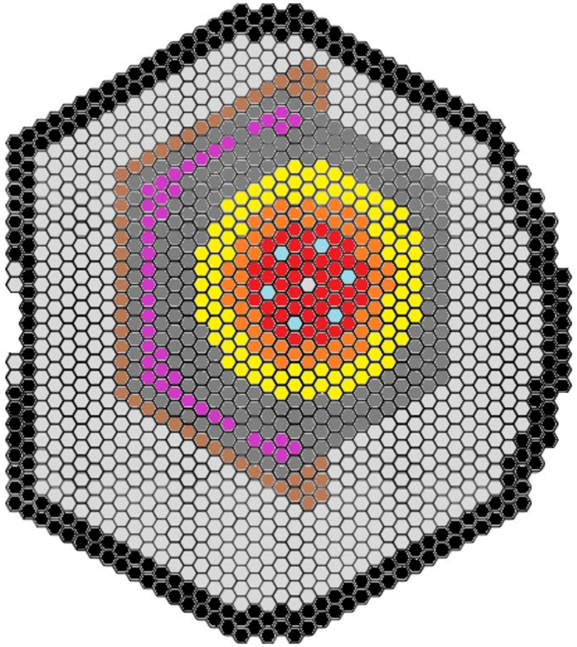
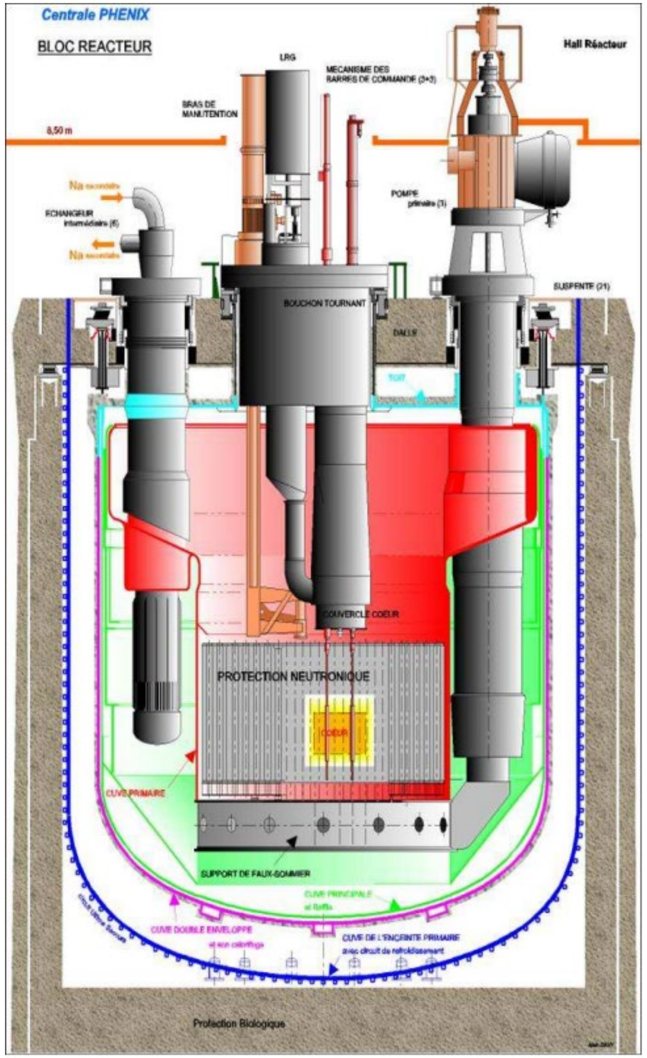
Simulation of Phenix cycles with the DARWIN-FR code package

Phenix reactor

CEA Marcoule, France
Pool-type Sodium cooled Fast Reactor **– 563 MWth**
35 operational years – more than **50 cycles**
100 fissile subassemblies
150 fertile blanket subassemblies
6 control rods
In-core experiments for irradiation purpose





Joël Guidez: Phénix, the experience feedback

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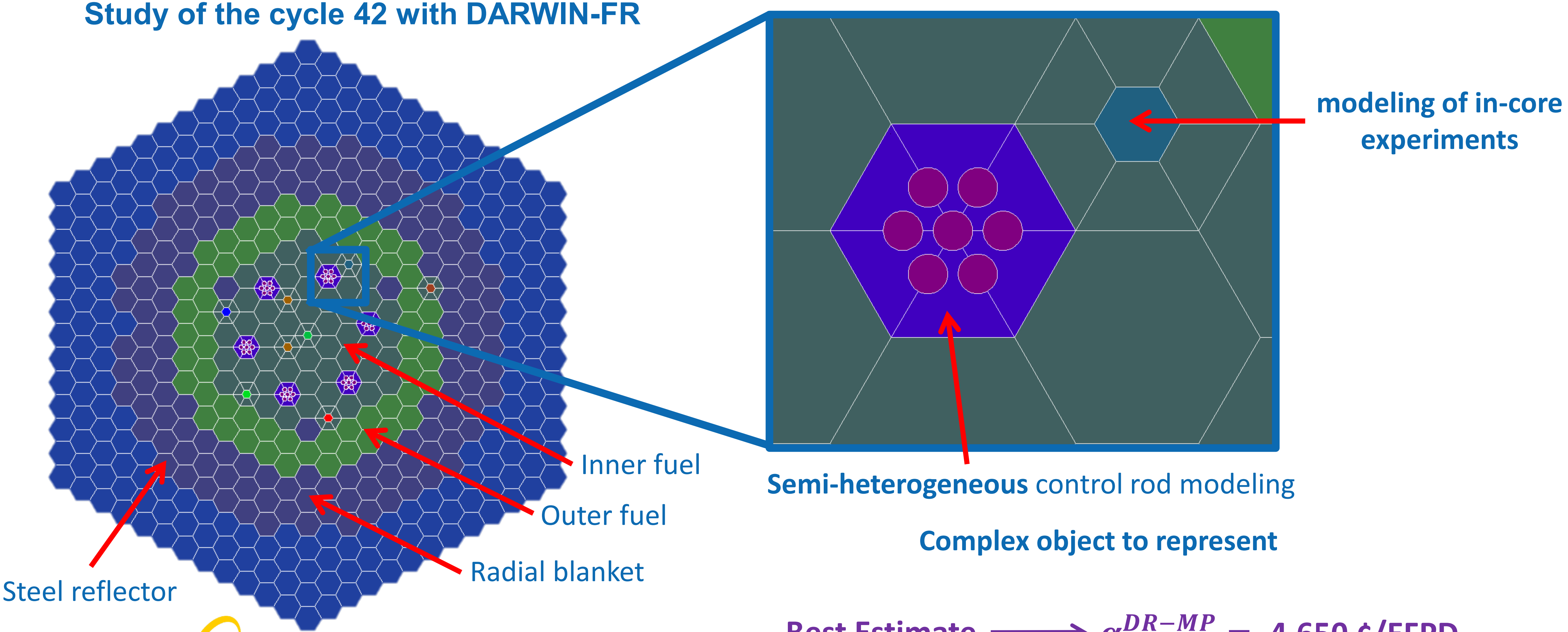
Simulation of Phenix cycles with the DARWIN-FR code package

Study of the cycle 42 with DARWIN-FR



Complex object to represent

Best Estimate ⟶ α_{BU}^{DR-MP} = **-4.650 ¢/EFPD**

Simulation of Phenix cycles with the DARWIN-FR code package

DARWIN-FR bias decomposition

"Real" value / experimental value

$$\overbrace{E}^{\text{"Real" value / experimental value}} = \underbrace{C_{HF}}_{\text{Equations "perfectly" solved}} + \underbrace{\mathrm{d}C_{ND} + dC_{MPdata}}_{\text{Error made by using assumed rather than the "real" input data (uncertainties)}}$$

Equations "perfectly" solved

Error made by using **assumed** rather than the "**real**" **input data (uncertainties)**

$$C_{HF} = \underbrace{C^{DR-MP}} + \underbrace{\Delta C_{AP3} + \Delta C_{MP} + \Delta C_{N_i^0} + \Delta C_{chain} + \Delta C_{tech} + \Delta^2(\ldots) + \cdots}$$

Equations solved with assumptions

Epistemic uncertainties (error made with assumptions) = $\boldsymbol{\Delta C}$

Bias decomposition = Estimate epistemic uncertainties

Simulation of Phenix cycles with the DARWIN-FR code package

DARWIN-FR bias decomposition

α_{BU}^{DR-MP} = - 4.650 ¢/EFPD

ΔC_{MP}	$\approx$	0 %	MP coupling contribution **0.9%** → Uncertainty over this (low) contribution → negligible
$\Delta C_{N_i^0}$	$\approx$	0 %	Database validated on BOC reactivity + Cycles done with D3R until cycle 48 and no difference between computed and initialized N_i^0
ΔC_{tech}	$\approx$	0 %	Cycle stable so the geometry doesn't change (significantly) during irradiation
ΔC_{chain}	$\approx$	0 %	Chain depletion (29 HN – 150 FP / instead of several thousands) developed for reactivity loss and validated in [Foissy 2020]
$\Delta^{n\geq 2}$	$\approx$	0 %	Assumption
ΔC_{AP3}	$\approx$	0 %	BOC reaction rate comparison between APOLLO-3-FR and the reference Monte-Carlo tool TRIPOLI-4® **To be investigated in depth**

[Foissy 2020] : Martin Foissy. *Développement d'une méthode de qualification et quantification des incertitudes des caractéristiques neutroniques du cœur d'ASTRID en fin de cycle*. PhD Thesis, Aix-Marseille, October 2020.

Simulation of Phenix cycles with the DARWIN-FR code package

DARWIN-FR bias decomposition

$$\frac{C^{DR-MP} \pm (\Delta C_{bias} + \Delta C_{ND})}{E \pm \Delta E}$$

2. Experimental reactivity loss

Experimental reactivity loss

What is reactivity loss ?

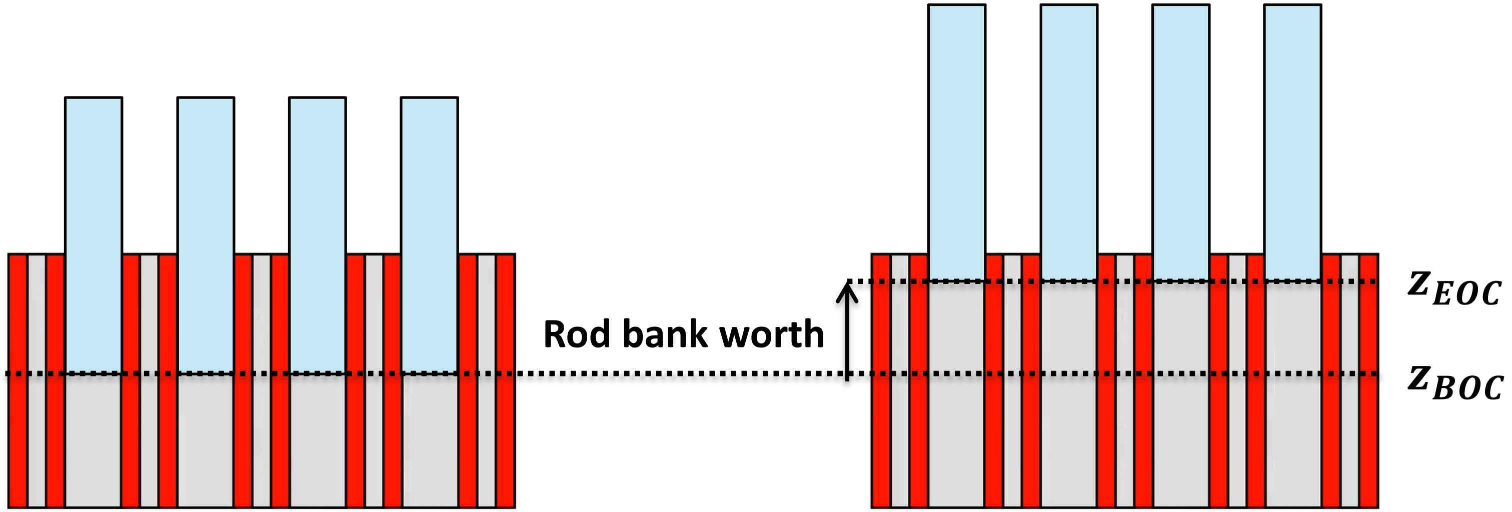
$$\rho_{RE}^{EOC} - \rho_{RE}^{BOC} = \rho_{CRW}^{EOC} - \rho_{CRW}^{BOC}$$

Reactivity loss = Rod Bank worth between z_{BOC} and z_{EOC}

$z(t)$?

$\rho_{RB}(z)$?

$$\rho = \rho_{RE} - \rho_{CRW} = 0$$

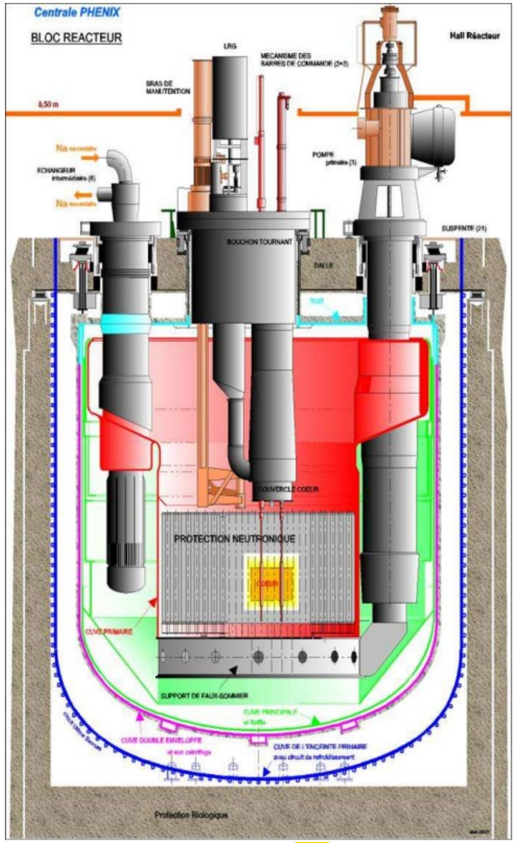


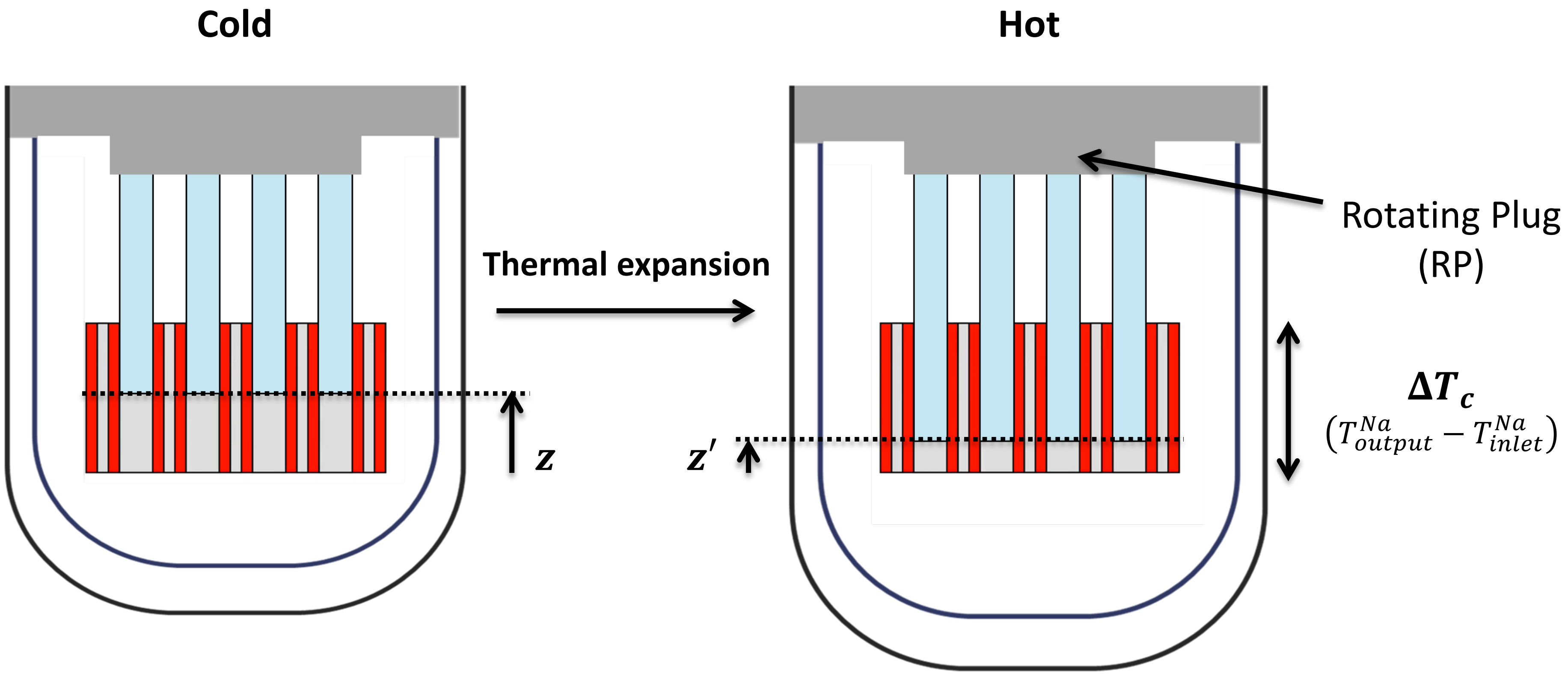
Beginning Of Cycle (BOC)

End Of Cycle (EOC)

Experimental reactivity loss

Axial position history of the Rod Bank through irradiation cycle → fundable inside cycle report, BUT…





$$z' = f_{expansion}(z, \Delta T_c, T_{RP}) = z + A \cdot \boldsymbol{\Delta T_c} + \mathrm{B} \cdot (\boldsymbol{T_{RP}} - C) + \mathrm{D}$$

The axial position must be corrected to take into account thermal expansion

Experimental reactivity loss

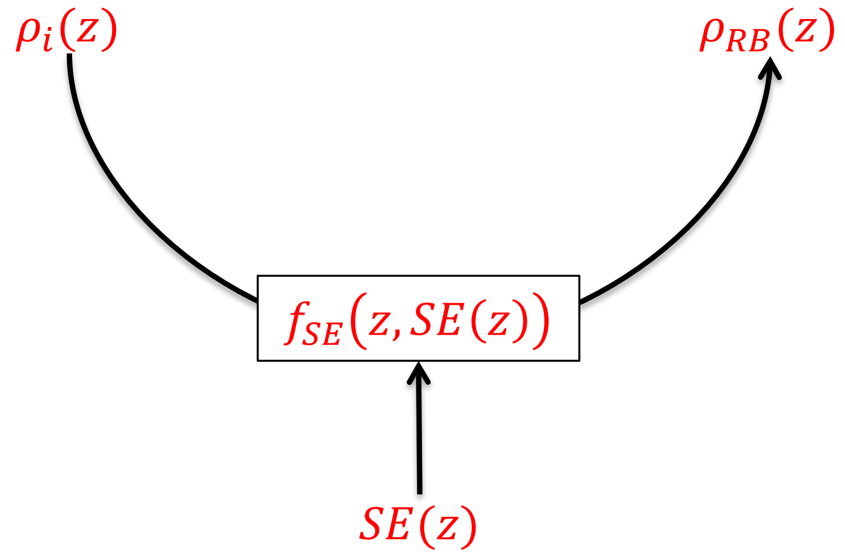
How to obtain the rod bank worth through axial position ($\boldsymbol{\rho_{RB}(z)}$)

Not possible to measure directly the rod bank worth for the upper part of the core ☹

Possible to only measure directly individual control rod worth $\rho_i(z)$ and collapse them into the $\boldsymbol{\rho_{RB}(z)}$ by taking into account the **shadow effect**

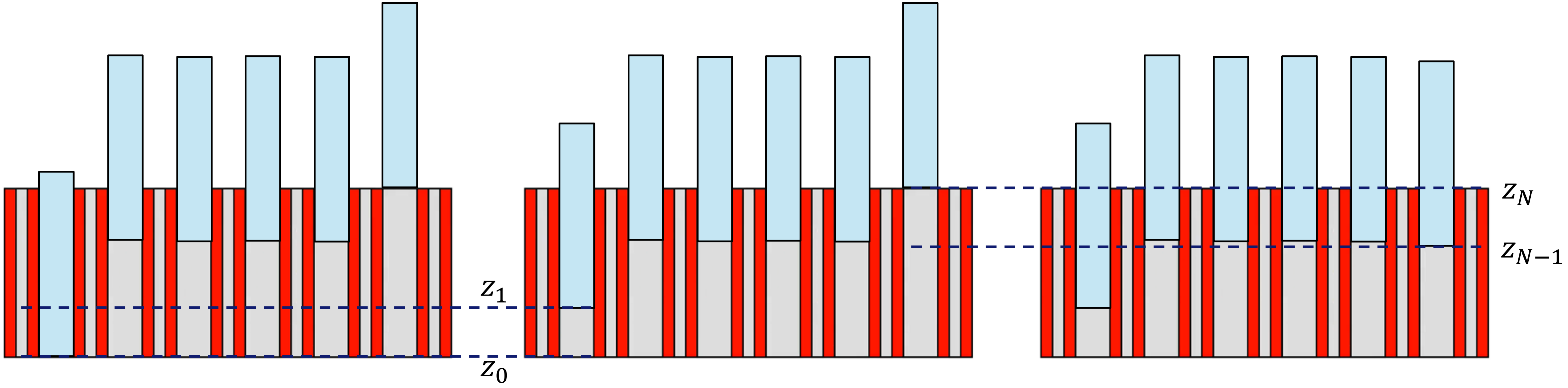
$$\sum_i \rho_i(z) \neq \rho_{RB}(z)$$

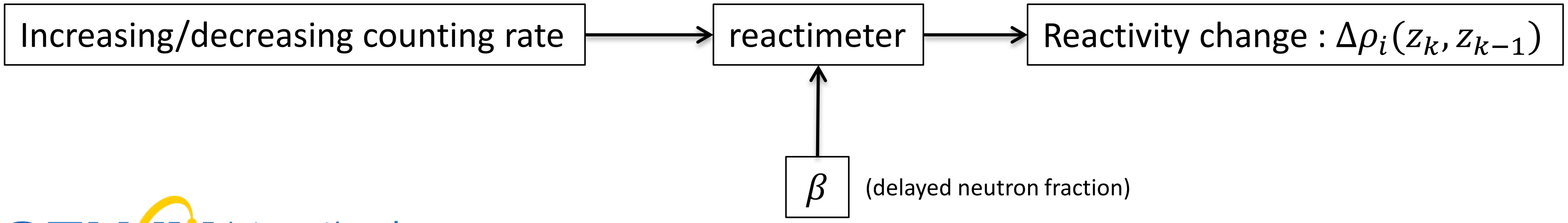
$$\rho_{RB}(z) = f_{SE}(z, SE(z))$$



Experimental reactivity loss

How to obtain each individual control rod worth ($\rho_i(z)$) → weight by balancing

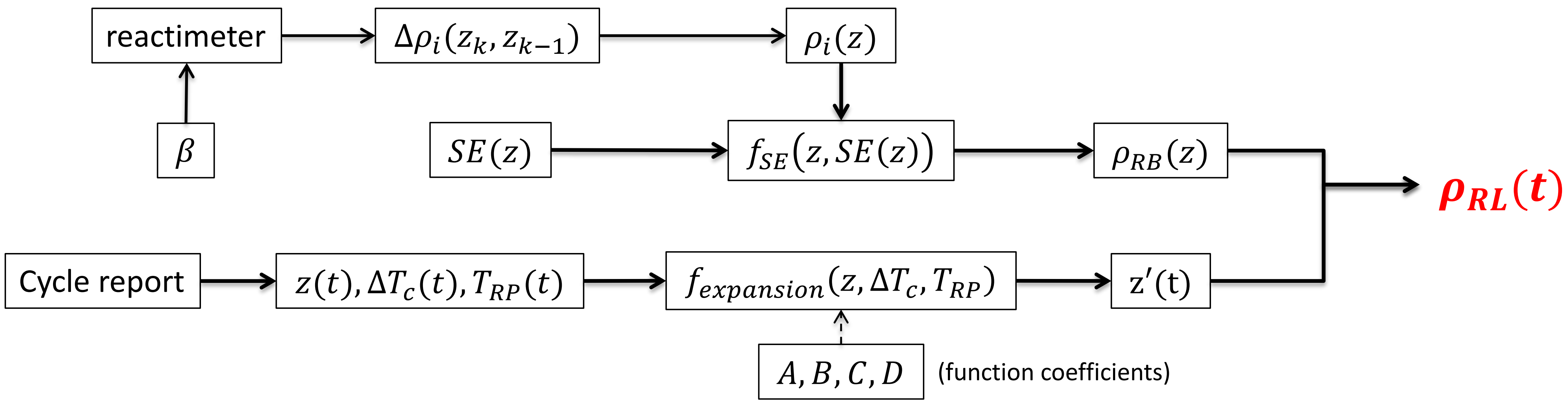




With all the $\Delta\rho_i(z_k, z_{k-1})$ we can build $\rho_i(z)$ for each control rod

Experimental reactivity loss

Global scheme of the reactivity loss curve construction



Before : Same β for every cycle | $SE(z) = $ cst for every cycle | expansion not considered for weight balancing | **no uncertainty**

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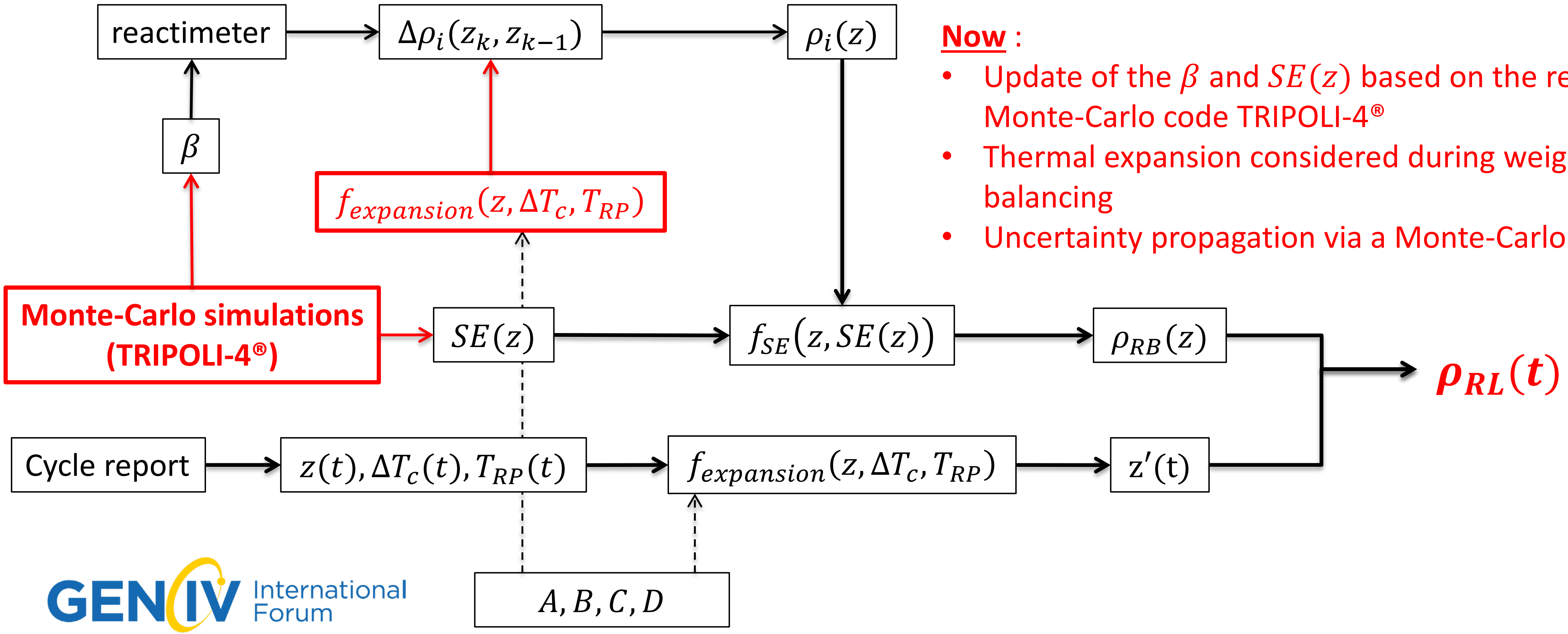
Experimental reactivity loss

Global scheme of the reactivity loss curve construction

Before : Same β for every cycle | $SE(z)$ = cst for every cycle | expansion not considered for weight balancing | **no uncertainty**

Now :

- Update of the β and $SE(z)$ based on the reference Monte-Carlo code TRIPOLI-4®
- Thermal expansion considered during weight balancing
- Uncertainty propagation via a Monte-Carlo method



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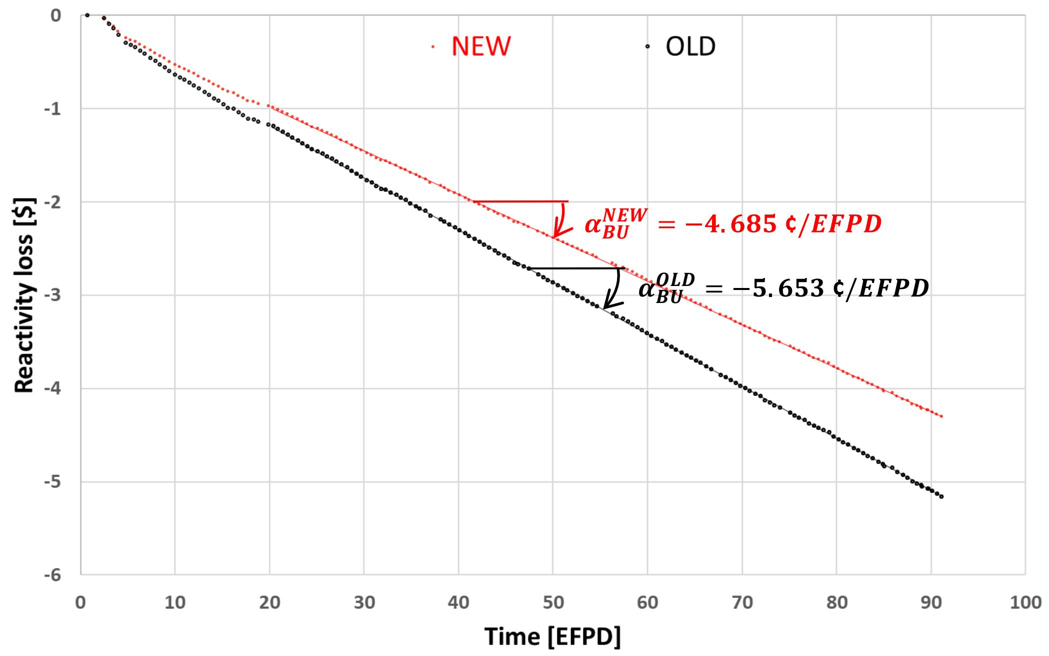
Reactivity loss coefficient actualization



$$\alpha_{BU}^{OLD} = -5.653 \text{ ¢}/EFPD$$

Updated Shadow-effect

$$\alpha_{BU}^{NEW_1} = -4.845 \text{ ¢}/EFPD$$

Updated β

$$\alpha_{BU}^{NEW_2} = -4,578 \text{ ¢}/EFPD$$

Thermal expansion during weight balancing

$$\alpha_{BU}^{NEW} = -4.685 \text{ ¢}/EFPD$$

To be compared to

$$\alpha_{BU}^{DR-MP} = -4.650 \text{ ¢}/EFPD$$

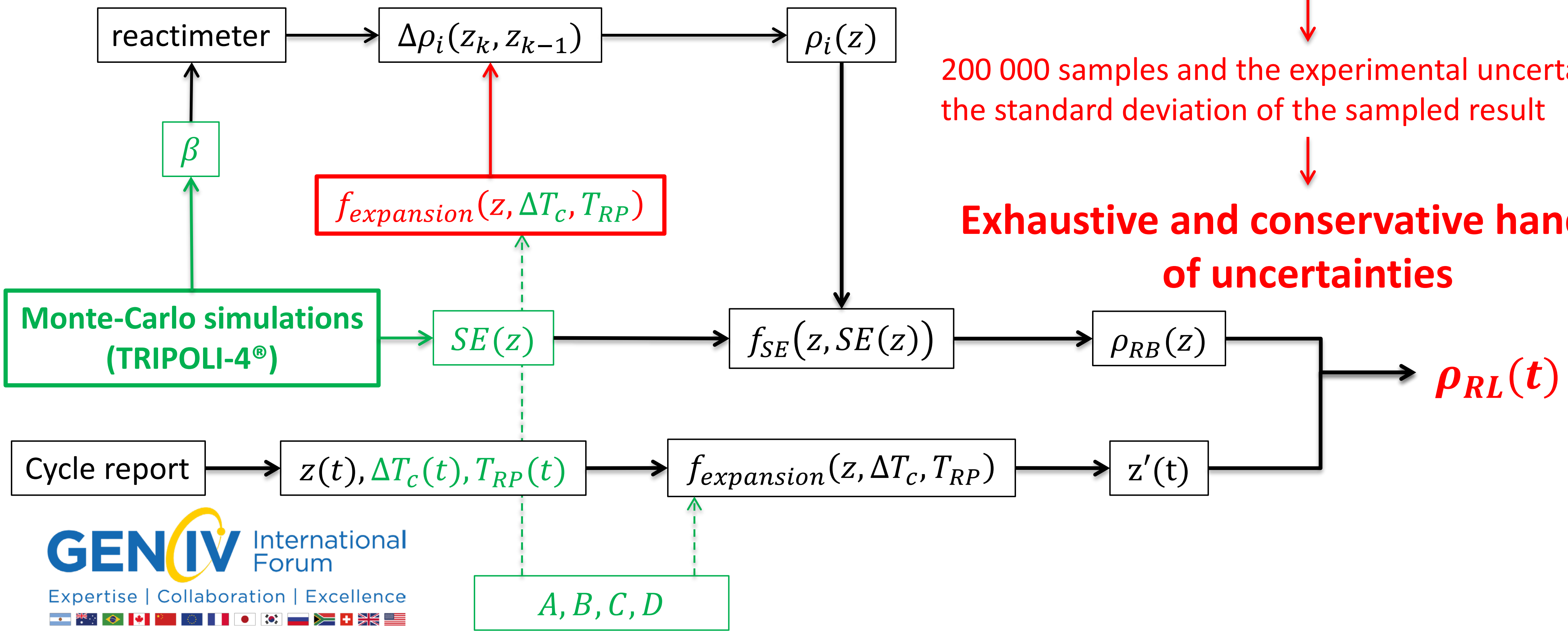
Experimental reactivity loss

Uncertainty propagation via Monte-Carlo method = Sampling the input data with the related distribution

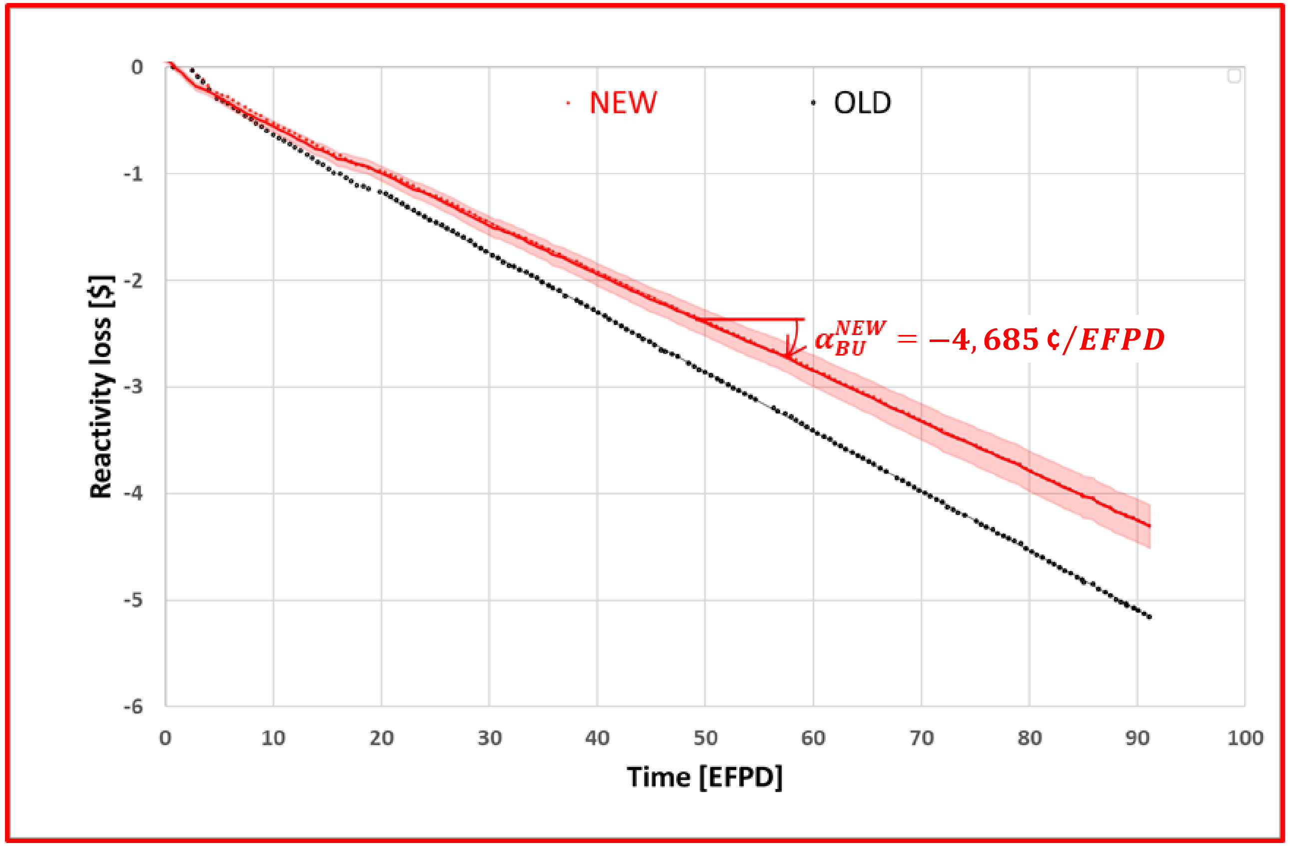
- For known uncertainties : correct distribution
- For unknown uncertainties : **conservative uniform distribution**

200 000 samples and the experimental uncertainty is the standard deviation of the sampled result

Exhaustive and conservative handling of uncertainties



Reactivity loss coefficient actualization



The most trustable value considering an exhaustive analysis

$$\alpha_{BU} = (-4.685 \pm 0.061)\ ¢/EFPD$$

What about the power uncertainty ?

Recap

Best-Estimate value : $\alpha_{BU}^{DR-MP} = -4.650$ ¢/EFPD

Bias decomposition : $\Delta\alpha_{\text{bias}} \approx 0$ (to be investigated)

"Clean" Experimental value: $\alpha_{BU}^{exp} = -4.685$ ¢/EFPD

Conservative Experimental uncertainty : $\Delta\alpha_{BU}^{exp} = 0.061$ ¢/EFPD | 1.3 %

Nuclear data uncertainty : $\Delta\alpha_{ND} = ?$

$$\frac{C^{DR-MP} \pm (\Delta C_{bias} + \Delta C_{ND})}{E \pm \Delta E}$$

→ If $\Delta E < \Delta C$ → DATA ASSIMILATION → dC_{ND}

3. Reactivity loss nuclear data uncertainty propagation

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Reactivity loss sensitivity calculation

Sensitivity → How the quantity of interest R is impacted by a **small** change in the parameter p → $S_p^R = \frac{p}{R}\frac{dR}{dp}$

- R → Quantity of interest : α_{BU}
- p → Parameters : $\sigma, \gamma, \kappa, \lambda, B, N_i^0$

↓

First order assumption → **Covariance matrix M** → $\frac{\Delta C_{ND}}{C} = \sqrt{S^T M S}$

≈ Uncertainties of every parameter p

$$\frac{C^{DR-MP} \pm (\Delta C_{bias} + \Delta C_{ND})}{E \pm \Delta E}$$

→ If $\Delta E < \Delta C$ → DATA ASSIMILATION → dC_{ND}

How to compute the sensitivities

In neutronics it is possible to "easily" obtain the sensitivity to the k_{eff} of cross-section → **Perturbation Theory (PT)**

Problems with local sensitivities computed with PT for depletion calculation? ⟶ Only for direct term in the Boltzmann equation
Not able to see all the indirect terms due to Bateman equation

For this kind of problems, specific formalism needs to be used → **Bateman/Boltzmann coupled sensitivities [Takeda, Williams in the 80's]**

Compute by backtracking in time

$$S_p^R = \frac{1}{R}\left[\underbrace{\left\langle p\frac{\partial R}{\partial p}\right\rangle}_{\text{Boltzmann (PT)}} + \underbrace{\int_{dt}\left\langle \mathcal{N}^*\left(\phi p\frac{\partial \mathcal{A}}{\partial p}\right)\mathcal{N}\right\rangle dt}_{\text{Bateman}} + \underbrace{P^*\left\langle p\frac{\partial P}{\partial p}\right\rangle}_{\text{Power}} + \underbrace{\left\langle \Gamma^* p\frac{\partial \mathcal{H}}{\partial p}\phi\right\rangle + \left\langle \Gamma p\frac{\partial \mathcal{H}^*}{\partial p}\phi^*\right\rangle}_{\text{Flux}}\right]$$

Implemented in **APOLLO-3®** and **first time** that this formalism is used on a **power reactor**

Finally, we don't want exactly the sensitivity to the k_{eff} but to the reactivity loss between the BOC and the EOC

EGPT : Equivalent Generalized Perturbation Theory

$$S_{\Delta\rho_{A\to B}}^{EGPT} = \frac{k_A}{k_B - k_A} S_{k_B} - \frac{k_B}{k_B - k_A} S_{k_A}$$

Uncertainty propagation

$$\frac{\Delta C_{DN}}{C} = \sqrt{{}^{T}S \cdot \left(M_{\sigma_{HN}} + M_{\sigma_{FP}} + M_{\gamma} + M_{\kappa} + M_{\lambda} + M_{B}\right) \cdot S}$$

$M_{\sigma_{HN}} + M_{\sigma_{FP}}$	→	**COMAC V1 (experimental covariances)**	$\sqrt{{}^{T}S M_{COMACV1} S} = \mathbf{7.36\ \%}$
M_{γ}	→	*Variances / ad-hoc covariances**	$\sqrt{{}^{T}S M_{\gamma} S} = 1.03\ \%$
M_{λ}	→	Variances / no covariances	$\sqrt{{}^{T}S M_{\lambda} S} = 0\ \%$
M_{B}	→	∅	$\approx 0\ \%$
M_{κ}	→	∅	$\approx 0\ \%$

TOTAL Coupled sensitivities – $\frac{\Delta C_{DN}}{C}$ **7.43 %** (7 days of uncertainties for a 100 days cycle)

TOTAL Boltzmann alone – $\frac{\Delta C_{DN}}{C}$ 2.19 % (classical PT miss a large amount of information)

With the help of* ***Luca Fiorito* *from SCK CEN*

Recap reactivity loss VVUQ

Best-Estimate value : $\alpha_{BU}^{DR-MP} = -4.650$ ¢/EFPD

Bias decomposition : $\Delta\alpha_{\text{bias}} \approx 0$ (to be investigated)

"Clean" Experimental value: $\alpha_{BU}^{exp} = -4.685$ ¢/EFPD

Conservative Experimental uncertainty : $\Delta\alpha_{BU}^{exp} = 0.061$ ¢/EFPD | 1.3 %

Nuclear data uncertainty : $\Delta\alpha_{ND} = 7.4\ \%$

$$\frac{C^{DR-MP} \pm (\cancel{\Delta C_{bias}} + \Delta C_{\mathrm{ND}})}{E \pm \Delta E} \longrightarrow \text{If } \Delta E < \Delta C \longrightarrow \text{DATA ASSIMILATION} \longrightarrow dC_{ND}$$

$$\frac{\Delta C_{ND}\ \text{(Nuclear Data uncertainties)}}{\Delta C_{\mathrm{AP3}}\ \text{(epistemic uncertainties)}} \gg 1$$

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4. Perspective on data assimilation using power reactor data

Assimilation perspective

What is data assimilation ? → Using the experimental value of an integral experiment to improve the knowledge of the input data = **Bayesian inference**

$$\left.\begin{matrix} \Delta p_1 & p_1 \\ \Delta p_2 & p_2 \\ \vdots & \vdots \\ \Delta p_{N-1} & p_{N-1} \\ \Delta p_N & p_N \end{matrix}\right\} \rightarrow \boxed{\text{Boltzmann/Bateman calculation}} \rightarrow \alpha_{BU}^{C} \pm \Delta\alpha_{BU}^{C_{DN}} \qquad \alpha_{BU}^{EXP} \pm \Delta\alpha_{BU}^{EXP}$$

Assimilation process wants to find the set of p_i and Δp_i that allow to obtain :

$\alpha_{BU}^{C} = \alpha_{BU}^{EXP}$ [correction of input data]

$\Delta\alpha_{BU}^{C_{DN}} = \Delta\alpha_{BU}^{EXP}$ [uncertainty reduction of input data]

By respecting some physical and experimental constraints (covariance matrix)

} **Minimization problem**

Problem : Optimization with brute force approach not reachable today (N > 10000)

→ But we can used **sensitivities**

Assimilation perspective

Covariance Matrix M_{prior}

$\rightarrow \Delta C_{ND}$

$$\sigma' = \sigma_{prior} + M_{prior} \cdot S^T \cdot \left(M_E + S \cdot M_{prior} \cdot S^T\right)^{-1} \cdot S \cdot \left(E - C(\sigma_{prior})\right)$$

$$M' = M_{prior} - M_{prior} \cdot S^T \cdot \left(M_E + S \cdot M_{prior} \cdot S^T\right)^{-1} \cdot S \cdot M_{prior}$$

Done with the **CONRAD** software

$\sigma', \gamma', B', \lambda', \kappa'$

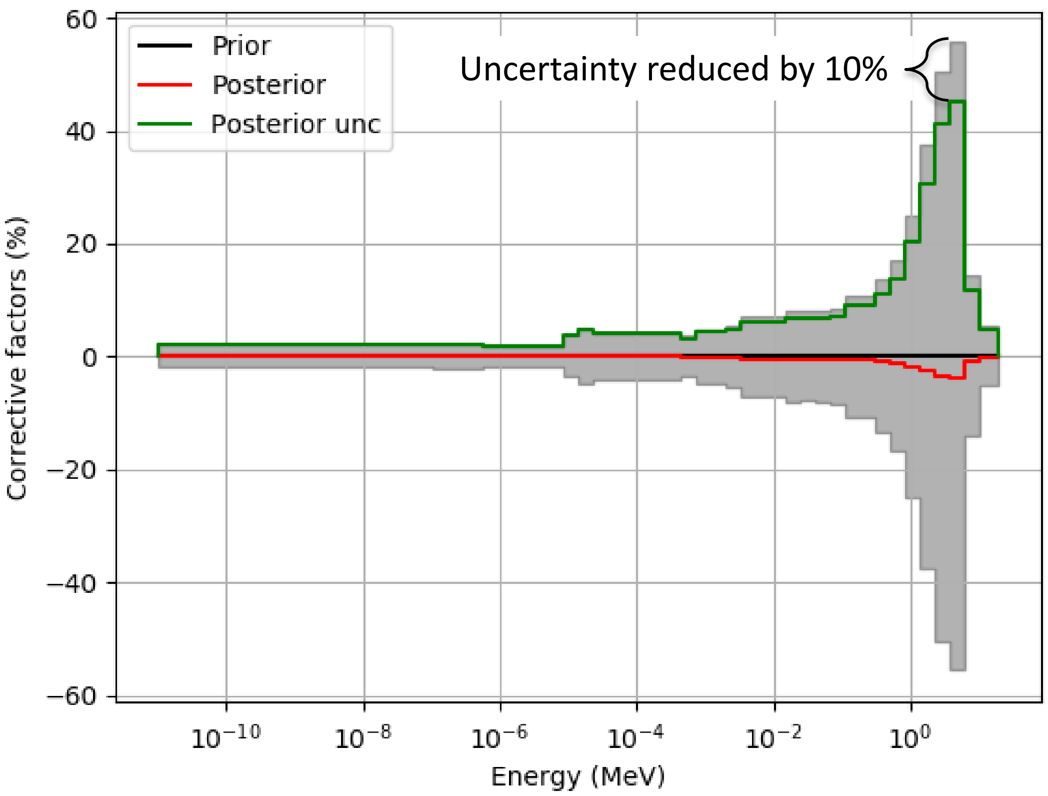
M'

$\rightarrow dC_{ND}$

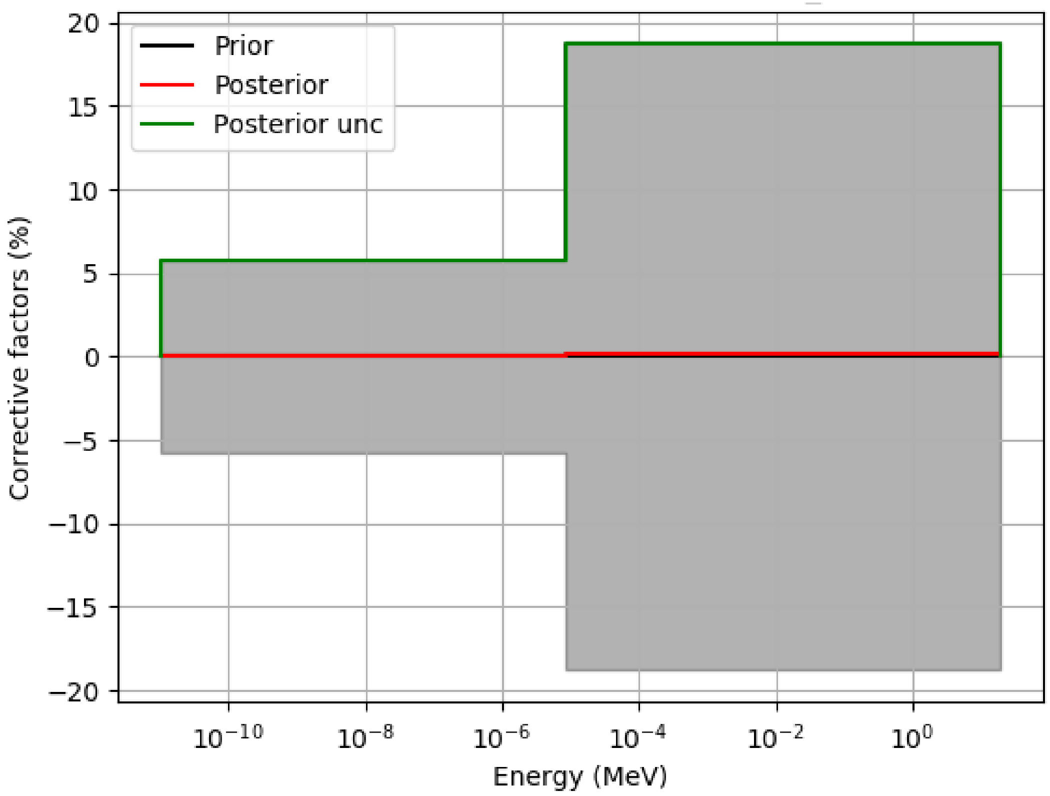
$\Delta C'_{ND}$

Some results for data assimilation exercises

Data Assimilation of the ^{240}Pu Capture



Data Assimilation of the $^{239}Pu \rightarrow ^{107}Pd$ Fission Yield



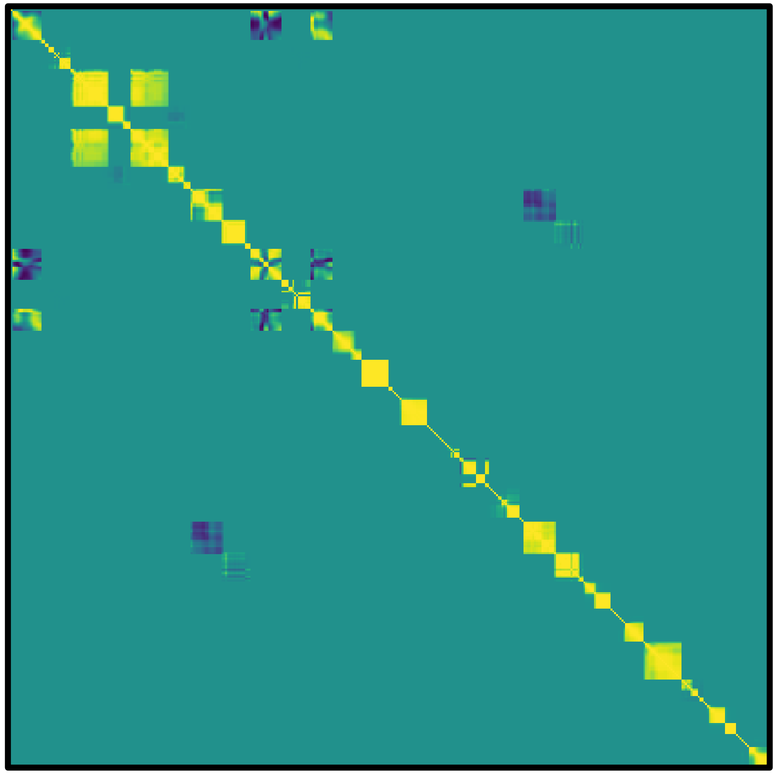
$$\frac{C(\sigma_{prior})}{E} - 1 = -0.75\% \longrightarrow \frac{C(\sigma_{posterior})}{E} - 1 = -0.03\%$$

Some results for data assimilation exercises

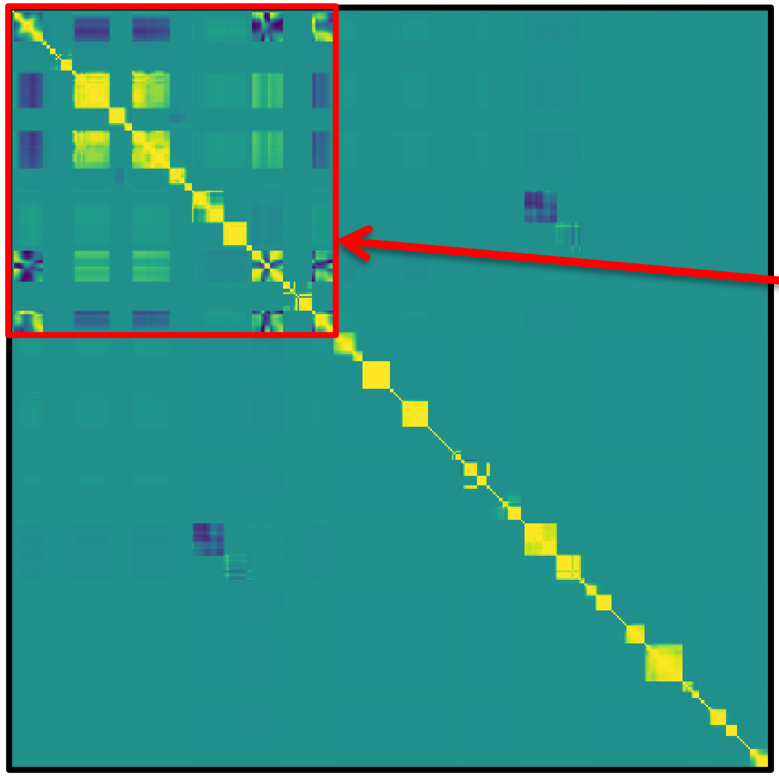
Largest contributor

Smallest contributor

A priori correlation Matrix



A posteriori correlation Matrix



$\Delta C_{ND} = 7.4\%$ → $\Delta C'_{ND} = 1.3\ \%$

Data assimilation mainly affects the six largest contributors

^{238}U Capture
^{240}Pu Fission
^{240}Pu Capture
^{239}Pu Capture
^{238}U Fission
^{238}U Inelastic

What is the physical value of those changes ?

How trustable is the initial correlation Matrix ?

How the initial correlation Matrix affect the result ?

…

Conclusions/Perspectives

The development of future reactor has to rely on **validated** simulation tool with mastered and **quantified uncertainties**

New generation tools allow to extend the field of VVUQ to **power reactor** → it has been used for the **Phenix reactivity loss**

Starting from JEFF 3.1.1 with **7.4%** nuclear data uncertainties to **1.3%**

Short term perspective
- Corrective factor
  - → compare with trends from JEFF 4.
  - → propagate to NDAST / ICSBEP / IRPhE to see the impact of such change
- Oriented further experiment towards some nuclear data
- Create adjusted cross-section on purpose (for a given reactor)

Long term perspective
- Perform the same exercise with other power reactor (JOYO, VTR, EBR-II, …)
- Uncertainty quantification + MP for core design purpose (lower the margins)

Upcoming Webinars

Date	Title	Presenter
20 March 2024	Overview of Canadian R&D Capabilities to Support Advanced Reactors	Lori Walters, CNL, Canada
17 April 2024	Multiphysics Depletion & Chemical Analyses of Molten Salt Reactors	Samuel Walker, INL, USA
22 May 2024	Joint GIF/IAEA Webinar: Regulatory Activities in support of SMRs and Advanced Reactor Systems	Panelists: • Ms. Paula Calle Vives, IAEA • Mr. Tarek Tabikh, CNSC • Dr. Greg Oberson, NRC Moderators: • Dr. Vladimir Kriventsev, IAEA • Dr. Patricia Paviet, PNNL