DE LA RECHERCHE À L'INDUSTRIE

Integral data assimilation of the MERCI-1 experiment for the nuclear data associated with the PWR decay heat computation

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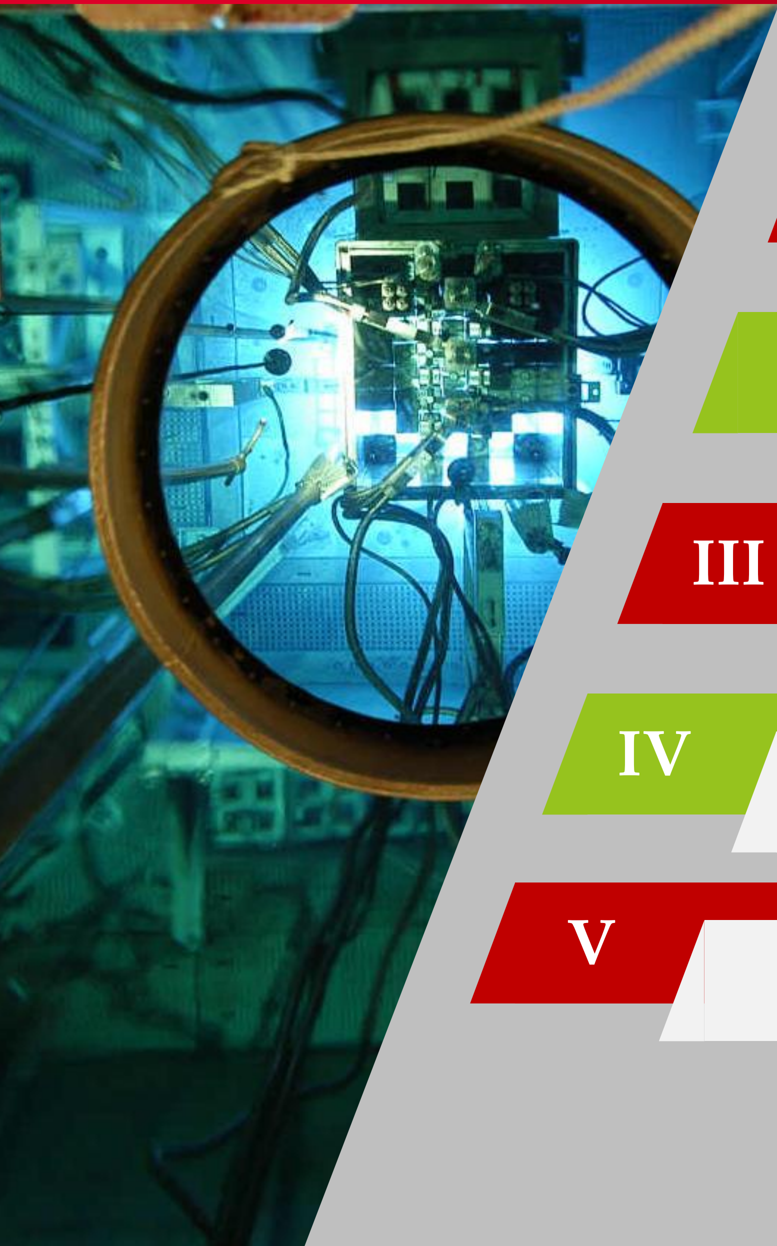
Summary

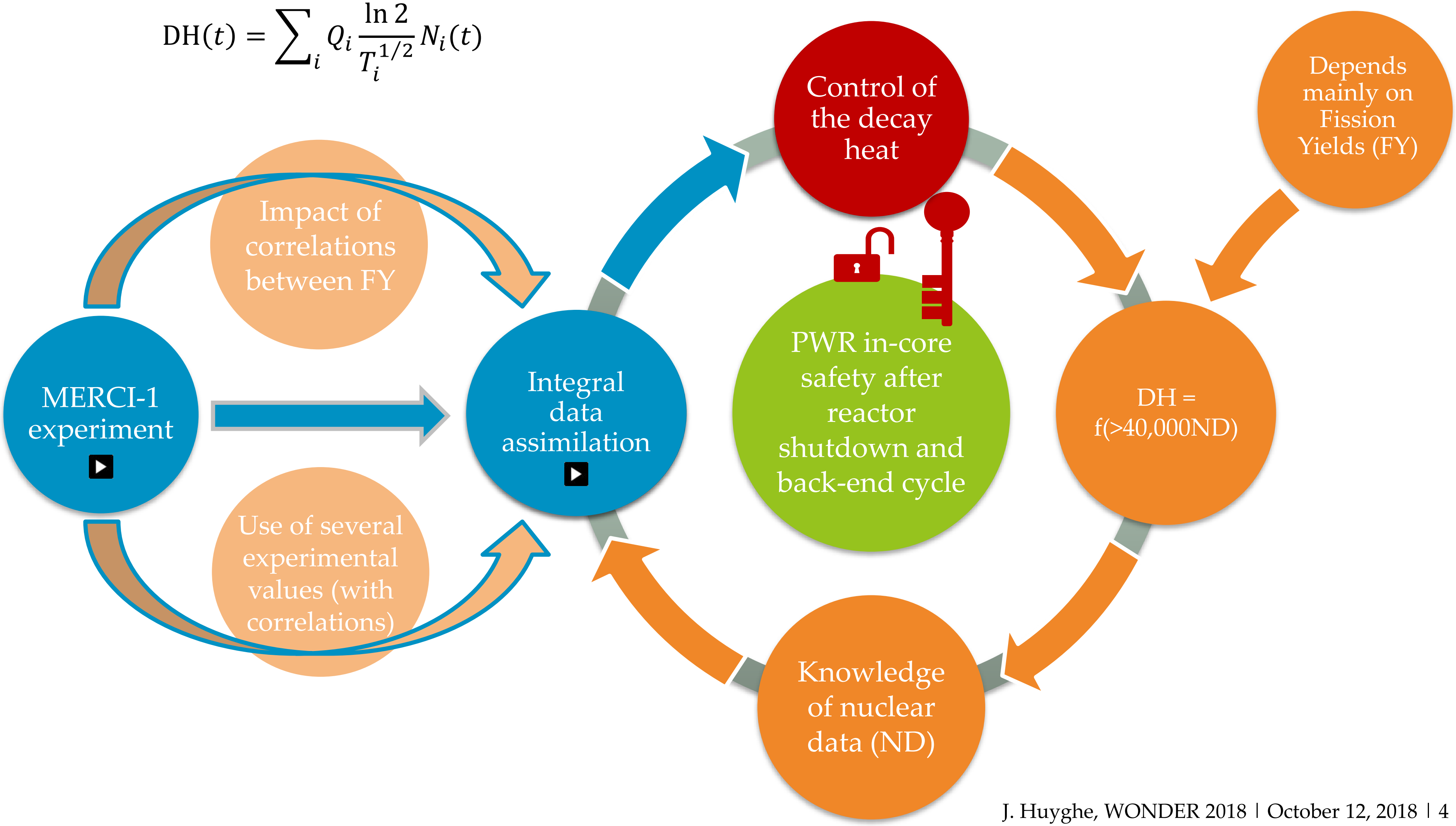


Introduction

Control of the decay heat for nuclear safety purposes

Decay heat (DH) = thermal power released by both radioactive decay of unstable fuel and material structure isotopes after reactor shutdown

$$\mathrm{DH}(t) = \sum_i Q_i \frac{\ln 2}{T_i^{1/2}} N_i(t)$$



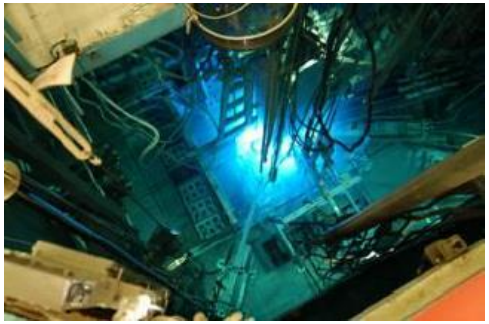
MERCI-1 experiment overview

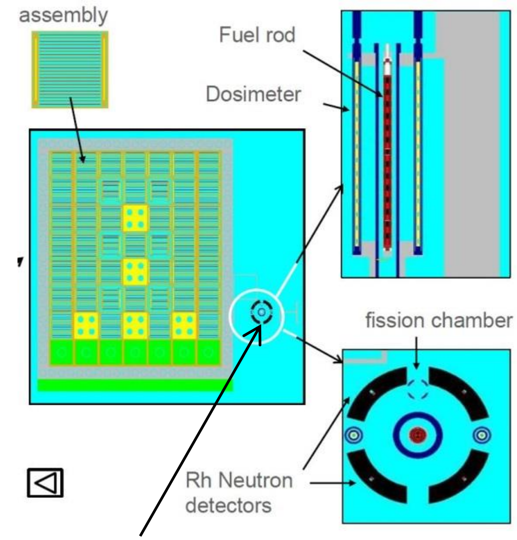
MERCI-1 integral experiment (2008)[1]

- Irradiation of a **PWR UOX fuel rod sample (e(^{235}U) = 3.7 wt.%)** in the OSIRIS reactor's reflector (CEA, Saclay, France) up to **3.6GWd/t$_{HM}$**
- OSIRIS reactor core loaded with U_3Si_2Al plates (e(^{235}U) = 19.75wt.%)
- Measurement of the decay heat released by the sample with the **MOSAIC calorimeter[2]** (**measurements from 45 minutes to 42 days of cooling time**) by an enthalpy balance on the secondary system of the calorimeter (heat pipe principle)[2]:

$$DH = Q_m C_p \Delta T \quad (1)$$

- Q_m: water mass flow
- C_p: heat capacity of water
- ΔT: temperature difference between the inlet and the outlet of the condenser





MERCI device

1. J.C. Jaboulay, S. Bourganel, "Analysis of MERCI decay heat measurement for PWR UO2 fuel rod", *Nuclear Technology, Vol. 177*, Jan. 2012
2. Ch. Blandin et al., "MERCI – MOSAIC: experimental tools for residual power measurement in the OSIRIS reactor", *IGORR 12*, 2009

Control of the uncertainties associated with the MERCI-1 experiment

MERCI-1 experimental uncertainty

$$DH = Q_m C_p \Delta T \quad (1)$$

Different sources of experimental uncertainties identified: **Q_m, C_p, ΔT**

- Assumed independent ➔ global uncertainty on DH obtained by quadratic summation
  → no correlations between Q_m and C_p
  → no correlations between Q_m and ΔT
  → correlations between C_p and ΔT determined: negligible in the propagation calculation

- The different uncertainty values associated with Q_m, C_p and ΔT were found in internal documents and the litterature[3,4]

- Uncertainties propagated to the DH ➔ **0.5% at 1 std for cooling times ∈ [45 min ; 42 days]**
  ➔ **1.0% at 1 std for cooling times ∈ [16 ; 21 days] ∪ [23 ; 25 days]**

3. https://webbook.nist.gov/chemistry/fluid/
4. W. Wagner, A. Pruss, "The IAPWS formulation 1995 for the thermodynamic properties of ordinary water substance for general and scientific use", *J. Phys. Chem. Ref. Data*, *31*, *2*, *387-535*, 2002

MERCI-1 calculation uncertainty

Different sources of calculation uncertainties associated with the interpretation of the MERCI-1 experiment:

- **Adjustment of the burnup reached at the end of irradiation**:
  ➔ adjustment performed by minimizing the calculation/experiment (C/E) discrepancies of the Nd concentrations (^{145,146,148,150}Nd): depends on the cumulated FY uncertainties of ^{235}U to ^{1xx}Nd
  ➔ **resulting uncertainty on the DH: 1.1% at 1 std**

- **Irradiation conditions: fuel temperature, coolant temperature and ^{235}U initial enrichment**
  ➔ evaluated by (separate) direct perturbations in the transport calculation
  ➔ **resulting uncertainty: between 0.1% at 45 min and 1.1% at 42 days of cooling (at 1 std)**

These different sources of calculation uncertainty + experimental uncertainty were propagated to the decay heat by quadratic summation (assuming they are all independent):
➔ result in a **global C/E decay heat uncertainty between 1.2 and 1.6% at 1 std** according to the cooling time considered

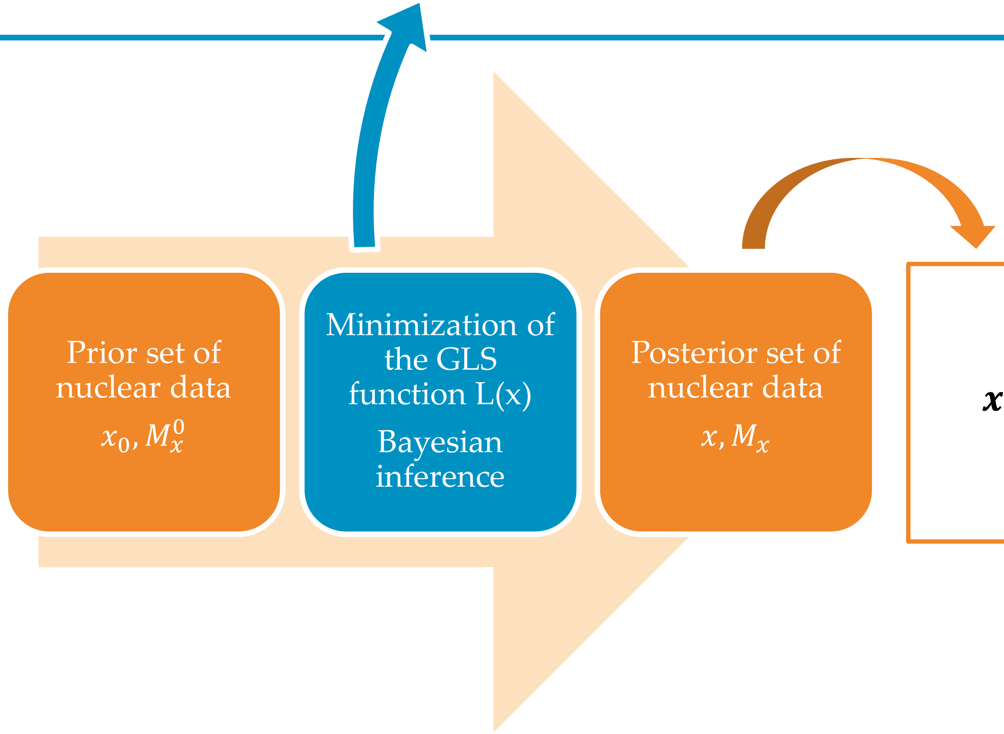
Integral Data Assimilation of the MERCI-1 experiment

CONRAD code

Integral data assimilation performed with the CONRAD code[5]: **CO**de for **N**uclear **R**eaction **A**nalysis and **D**ata assimilation (developed at CEA, Cadarache)

➔ assimilation of integral experiments (**C/E discrepancies + uncertainties ($M_{C/E}$)**) to provide feedback on nuclear data of interest for the decay heat

$$L(\boldsymbol{x}) = (\boldsymbol{x} - \boldsymbol{x_0})^T {M_x^0}^{-1} (\boldsymbol{x} - \boldsymbol{x_0}) + (\boldsymbol{C}(\boldsymbol{x}) - \boldsymbol{E})^T M_{C/E}^{-1} (\boldsymbol{C}(\boldsymbol{x}) - \boldsymbol{E})$$



Posterior ('updated') set of nuclear data:

$$\boldsymbol{x} = \boldsymbol{x_0} - M_x^0 S^T \left(S M_x^0 S^T + M_{C/E}\right)^{-1} (\boldsymbol{C}(\boldsymbol{x_0}) - \boldsymbol{E})$$

$$M_x = M_x^0 - M_x^0 S^T \left(S M_x^0 S^T + M_{C/E}\right)^{-1} S M_x^0$$

5. C. De Saint-Jean et al., "Status of CONRAD, a nuclear reaction analysis tool", *International Conference on Nuclear Data for Science and Technology*, 2007

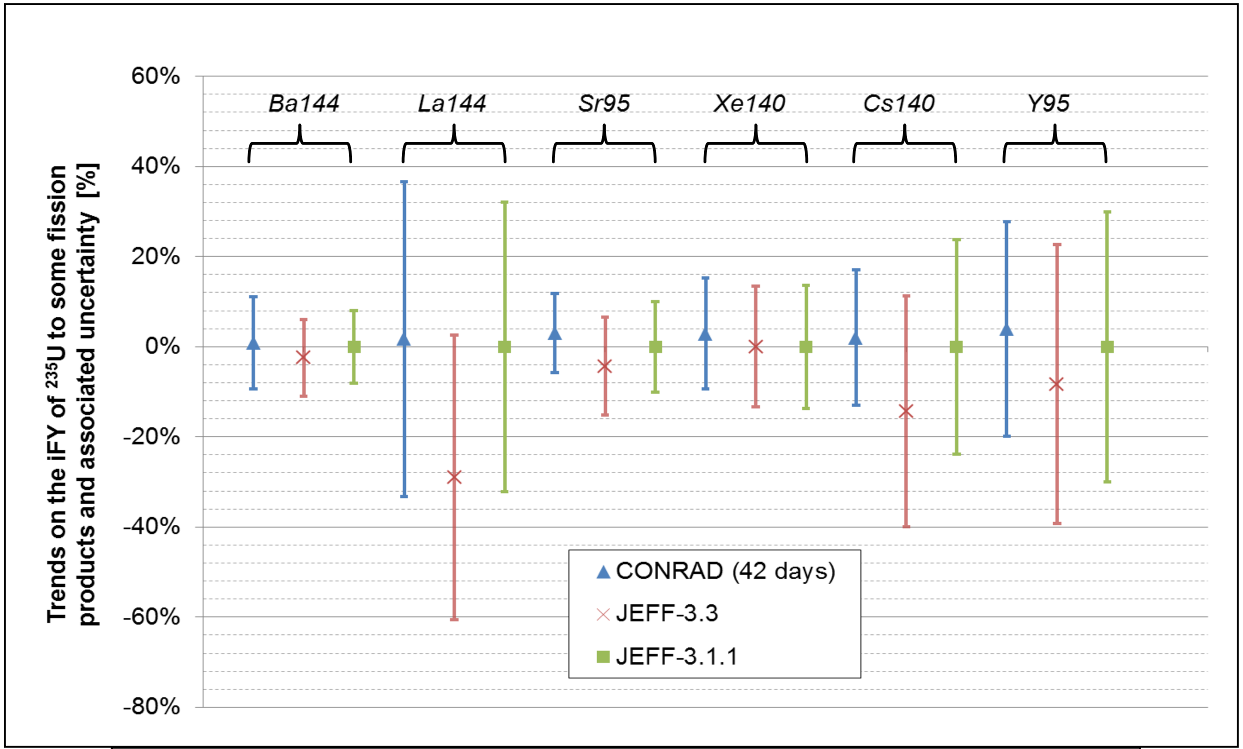
1. Assimilation of a particular MERCI-1 exp. value

Example case: standard **PWR UOX fuel / BU = 15GWd/t$_{HM}$ / 1 year of cooling** (e.g. fuel transport issues)

→ Assimilation of the last DH measurement of MERCI-1, *i.e.* at 42 days of cooling (C/E – 1 = -0.83% ± 1.6%)

→ DH = mainly sensitive to **independent FY (iFY) of ^{235}U to ^{140}Xe, ^{140}Cs, ^{95}Sr, ^{95}Y, ^{144}La, ^{144}Ba** (42 days / 1 year)

→ parameters fitted with CONRAD



Feedbacks on JEFF-3.1.1 independent fission yield (iFY) data after assimilation of the MERCI-1 experimental at 42 days of cooling with CONRAD and comparison to JEFF-3.3 trends

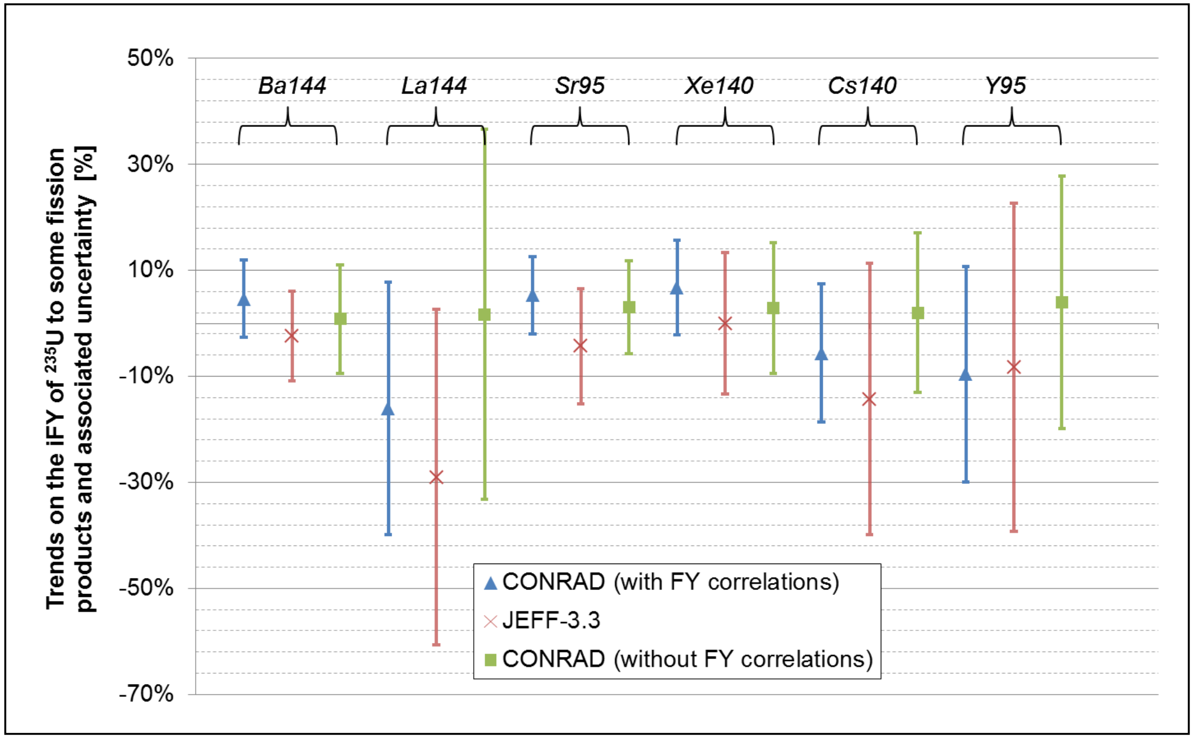
- **Consistent trends** (posterior mean value + uncertainty) **with JEFF-3.3** at 1 std
- No significant change in terms of uncertainty except for iFY of ^{235}U to ^{140}Cs and ^{95}Y (reduced)

2. Impact of correlations between iFY data

DH mainly sensitive to iFY // JEFF-3.1.1 does not provide covariance matrices for iFY

➔ covariance matrices for both fissile systems of ^{235}U and ^{239}Pu produced at the CEA[6] associated with JEFF-3.1.1 iFY data, stored in the COMAC covariance matrix database[7]

→ Same integral data used for the assimilation (*i.e.* MERCI-1, 42 days) ➔ impact of correlations between iFY



- **More consistent trends** (posterior mean value + uncertainty) **with JEFF-3.3** at 1 std (in particular for ^{144}La, ^{140}Cs, ^{95}Y)
- **Reduced associated uncertainties** ➔ 15 to 30% uncertainty reduction compared to the 'without iFY correlations' case

➔ **The iFY correlations will be taken into account from now on for this study**

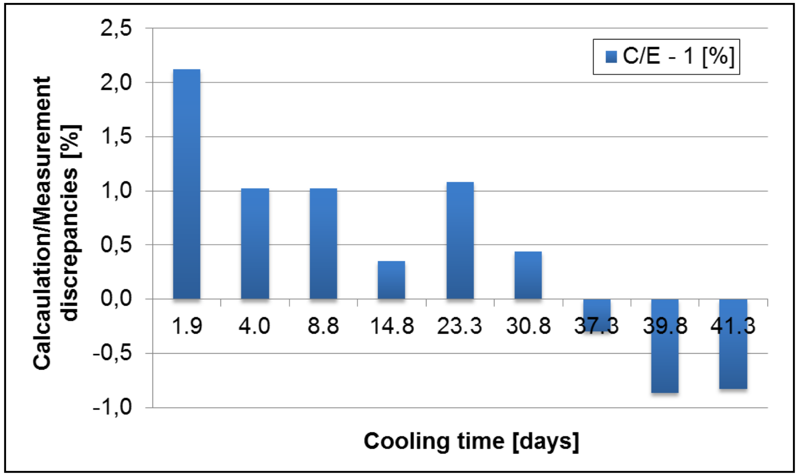
6. N. Terranova, "Covariance evaluation for nuclear data of interest to the reactivity loss estimation of the Jules Horowitz Material Testing Reactor", PhD thesis, 2016
7. P. Archier et al., "COMAC: Nuclear data covariance matrices library for reactor applications", Proc. Int. Conf. PHYSOR, 2014

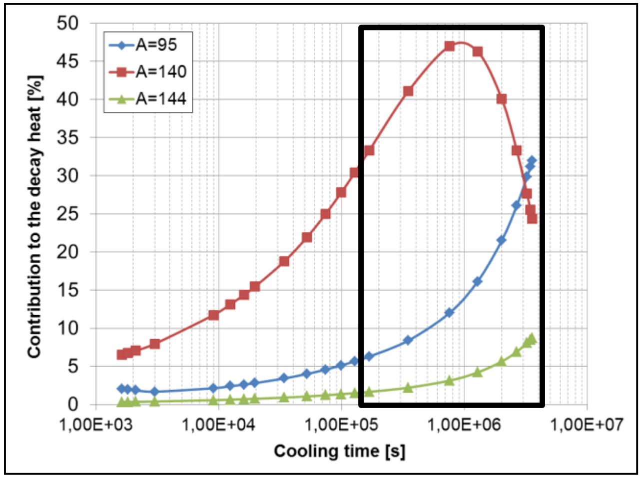
3. Assimilation of several experimental values – Which experimental data?

Improve the data assimilation process → several experimental data used simultaneously, *i.e.* MERCI-1 measurements at different cooling times → which experimental data?

→ Choice: based on the relative contribution of the fission products of interest to the DH (main masses A=95, 140 and, marginally, 144)

➔ **9 experimental values considered** (example)





→ The simultaneous use of several experimental values coming from the same experiment raises issues of experimental correlations to consider for the data assimilation → determination?

3. Assimilation of several experimental values – Experimental correlations?

Determination of the **experimental covariances**?

$$DH = Q_m C_p \Delta T \quad (1)$$

$$cov(DH_a, DH_b) = cov\left(Q_{m_a} C_{p_a} \Delta T_a, Q_{m_b} C_{p_b} \Delta T_b\right)$$

The calculation decomposition involves several terms of covariance:

- $\alpha \times cov\left(C_{p_a}, C_{p_b}\right)$
- $\beta \times cov(T_a, T_b)$
- $\gamma \times cov(Q_{m_a}, Q_{m_b})$

→ $\alpha \times cov\left(C_{p_a}, C_{p_b}\right)$ determined by performing a polynomial regression (3rd order in good accordance with experimental data of C_p) of C_p vs. T :

$$C_p(T) = aT^3 + bT^2 + cT + d$$

a, b, c and d determined with associated variances and covariances ➔ propagation to a $\alpha \times cov\left(C_{p_a}, C_{p_b}\right)$

➔ numerical applications for the nine experimental values taken: **negligible term** (given the values of α,β,γ)

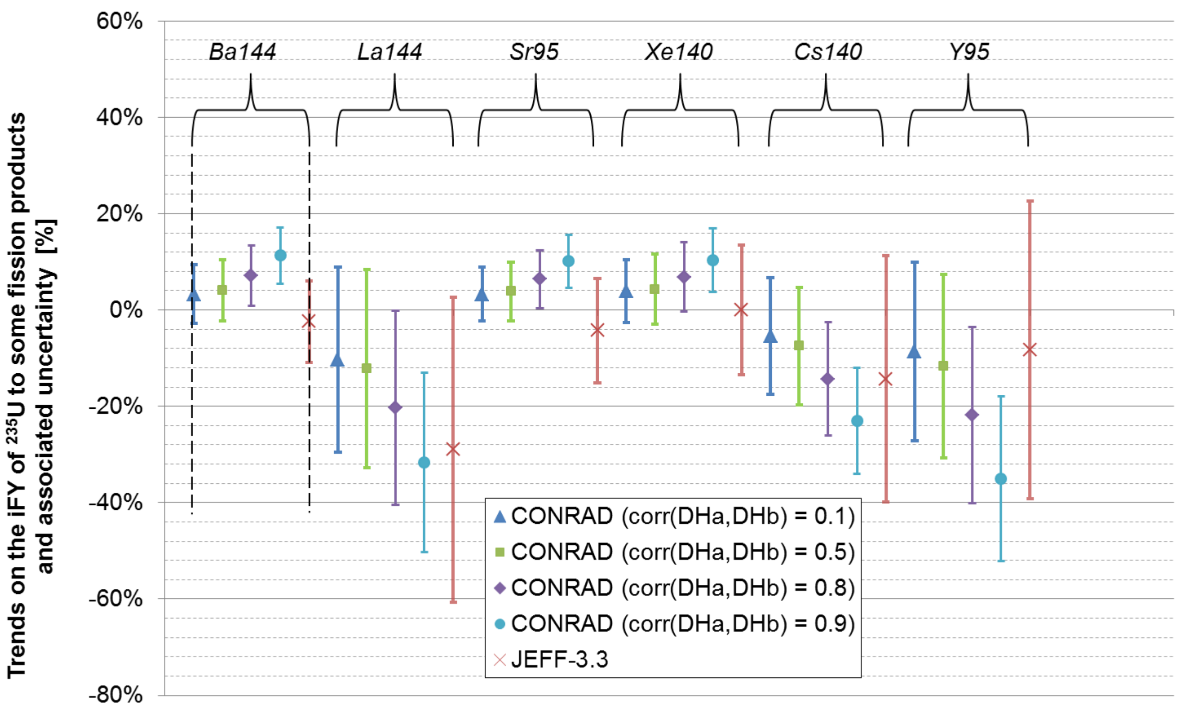
→ $cov(T_a, T_b)$, $cov(Q_{m_a}, Q_{m_b})$ could not be assessed → lack of information thereon in the experimental process

→ other methods?

→ **Different tests were performed** (with different experimental correlation values) to **measure the sensitivity of the assimilation results due to the experimental correlations considered**

3. Assimilation of several experimental values – Results

→ Different tests performed with experimental correlations of 0.1, 0.5, 0.8, 0.9

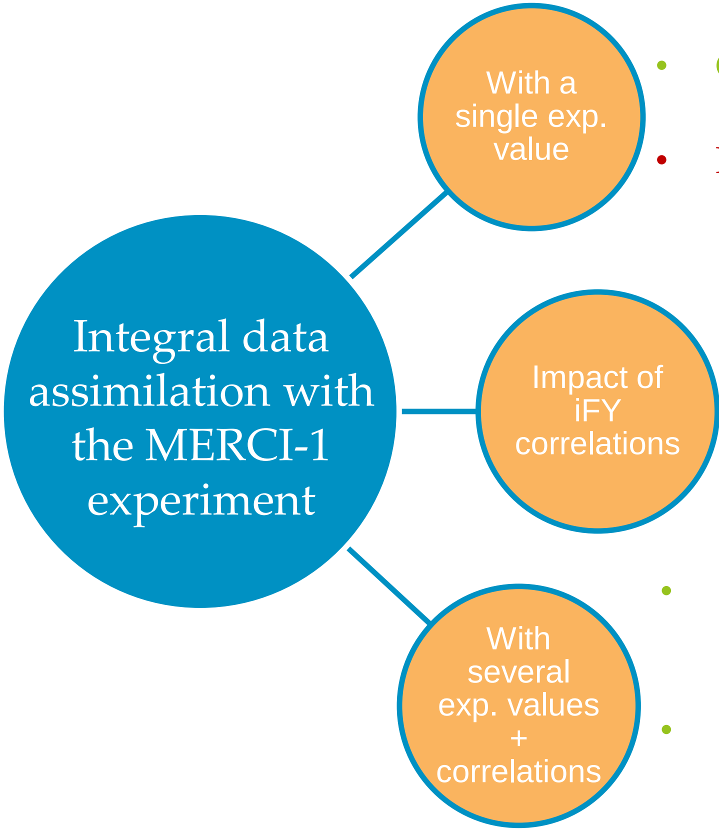


- **Consistent trends with JEFF-3.3 at 1 std regardless of the experimental correlations** considered between each couple of DH values
- The **sensitivity of the assimilation results due to the experimental correlations** considered is **lower** than the **sensitivity due to the inclusion of correlations between iFY**
- The lower the exp. correlation, the more independent each experiment is with each other, and the more restrained the trends on each iFY are ➔ cf. C/E discrepancies

- Depending on the iFY studied, the trends get closer to JEFF-3.3
  - with lower exp. correlations for ^{144}Ba, ^{140}Xe, ^{95}Sr and ^{95}Y
  - with higher exp. correlations for ^{144}La and ^{140}Cs

Conclusions and perspectives

Conclusions and perspectives



- Consistent trends with JEFF-3.3
- No significant change in terms of uncertainty

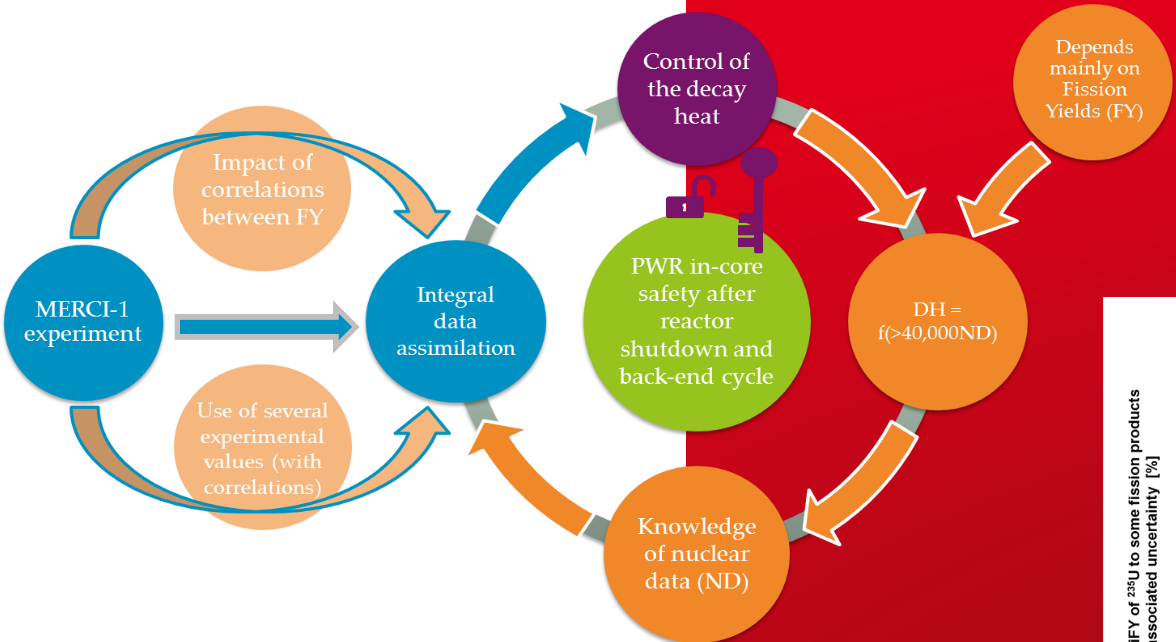
- More consistent trends with JEFF-3.3
- Reduced associated uncertainties

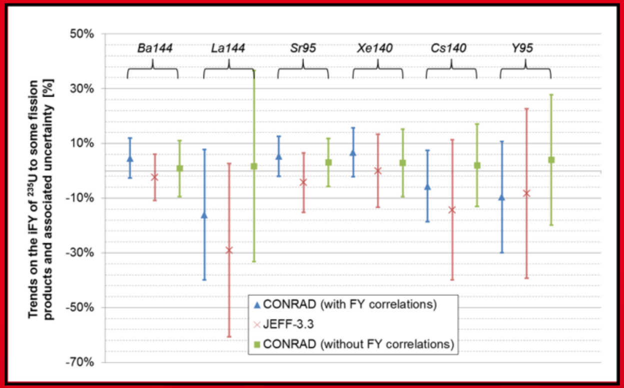
- Consistent trends with JEFF-3.3 at 1 std regardless of the experimental correlations
- Sensitivity of the assimilation results due to the exp. correlations < sensitivity due to the inclusion of correlations between iFY

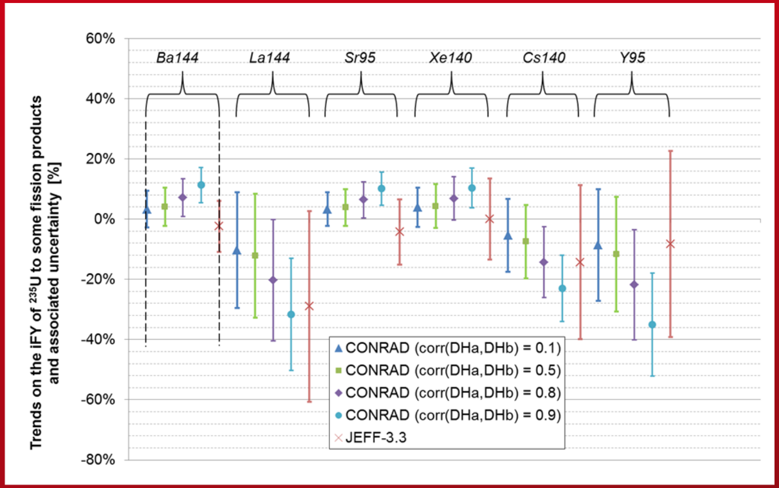
➔ Assimilating several correlated MERCI-1 experimental values and adding covariance information on iFY result in trends in better accordance with JEFF-3.3

➔ Need to accurately assess the experimental correlations since it has a direct impact on the assimilation results

Thank you for your attention







$$L(\boldsymbol{x}) = (\boldsymbol{x} - \boldsymbol{x}_0)^T M_x^{0^{-1}} (\boldsymbol{x} - \boldsymbol{x}_0) + (\boldsymbol{C}(\boldsymbol{x}) - \boldsymbol{E})^T M_{C/E}^{-1} (\boldsymbol{C}(\boldsymbol{x}) - \boldsymbol{E})$$

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