NUCLÉAIRE
& PARTICULES

APRENDE

Experimentalists-Evaluators Workshop

Decay heat calculations with JEFF-4.0 fission yields and decay data

L. Giot, F. Esposito

Task 4.3.2 Fission yields benchmarking

Lausanne, 07/07/2026

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Decay heat calculations

Summation method

$$DH(t_c) = f(t_c) = \sum_{i}^{n} N_i(t_c)\, \lambda_i\, \overline{E}_i$$

N_i : Number of nuclei i at cooling t_c

λ_i : Decay constant

$\overline{E}_i$: Mean decay energy of nucleus i

Atomic Densities N_i : solving Bateman's equations

Transport and depletion calculations : reactor model + neutronic code

$$\frac{\partial N_i(t)}{\partial t} = \sum_{j \neq i} \left(b_{j \to i}\, \lambda_j + \langle \sigma_{j \to i} \phi \rangle \right) N_j(t) - \left(\lambda_i + \langle \sigma_i \phi \rangle \right) N_i(t)$$

production & disappearance per radioactive decays & nuclear reactions

~ 40 000 nuclear data: σ, $\overline{E}$, Branching Ratio, λ, Fission Yields, $\overline{\nu}$

=> Complex calculation (reactor model + depletion)

=> Quality of the code but also of the input data !

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Decay heat calculations

- **Summation method**

$$DH(t_c) = f(t_c) = \sum_{i}^{n} N_i(t_c)\, \lambda_i\, \overline{E_i}$$

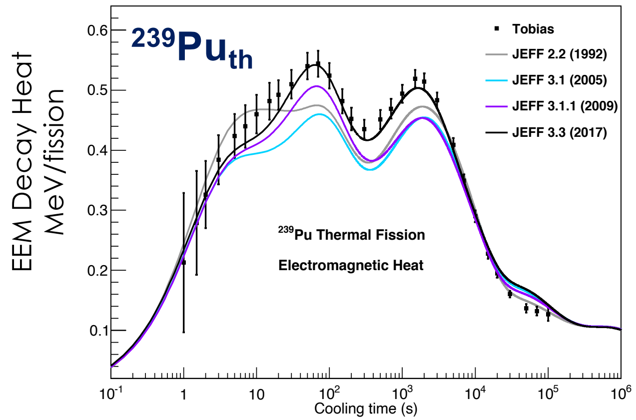
- $\overline{E_i}$ usually divided in 3 parts in evaluated librairies(e.g ENDF, JEFF, JENDL) :

$$\overline{E}_{LP} = \overline{E}_{\beta-} + \overline{E}_{\beta+} + \overline{E}_{e-} + \cdots$$ Light particles component

$$\overline{E}_{EM} = \overline{E}_{\gamma} + \overline{E}_{x-ray} + \overline{E}_{anni.rad.} + \cdots$$ Electromagnetic component

$$\overline{E}_{HP} = \overline{E}_{\alpha} + \overline{E}_{SF} + \overline{E}_{p} + \overline{E}_{n} + \cdots$$ Heavy particules component

See A. Algora's talk



A. L. Nichols et al., EPJ A 59 (2023)

- **$\overline{E_i}$ measurements & Pandemonium effect**

Before the 90s, conventional detection techniques: high resolution γ-ray spectroscopy

Excellent resolution but efficiency which strongly decreases with increasing energy

Risk of overlooking the existence of β^- feeding into the high energy nuclear levels of daughter nuclei

Incomplete decay schemes: overestimate $\overline{E}_{beta}$, underestimate $\overline{E}_{gamma}$

=> Most suitable technique to re-measure key nuclei:
Total Absorption Gamma Spectroscopy using 4π detectors (ex: NaI, LaBr3)

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How/Why to improve FY & Decay data for inventory and DH calculations ?

- **From the industry perspective:**
  validation = calculations (given version of the depletion code + given library) on a set of benchmarks (modeling and/or experimental values), quantification of the differences to get some margins

  => Less feedback on FY and DD new needs or needed improvments wrt XS, $\overline{\nu}$ ..

  => To be included/more visible in the NEA HPRL list ? => more exchanges …

  ex (from EDF): MOX DH between 10 days and 1 year, contribution of ^{242}Cm

- **From the nuclear data perspective:**
  comparison between experimental values (PIE and DH measurements) and calculations

  => often limited fission pulse cases & assemblies

  => more measurements needed from irrradiation experiments

  only one measurement set for $^{241}Pu_{th}$ & $^{239}Pu_{fast}$ …

=> The simplest the set-up is, the easiest to disentangle the effects and then to identify the nuclear data to be improved

	Nucleus	Measurements	Cooling time	Uncertainty Range %	Year	Authors
Fission induced per thermal neutrons	^{235}U	β, γ	0.4 - 10^5 s	3.2% -9.5 % 2.5% -24.1% 2.5% - 8.6%	1989, 1980,1997	Dickens, Tobias, Lowell, others
	^{239}Pu	β, γ	1 - 10^5 s	2.3% - 6.9% 2.7% -60.9% 2 % - 9.9 %	1989, 1980,1997	Dickens, Tobias, Lowell, others
	^{241}Pu	β, γ	3 - 1.2 10^4 s	4% - 11.1%	1980, 1989	Dickens
Fission induced per fast neutrons	^{239}Pu	β, γ	19 - 2.4 10^5 s	2.4% - 5.7%	1982	Akiyama
	^{233}U	β, γ	19 - 2.4 10^5 s	3.2% -7.5%	1982, 2002	Akiyama, Ohkawachi
	^{235}U	β, γ	19 - 2.4 10^5 s	2.1% - 6.1%	1982	Akiyama
	^{238}U	β, γ	0.4 – 2.4 10^5 s	3.8% - 20% 1.8% - 5.3%	1997, 1998	Akiyama, Lowell
	^{232}Th	γ	19 - 2.4 10^5 s	3.7 %- 9.2 %	1997	Akiyama
	^{237}Np	γ	264 - 2 10^4 s	not given	2002	Ohkawachi

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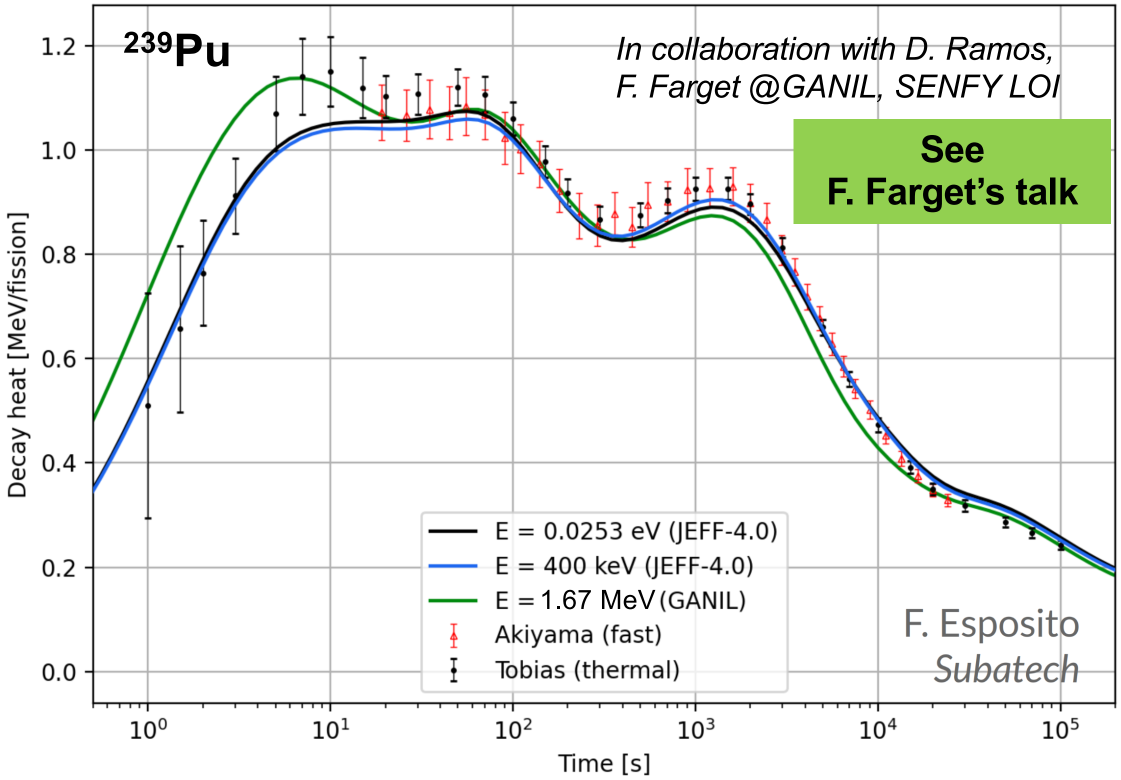
Why to improve FY & Decay data for inventory and DH calculations ?



- Fast reactors: FY distribution depends on neutron spectrum

=> needs of FY measured at different neutron energies, as done per the GANIL team

=> Extra heat at short cooling time ?

=> needs of DH fission pulse measurements for $^{239}Pu_{fast}$ with lower uncertainties

but also for other Pu isotopes ….

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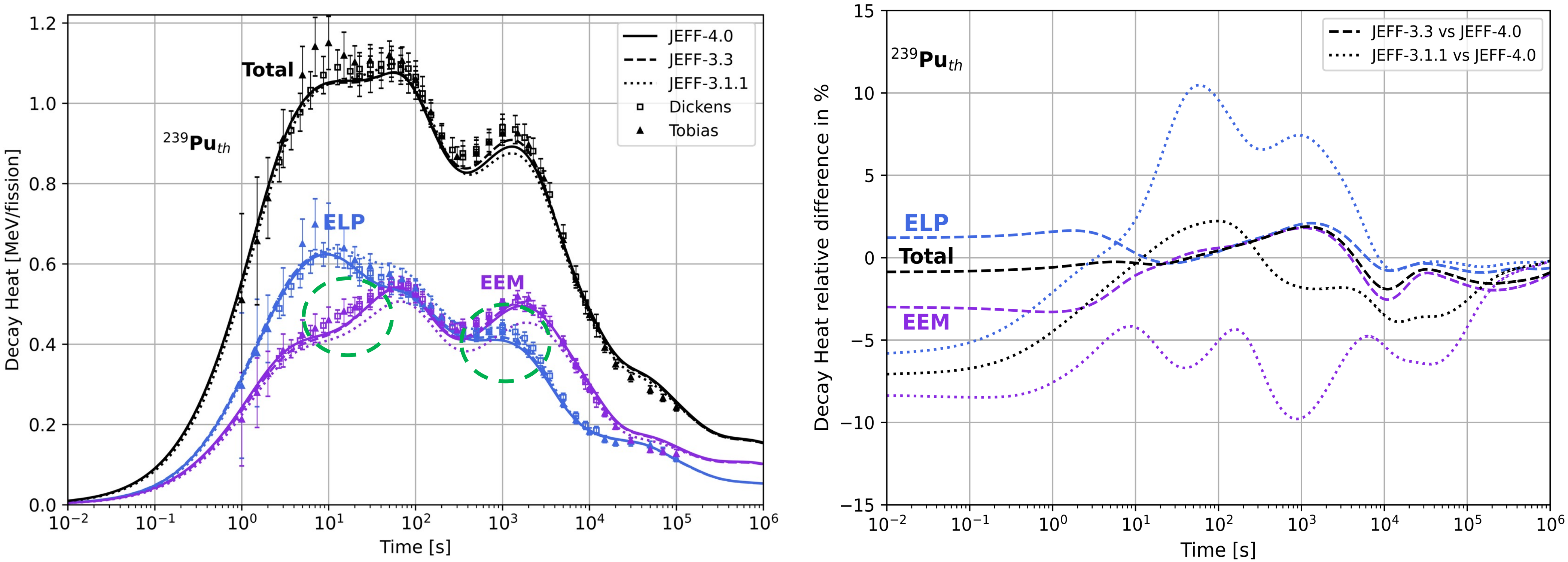
Impact of new TAGS data in JEFF-4.0 decay data library : $^{239}Pu_{th}$

JEFF-3.3 new mean decay energies : ^{105}Mo,^{104,105,106,107}Tc,^{87,88}Br, ^{92,94}Rb

JEFF-4.0 new mean decay energies included : ^{93}Rb, ^{96gs,96m,99}Y, ^{103,108}Tc, ^{99}Y, ^{138}I, ^{142}Cs



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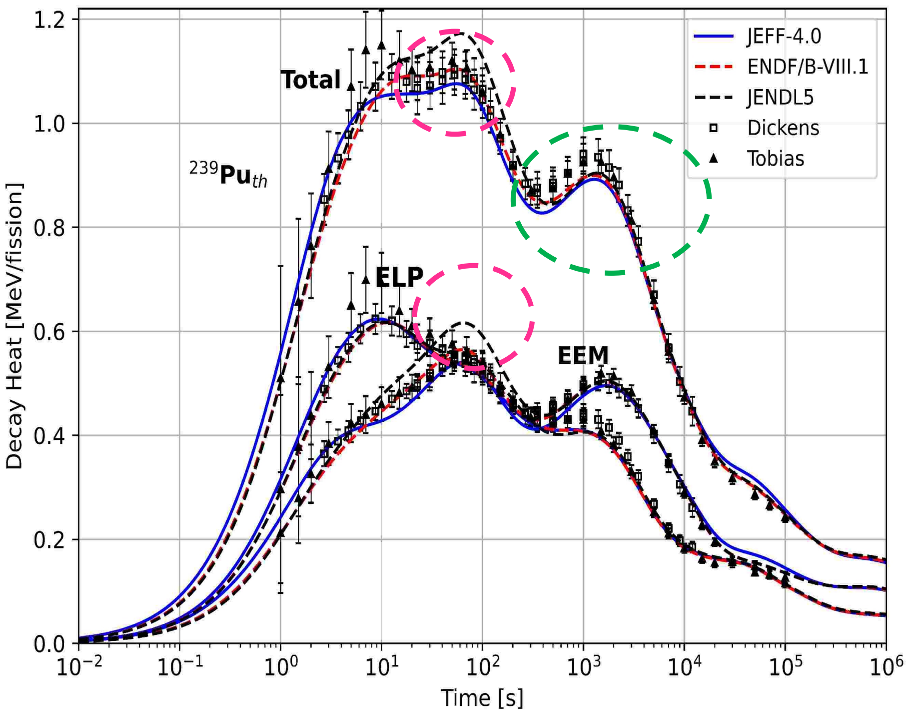
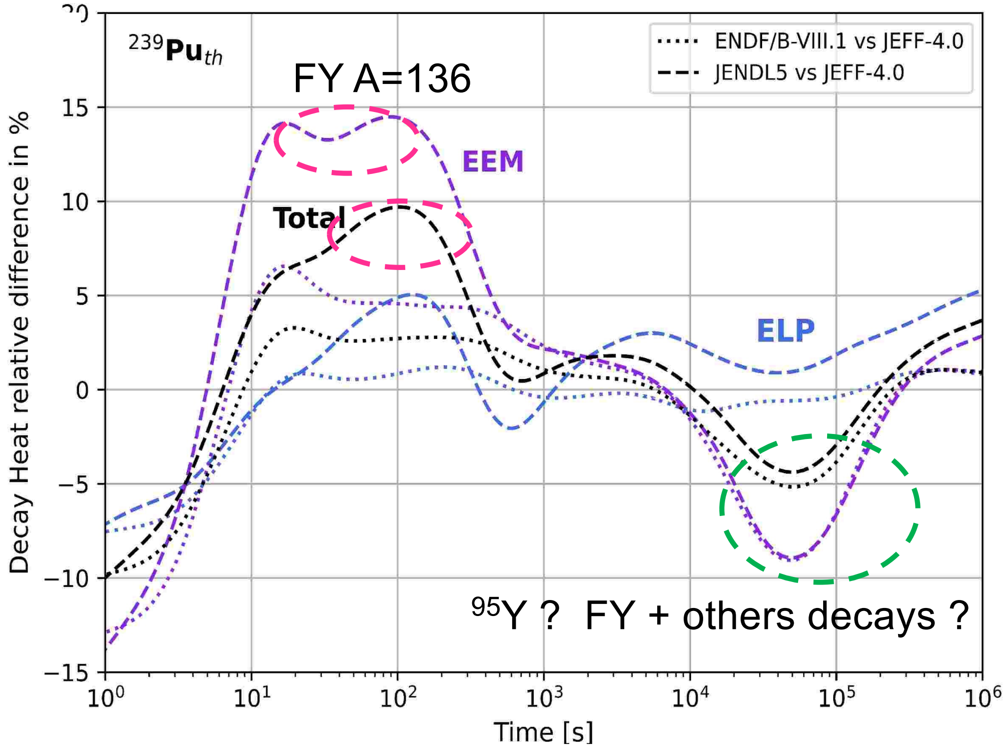
ENDF/B-VIII.1(same than ENDF/B-VIII.0) new decays included : ^{82,83}Ge, ^{82,86}As, ^{88,89,90,91}Br, ^{90}Kr, ^{93,95,96}Rb, ^{95}Sr, ^{95,98,99}Y, ^{134}Sb, ^{138}I, ^{140,141}Cs, ^{142}Ba, ^{143,144,145}La *TAS published not in JEFF* *TAS published in JEFF*





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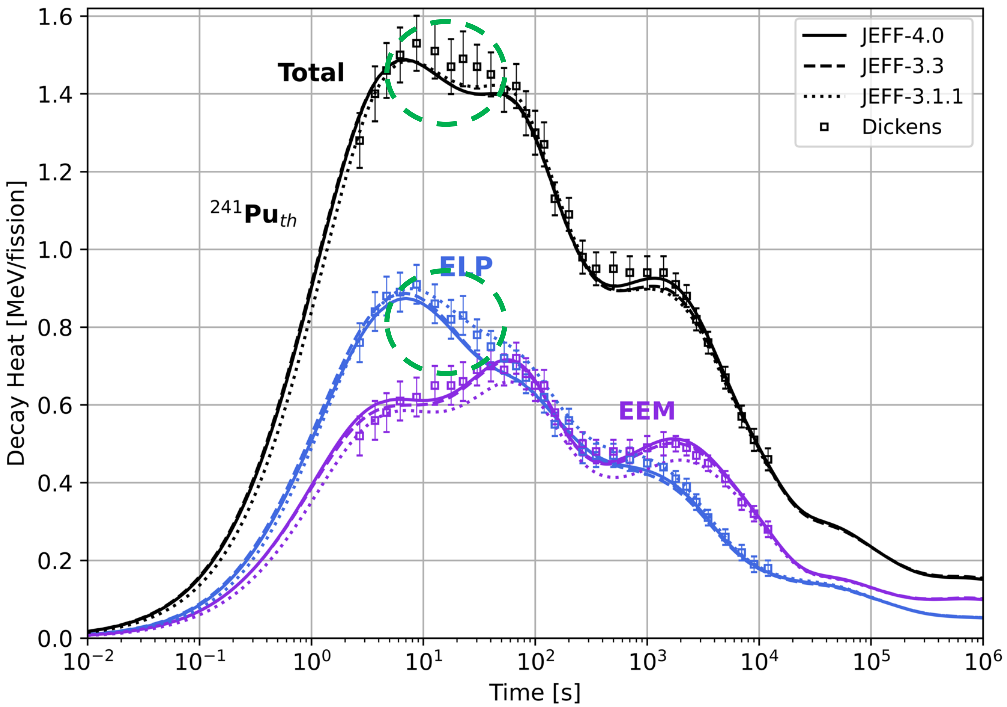

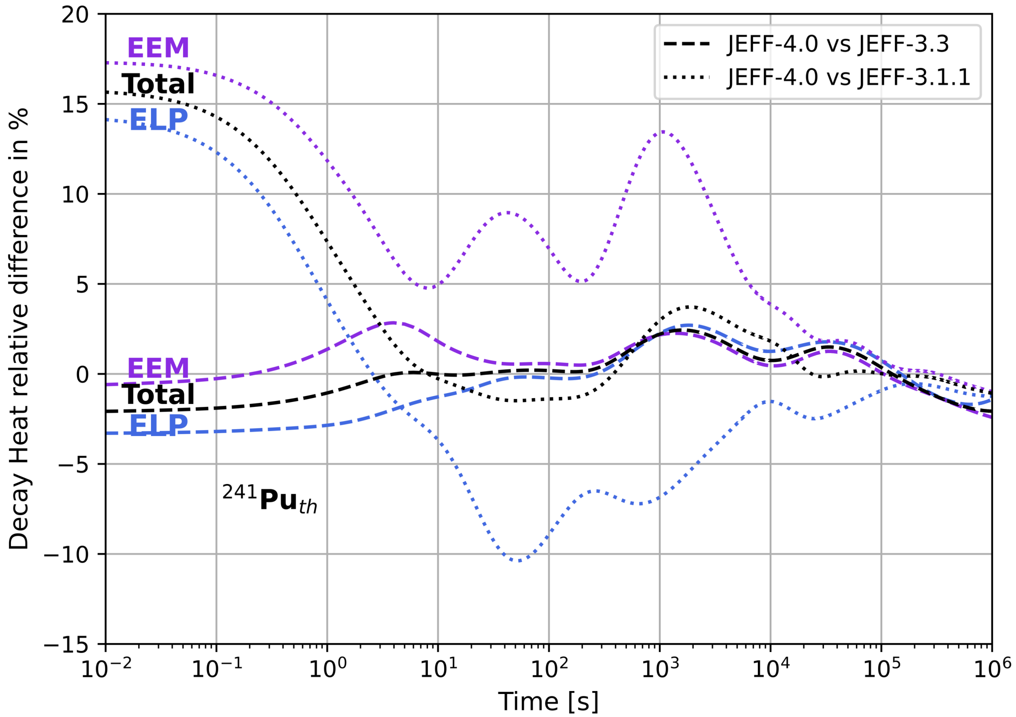

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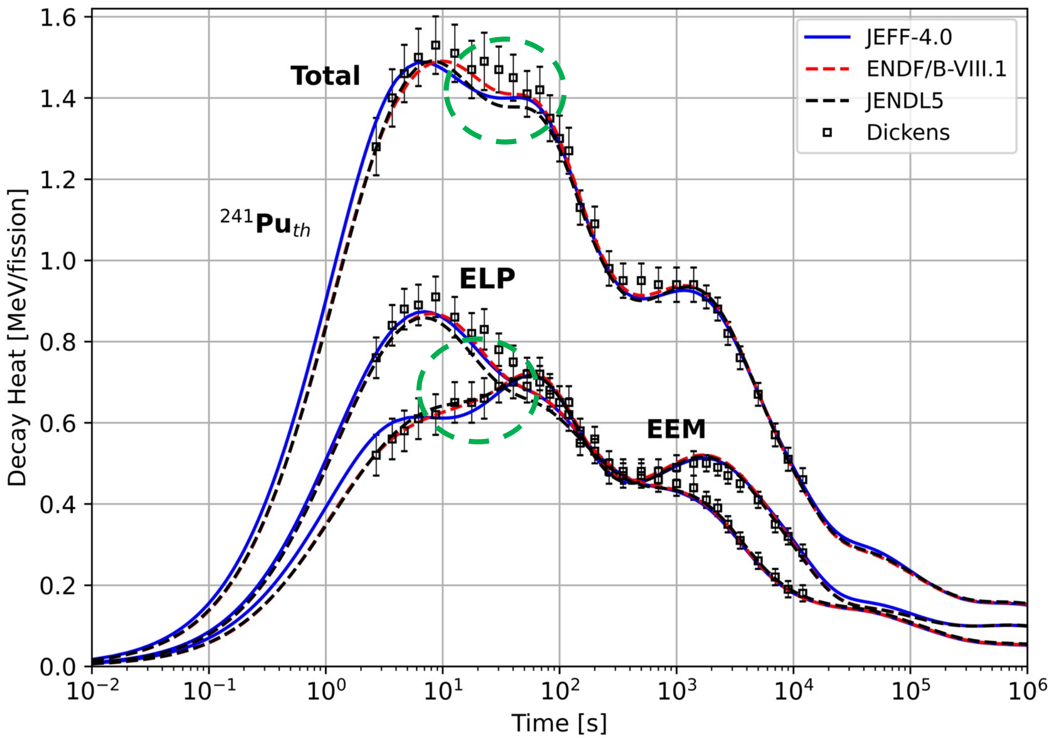

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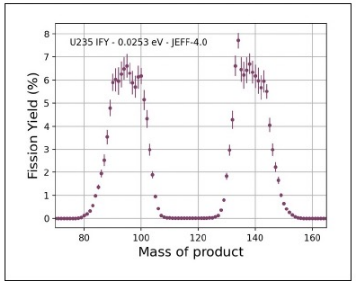
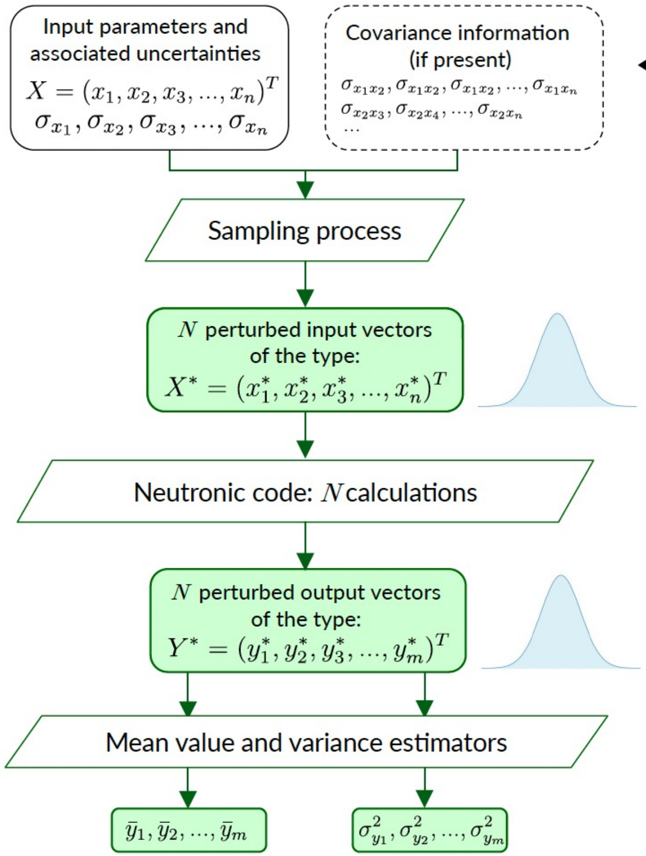
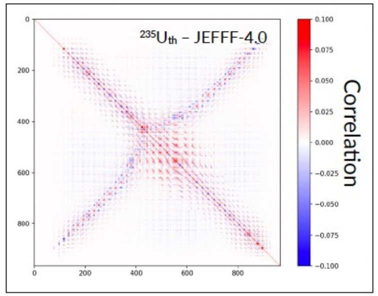
ND uncertainty propagation – Monte Carlo approach

Cocodrilo code







Code-to-code comparisons

Influence of the sampling distribution

Results with JEFF-4.0

Results using CEA's random fission yields

Recent work focussed on FY
See F. Esposito et al., WONDER 2026 proceeding

More complex cases

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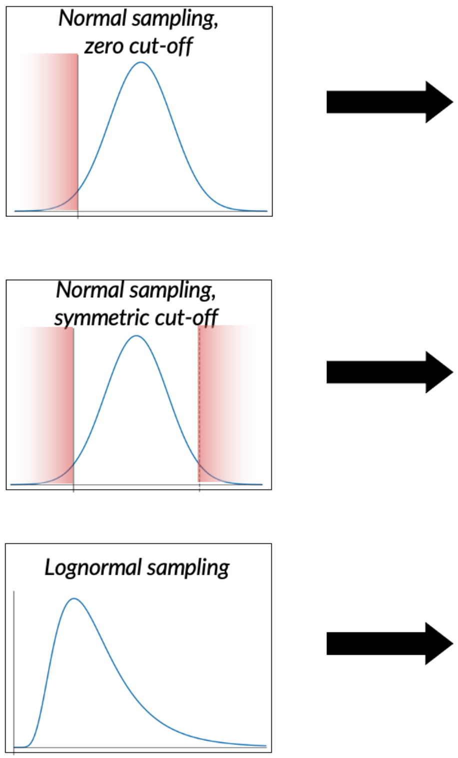
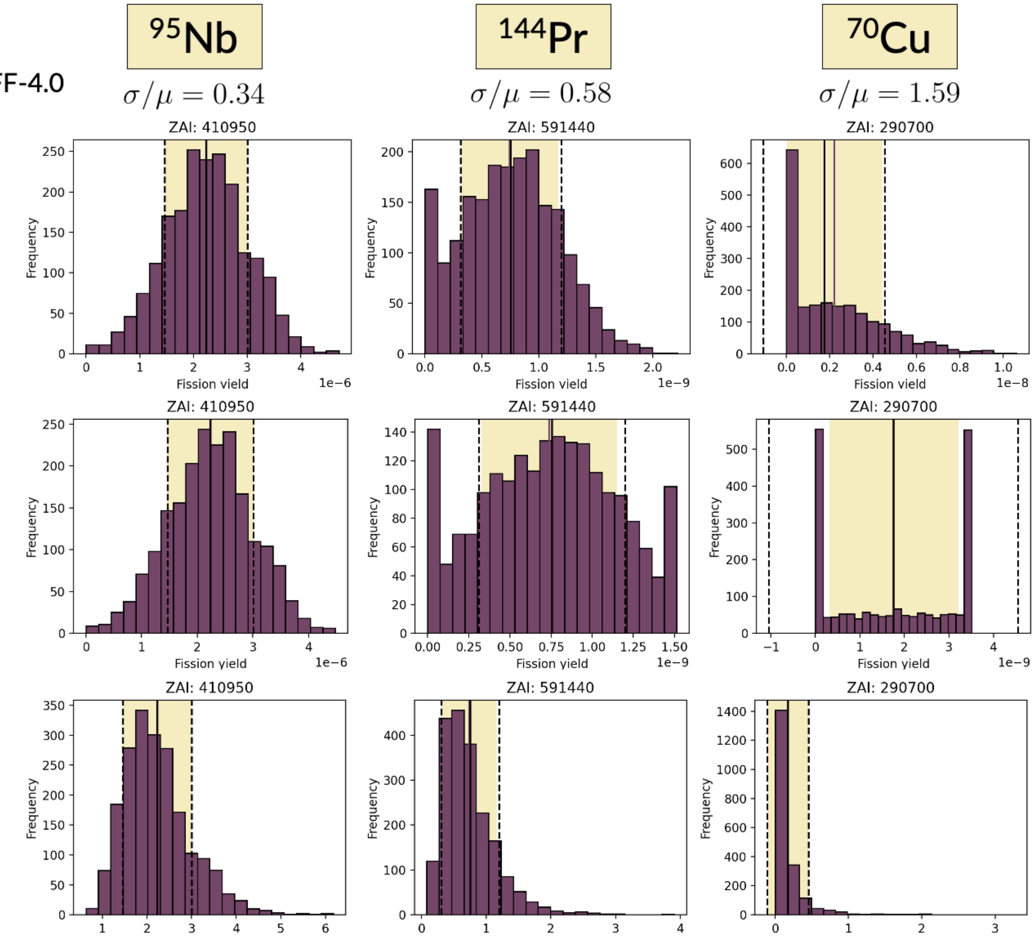
FY uncertainty propagation : Influence of the sampling distribution

Different choices are possible on the sampling distribution and on the treatment of negative values. Example with 2000 samples, $^{235}U_{th}$, JEFF-4.0





Purple bins
Samples distribution

Purple solid line
Mean of the samples

Yellow background
1 standard deviation of the samples

Black solid line
Reference mean

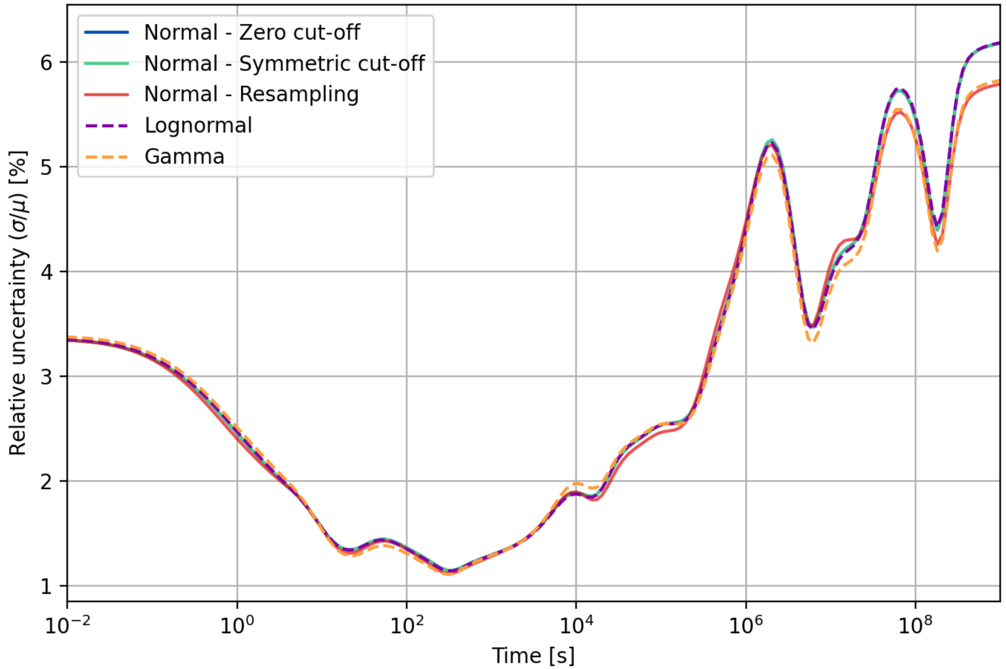
Black dashed line
Reference standard deviation

FY uncertainty propagation : Influence of the sampling distribution

Does the choice have an impact on the final decay heat uncertainty?

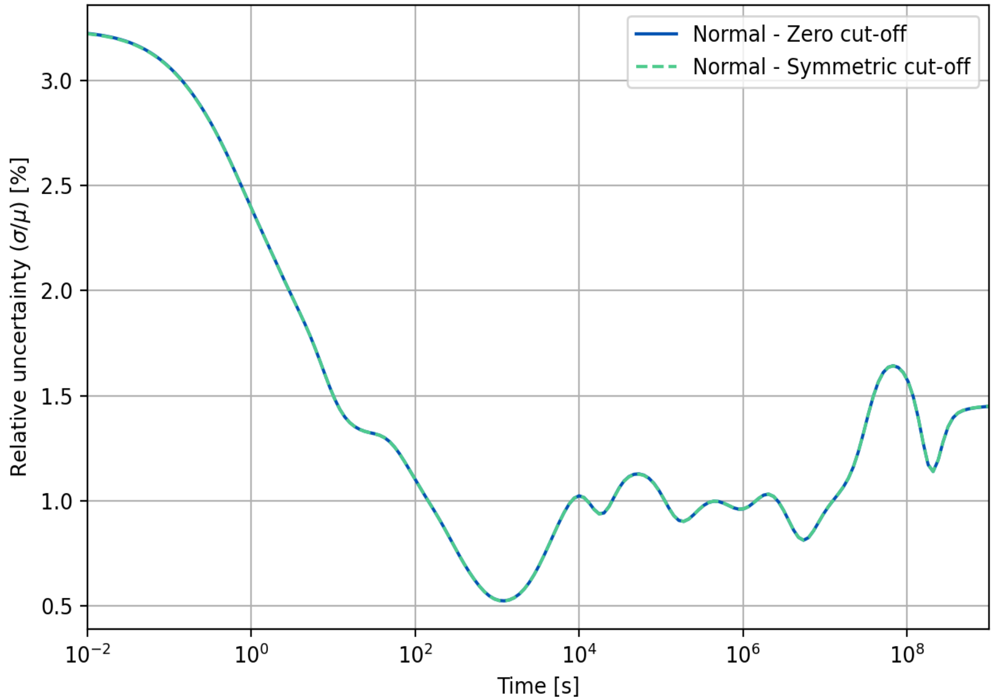
Test case: $^{239}Pu_{th}$ – JEFF-4.0 fission yields – 2000 samples

Without covariance matrix for fission yields



Max difference: <0.41%

With covariance matrix for fission yields



Max difference: <0.002%

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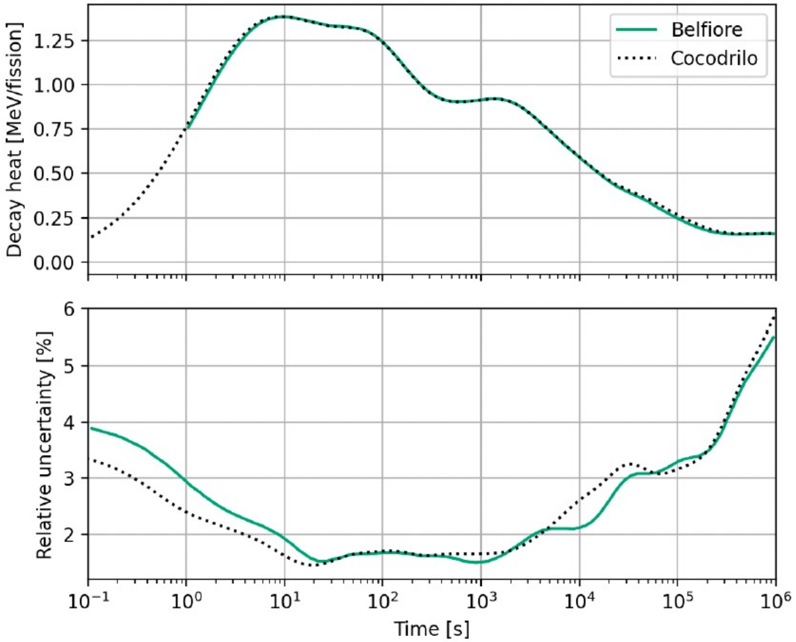
FY uncertainty propagation : Code-to-code comparisons

Belfiore[1]: Monte Carlo approach (SANDY code)

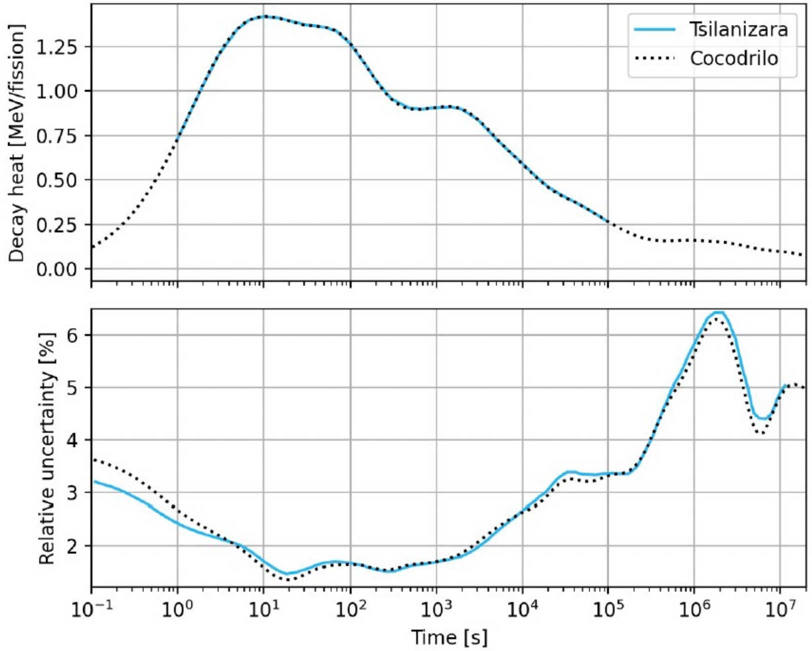
Fission Pulse from $^{235}U_{th}$ – JEFF-3.3. 200 samples with Normal sampling, symmetric cut-off. **Differences may be explained by the small number of samples.**



[1]E. Belfiore. "Sensitivity and Uncertainty Analysis for Nuclear Data of Relevance in Spent Nuclear Fuel Characterization", Master Thesis, (2023)

Tsilanizara[2]: S/U approach

Fission Pulse from $^{235}U_{th}$ – JEFF-3.1.1. **Differences may be explained by the different approach for uncertainties propagation.**



[2]A. Tsilanizara and T. Huynh. "New feature of DARWIN/PEPIN2 inventory code: Propagation of nuclear data uncertainties to decay heat and nuclide density". In: Annals of Nuclear Energy 164 (2021)

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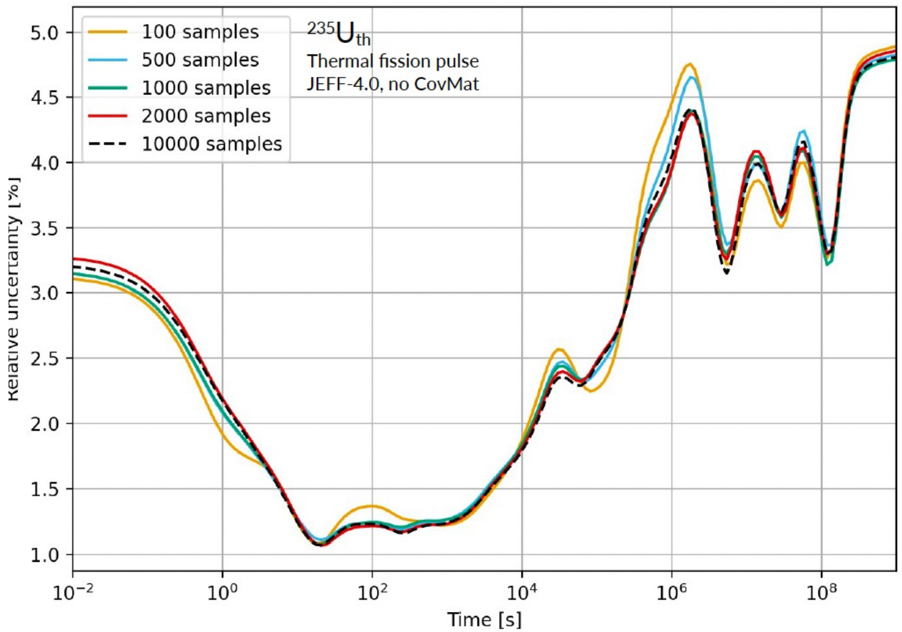

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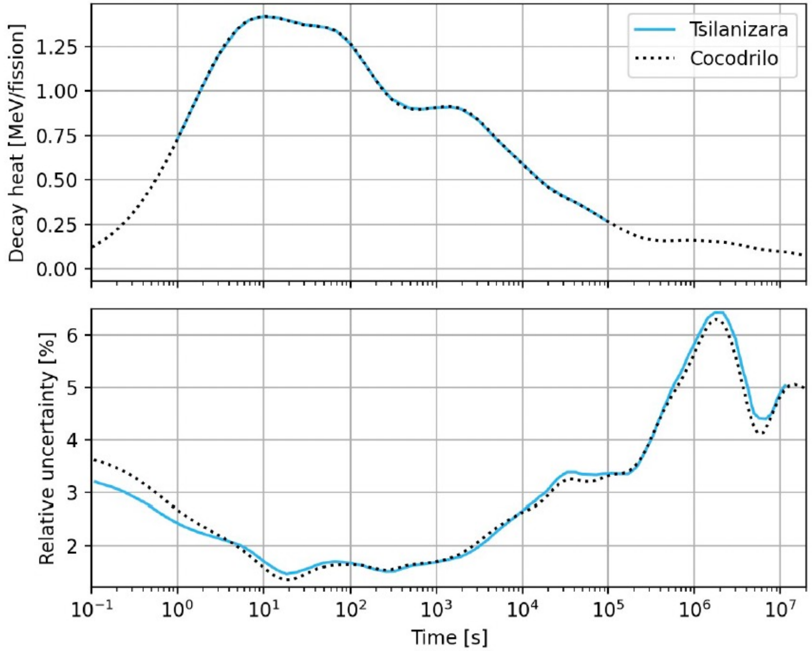

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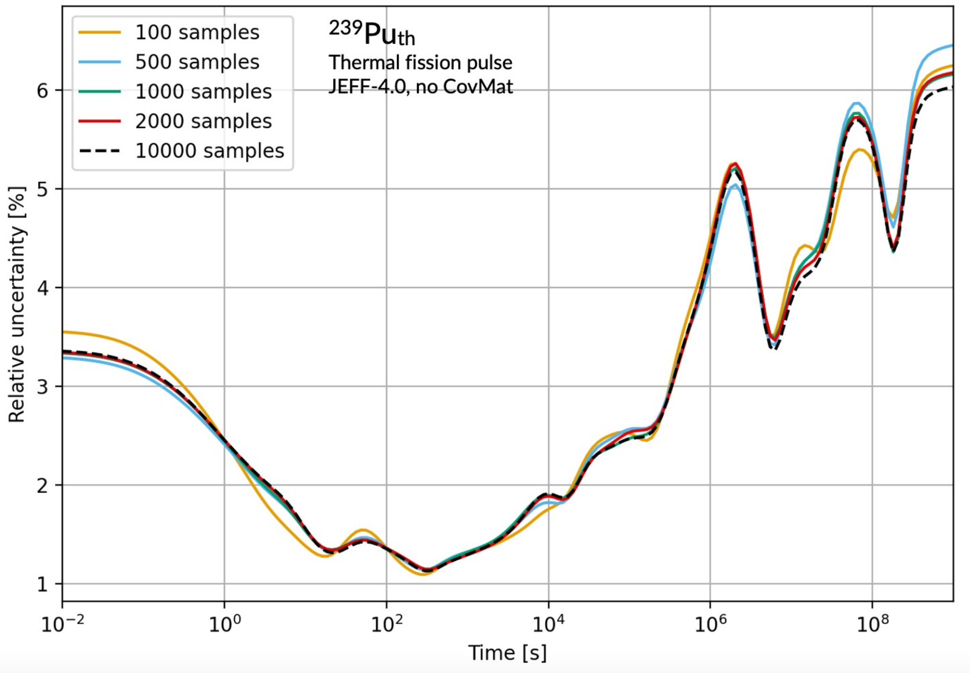

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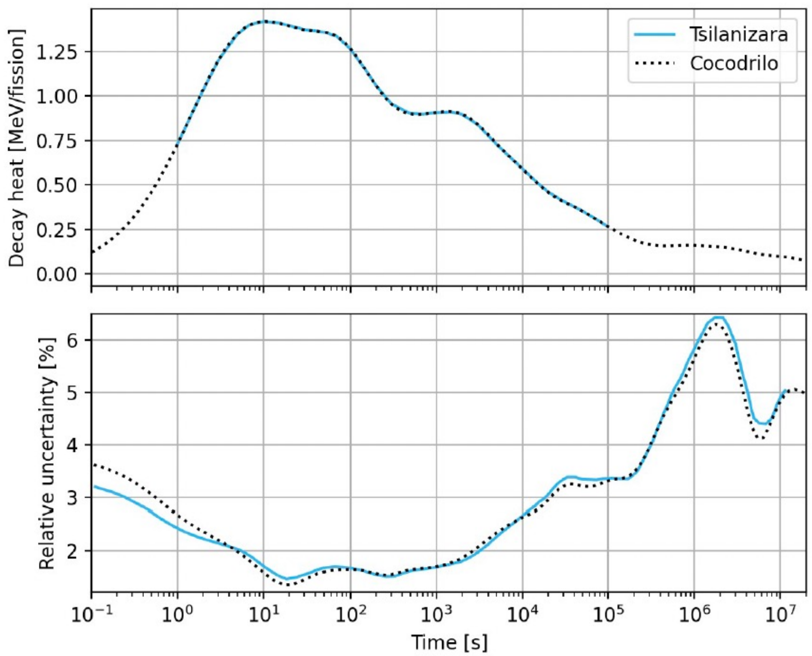

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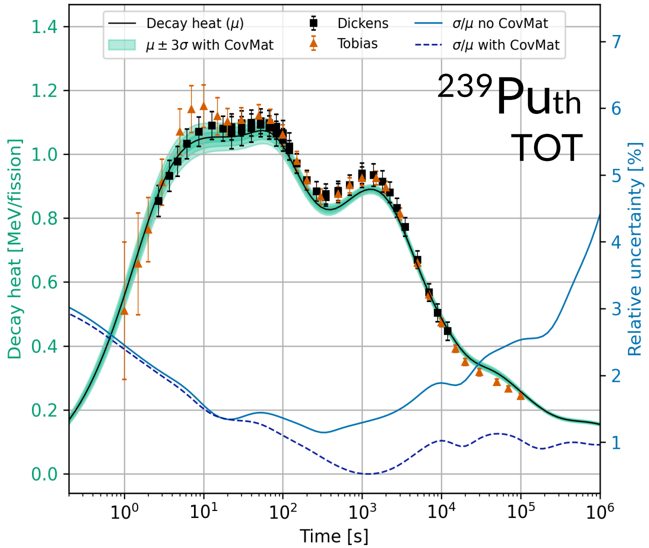
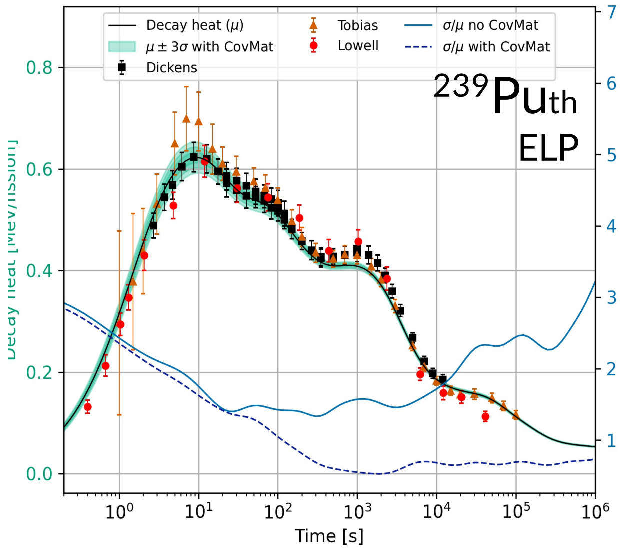
$^{239}Pu_{th}$ fission pulse decay heat – JEFF-4.0

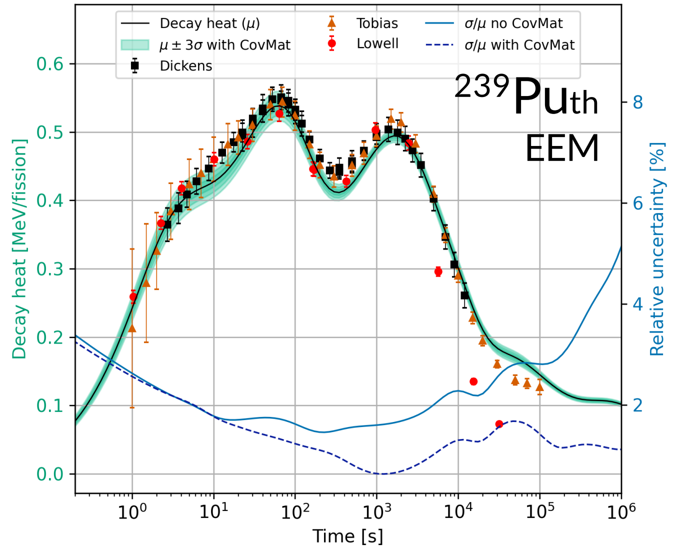
Total decay heat



Light particles component



Electromagnetic component



from Cocodrilo code, FY uncertainty only, 2000 samples,

Sampling method: Normal distribution, symmetric cut-off, w/o covariances matrices

μ = mean value

σ = standard deviation

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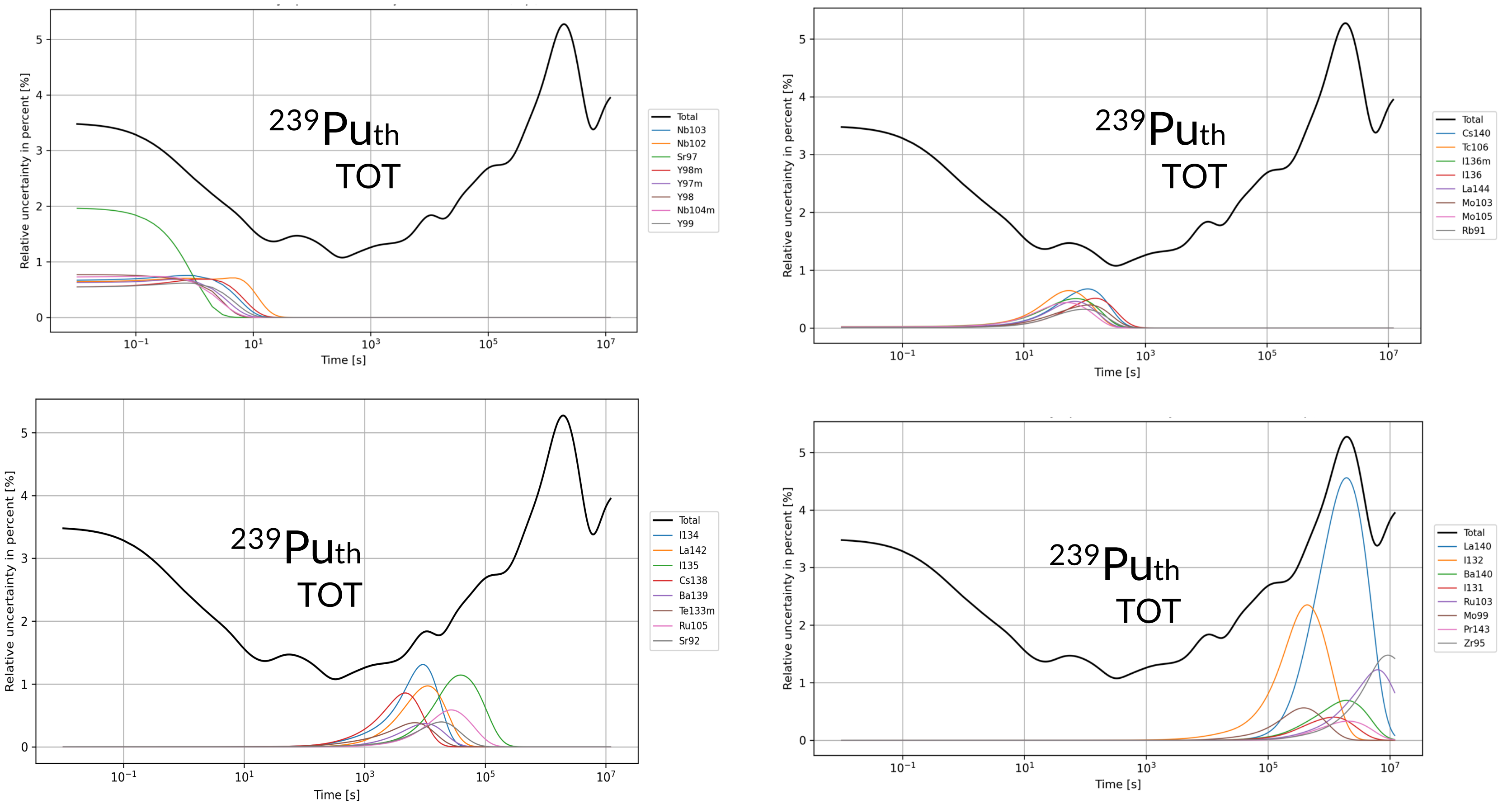
$^{239}Pu_{th}$ fission pulse decay heat – Contribution of nuclides to uncertainty

JEFF-4.0+ FY sampling, no CovMat



$^{99,103,105}Mo$

^{91}Rb

$^{102,103,104m}Nb$

$^{131,136,136m}I$

^{106}Tc

$^{138,140}Cs$

$^{140,144}La$

^{95}Zr

$^{139,143}Ba$,

^{103}Ru,

$^{140,144}La$

$^{97m,98,98m,99}Y$

$^{97,92}Sr$

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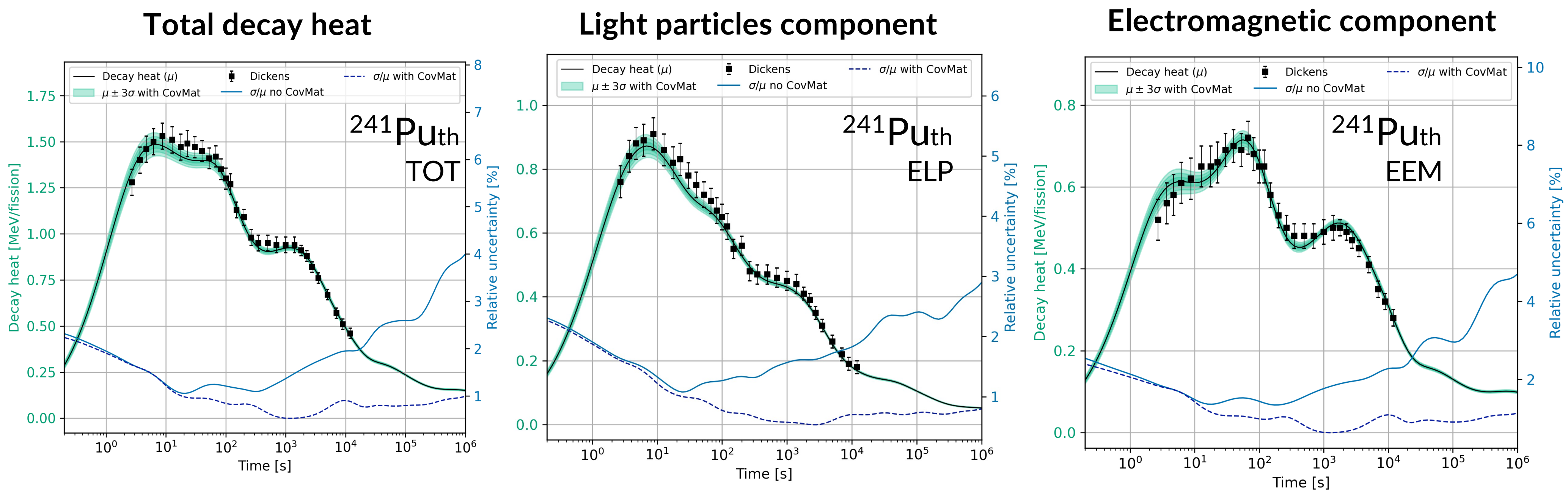
$^{241}Pu_{th}$ fission pulse decay heat – JEFF-4.0



from Cocodrilo code, FY uncertainty only, 2000 samples,

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σ = standard deviation

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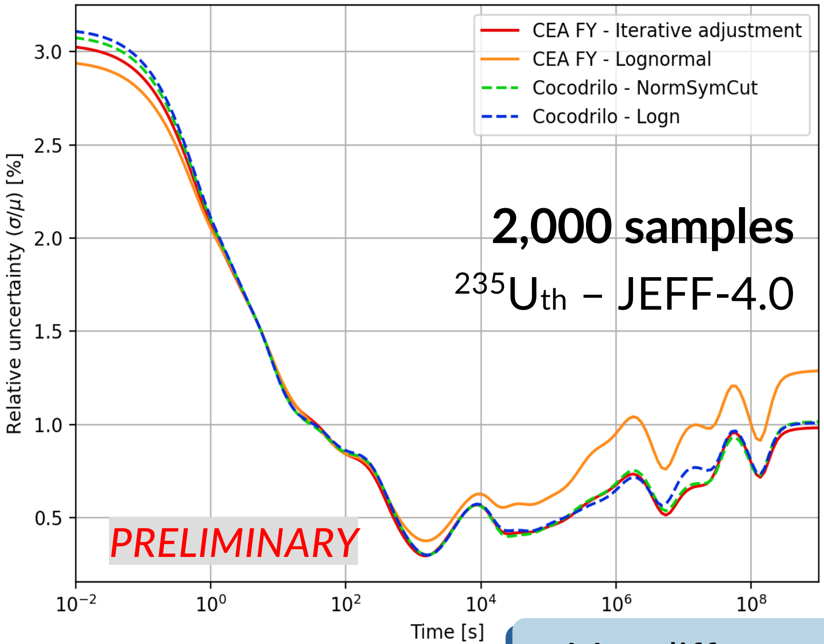
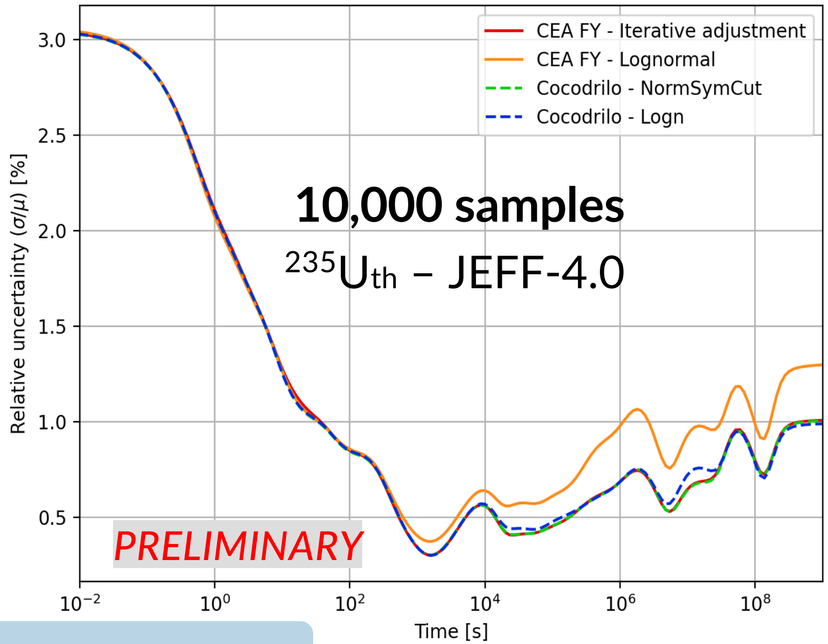
FY uncertainty propagation – using CEA's already sampled FY files

Results directly using samples generated by CEA[1]: JEFF-4.0 files made available in April 2026 within APRENDE for Independent Fission Yields on 4 thermal systems. They are **10'000 samples with constrain on Cumulative Fission Yields.**





Max difference: ~0.35% for both cases

[1]G. Kessedjian et al., "*Monte Carlo Fission Yield files for the 4 major fissile nuclei*", Nuclear Data Week - JEFF meeting / APRENDE, 13-17 April 2026

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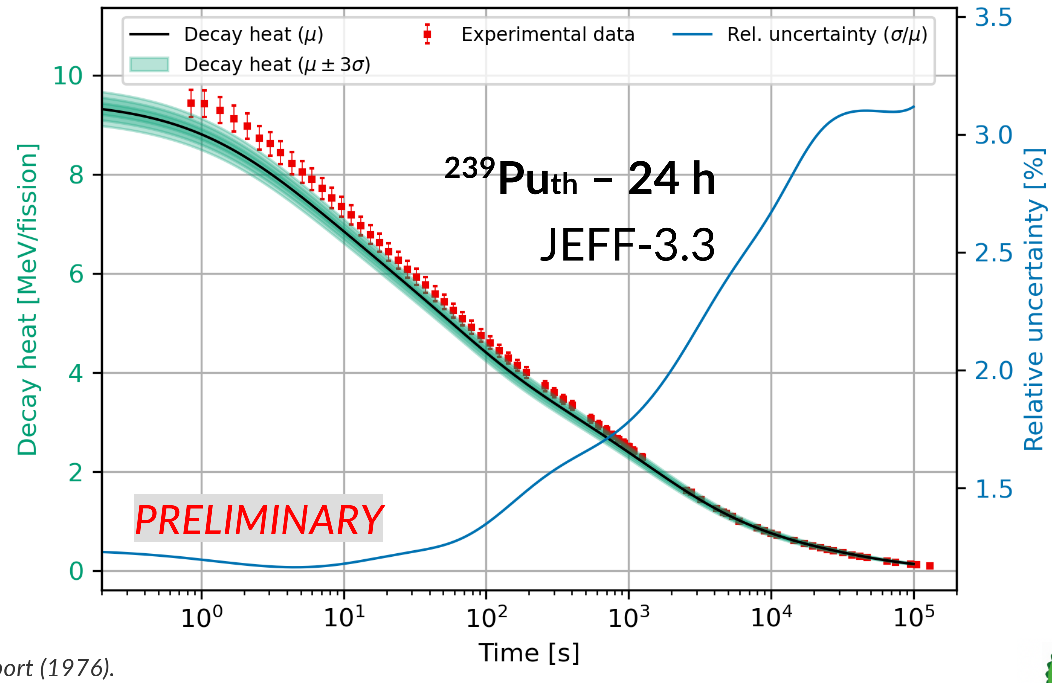
More complex cases foreseen: Irradiation of samples with water moderated ^{252}Cf source

Collaborative work with Sofia Portolan (PSI, EPFL), Dimitri Rochman (NAGRA)

- Experimental program supported per EPRI (Friesenhahn et al. 1976,1979)

- Decay heat measurements available for longer irradiation times than fission pulses

Target	Irradiation time	Cooling time
^{235}U	24 hours	1s -1.8 days
^{235}U	35 days	1s - 2.4 days
^{235}U	1 000 s	1s - 0.6 days
^{235}U	20 000 s	1s - 1.2 days
^{239}Pu	24h	1s - 1.5 days
^{239}Pu	1 000s	1s - 5500 s



[1]S. J Friesenhahn et al., 235U Fission Product Decay Heat from 1 to 105 seconds, EPRI report (1976).
[2]S. J Friesenhahn et al., Measurement of 239Pu and 235U Fission Product Decay Power From 1 to 105 Seconds, EPRI report (1979).

Conclusions and Outlooks

- Impact of new TAGS data on DH calculations => needs of new DH fission pulses measurements for Pu isotopes
- Development of **Cocodrilo code** with studies on FY samplings
- First application to the new **JEFF-4.0** library release and covariance matrices
- Very **small impact** of the chosen sampling distribution on fission pulse calculations
- Tools ready for more detailed studies

- Take over previous studies on Decay Data sampling with Cocodrilo
- Automatized tools to identify Pandemonium nuclei (J. Halwani Phd on MSR) applied now to thermal fission pulses
- More complex cases (pincell, PWR assemblies, MSR case) => coupling with Coconust (A. Laureau, LPSC)

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Thank you for your attention

Acknowlegments

CNRS-IN2P3 MSR team (LPSC-Grenoble, Subatech): Michel Allibert, Louiliam Clot, L. Giot, Daniel Heuer, Axel Laureau, Elsa Merle

on this topic :
PhD students: Francesco Esposito, Yohannes Molla, Jad Hawani
interns : Florent Hervy, David Laks

GANIL: Fanny Farget, Diego Ramos

Support of Master project DONEE: (CNRS)

NAGRA: Dimitri Rochman **PSI:** Sofia Portolan

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TAS collaboration : IFIC Valencia, SEN team@Subatech, Univ. of Surrey)

For collaborative work or scientific discussions !

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Thank you!

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Procedure used per CEA for FY sampling

SetZero

$G(\boldsymbol{Y};\bar{\mathbf{y}};\boldsymbol{\Sigma})$ and $\sigma_i^2 = \Sigma_{ii}$

- spectral decomposition

  $\boldsymbol{\Sigma} = \mathbf{P}\cdot\mathbf{D}\cdot\mathbf{P}^{\mathbf{T}}$

- Sampling

  $\boldsymbol{S} \rightarrow \mathcal{N}(\mathbf{0},\mathbf{I_n})$

  $\mathbf{y}_s = \bar{\mathbf{y}} + \mathbf{P}\cdot\mathbf{D}^{1/2}\cdot\boldsymbol{S}$

- Regularization

  $if\ y_{s,i} < 0;\ y_{s,i} = 0$

LogNormal

$\bar{y}_i^{LN} = log\left(\frac{\bar{y}_i^2}{\sqrt{\sigma_i^2+\bar{y}_i^2}}\right)$ $\quad (\sigma_i^{LN})^2 = log\left(1+\frac{\sigma_i^2}{\bar{y}_i^2}\right)$

$\Sigma_{ij}^{LN} = \underbrace{log\left(1+\frac{\Sigma_{ij}}{\bar{y}_i\cdot\bar{y}_j}\right)}$

- Regularization

  $Arg > 0$ $\quad Arg < 0$

  $\Sigma_{ij}^{log} \approx \underbrace{\frac{\Sigma_{ij}}{\sigma_i\cdot\sigma_j}}_{Corr_{ij}}\cdot\sigma_i^{LN}\cdot\sigma_j^{LN}$

- Sampling

  $\boldsymbol{\Sigma}^{LN} = \mathbf{P}\cdot\mathbf{D}\cdot\mathbf{P}^{\mathbf{T}}$

  $\mathbf{y}_s^{\mathbf{LN}} = \bar{\mathbf{y}}^{LN} + \mathbf{P}\cdot\mathbf{D}^{1/2}\cdot\boldsymbol{S}$

  $\boldsymbol{S} \rightarrow \mathcal{N}(\mathbf{0},\mathbf{I_n})$

  $y_{s,i} = exp(y_{s,i}^{\mathrm{LN}})$

iterative adjustment

- *Cholesky decomposition*

  Find L : $\mathbf{Cov_Y} = \mathbf{LL^T}$

- Sampling

  $\boldsymbol{S} \rightarrow \mathcal{N}(\mathbf{0},\mathbf{I_n})$

  $\mathbf{y}_s = \bar{\mathbf{y}} + \boldsymbol{L}\cdot\boldsymbol{S}$

- Regularization

  $\mathbf{y}_s = |\mathbf{y}_s|$

- k Iterative process

$$\boldsymbol{y_{s,i}^k} = \left|\left(\boldsymbol{y_{s,i}^{k-1}} - \overline{\boldsymbol{y_{s,i}^{k-1}}}\right)\cdot\frac{\boldsymbol{\sigma_i}}{\boldsymbol{\sigma_{y_{s,i}^{k-1}}}} + \bar{\boldsymbol{y}}_{\boldsymbol{i}}\right|$$

Slide taken from: S. M. Cheikh, A. Chebboubi, G. Kessedjian, O. Serot, D. Bernard, *Monte Carlo Fission Yield files for the 4 major fissile nuclei*, Nuclear Data Week - JEFF meeting / APRENDE, 13-17 April 2026

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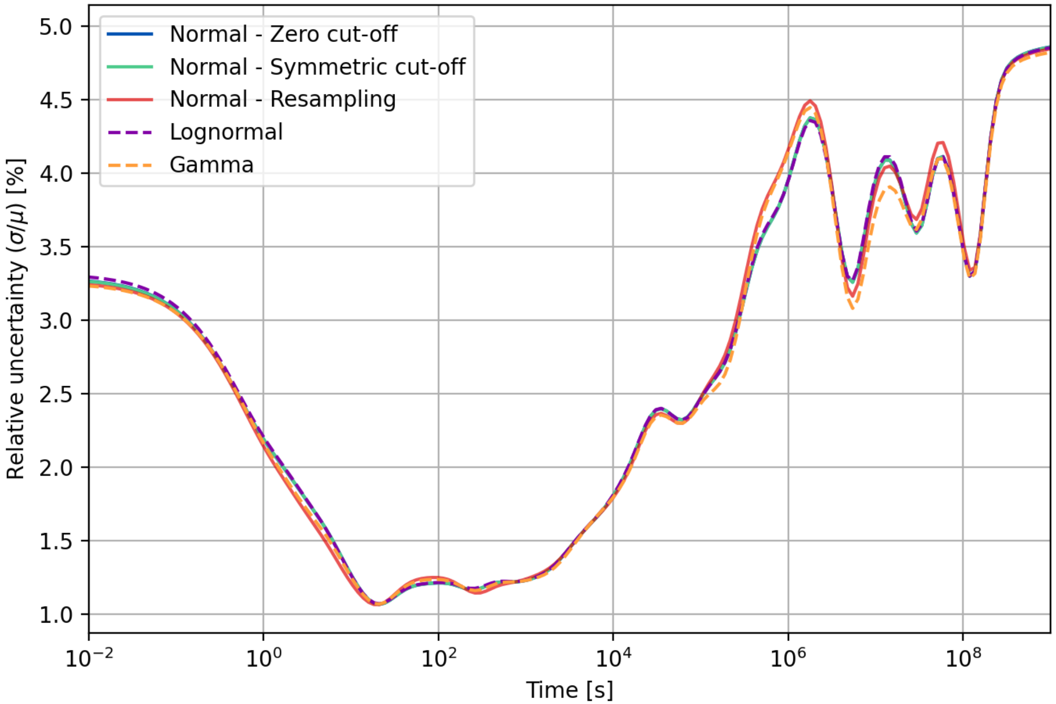
FY uncertainty propagation : Influence of the sampling distribution

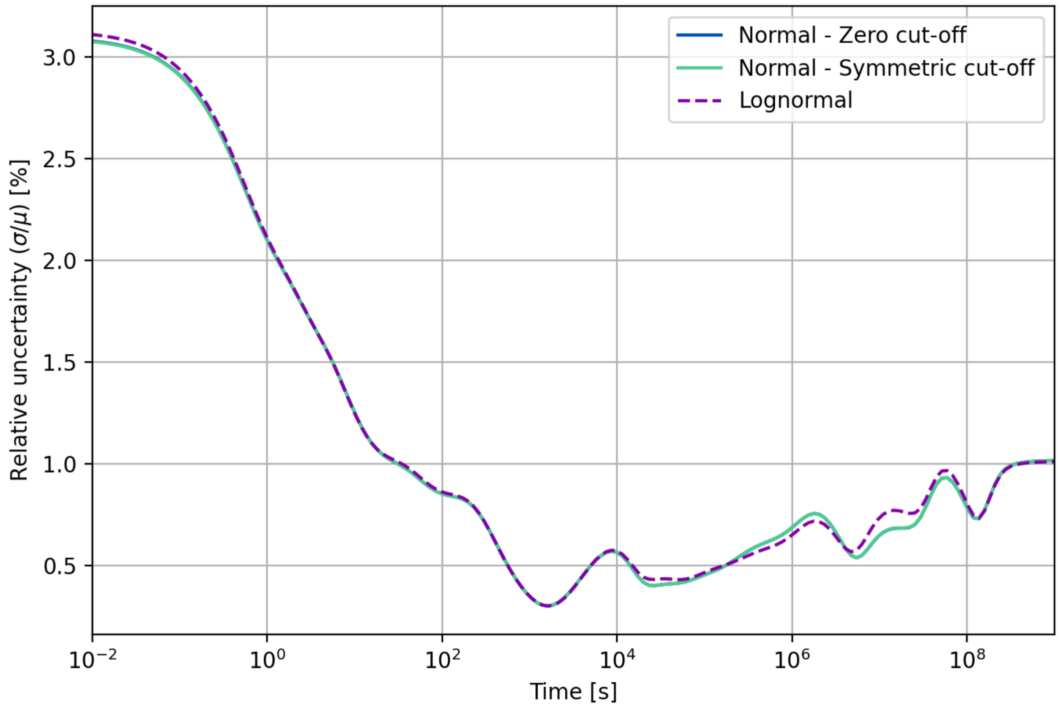
Does the choice have an impact on the final decay heat uncertainty?

Test case: $^{235}U_{th}$ – JEFF-4.0 fission yields – 2000 samples

Without covariance matrix for fission yields



With covariance matrix for fission yields



Max difference: <0.3%

Max difference: <0.15%

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