APRENDE

Nuclear data applications at SCK CEN

Two case studies

27/2/2025

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SCK CEN

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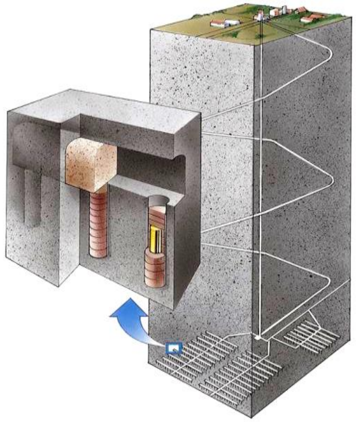
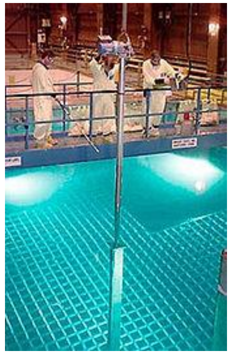
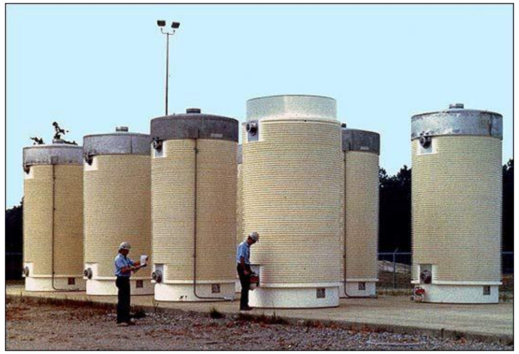
Spent nuclear fuel (SNF) characterization

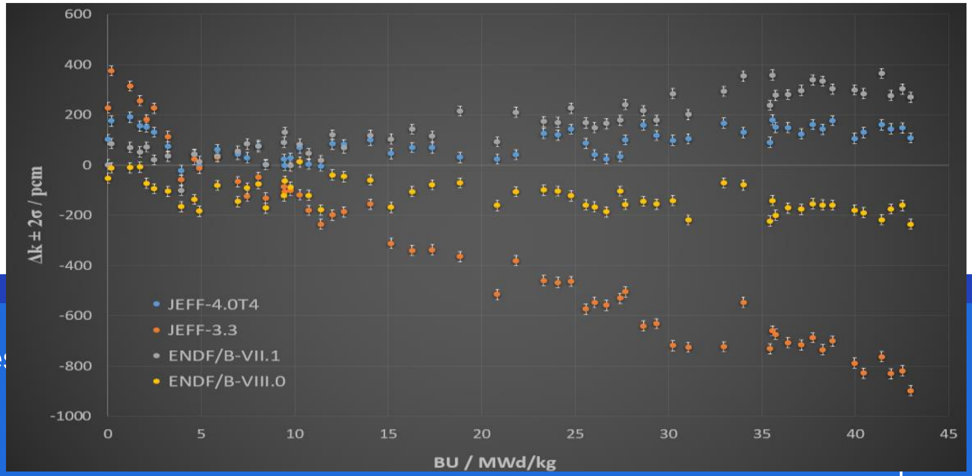


A safe, secure, ecological and economic transport, storage and final disposal of SNF requires a characterization of:





- Decay heat
- Neutron emission
- γ-ray emission
- Reactivity (Burn Up Credit (BUC), i.e. Fission Product (FP), actinides)
- Fissile material (Nuclear Safeguards, i.e. ^{235}U, ^{239}Pu)
- Specific nuclides (Long term safety)
  i.e. ^{14}C, ^{36}Cl, ^{79}Se, ^{94}Nb, ^{99}Tc, ^{129}I, ^{226}Ra, ^{237}Np



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Spent nuclear fuel (SNF) characterization

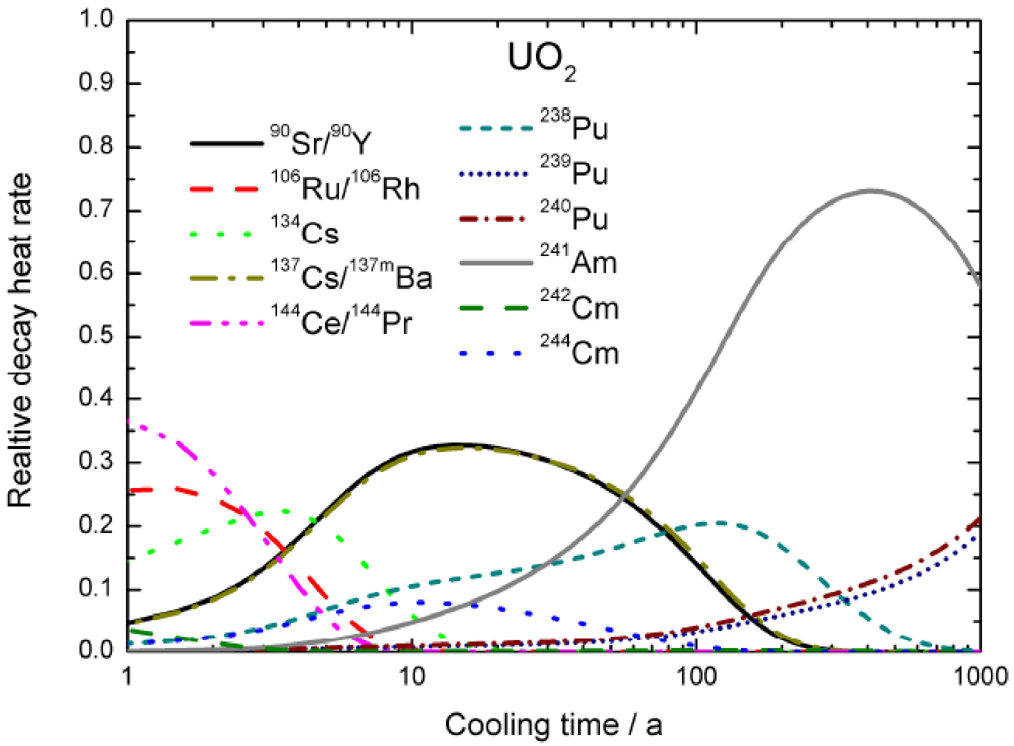
Modelling & simulation (M&S)

Summation methods (first principle)

Decomposition into nuclide contributions

Nuclide inventory + Nuclear data

Example: decay heat rate $H(t) = \sum_i \boldsymbol{\lambda_i E_{d,i}} N_i(t)$



Radioactive decay data

- Decay constants
- Recoverable decay energy

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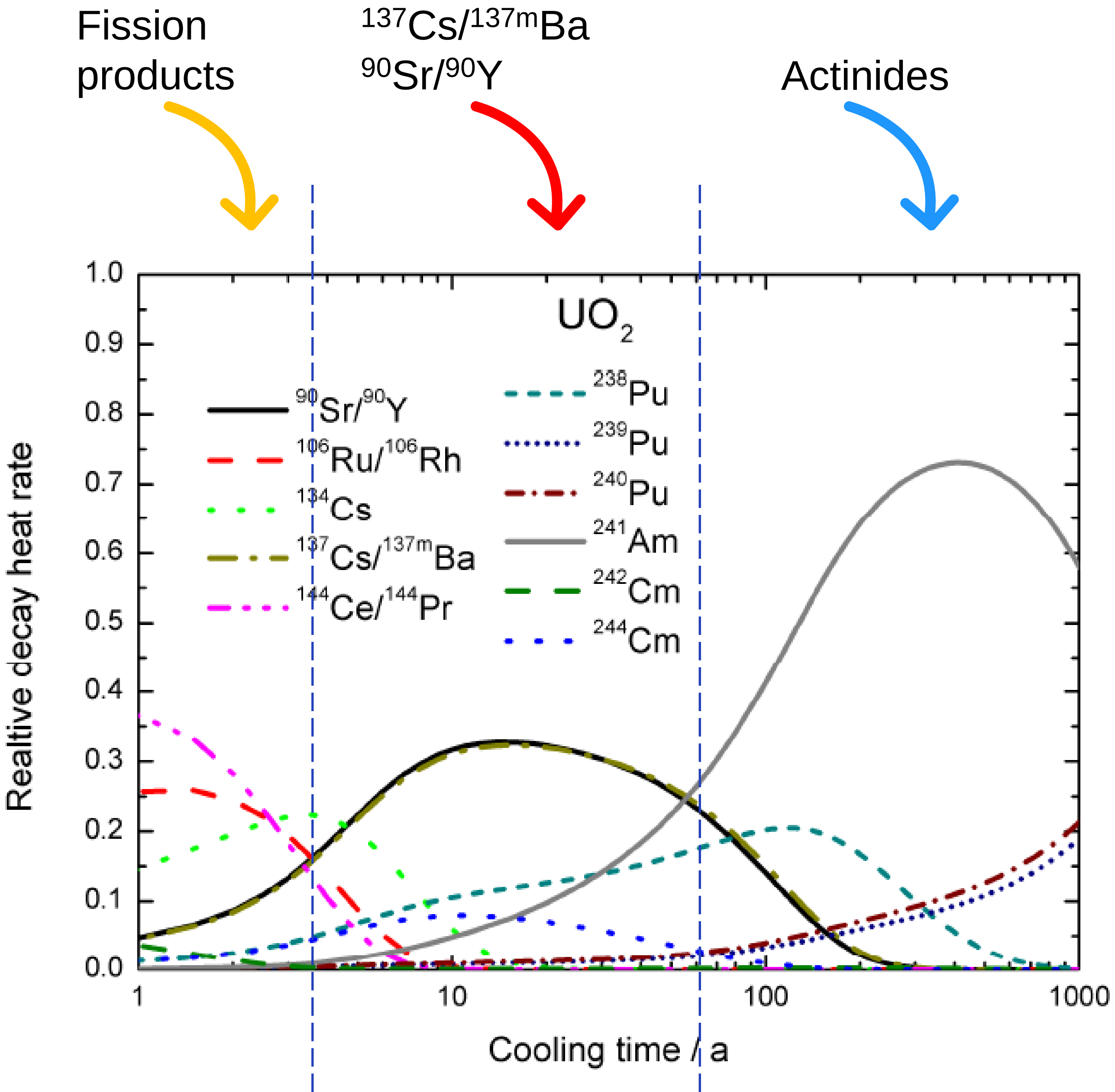
Major contributors

From hundreds of nuclides at short cooling times…

…to only a handful!

Problem specific:

- UOX / MOX
- Initial enrichment (IE)
- Fuel burnup (BU)
- Cooling time (CT)



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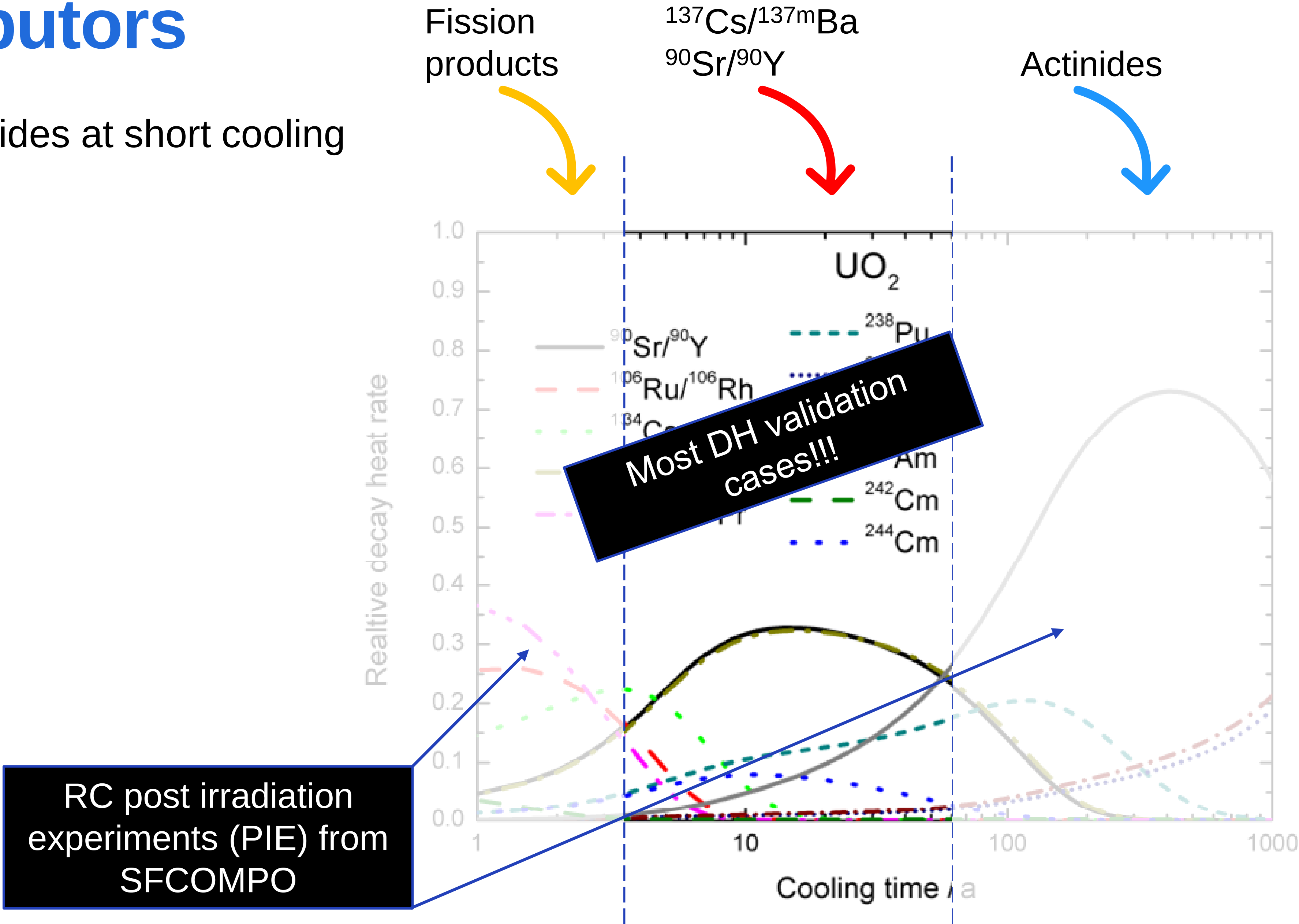
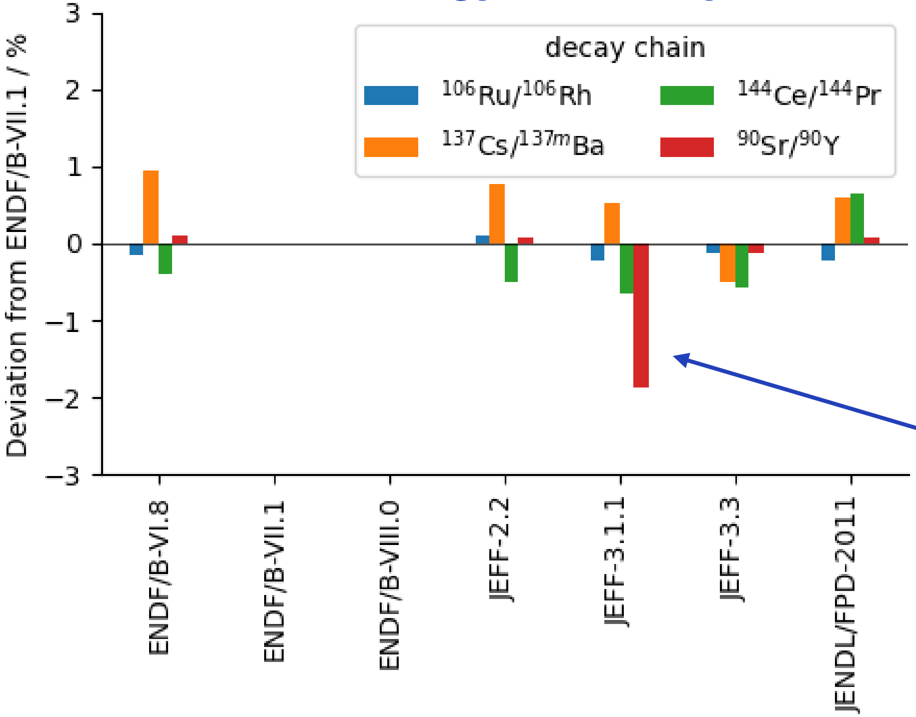
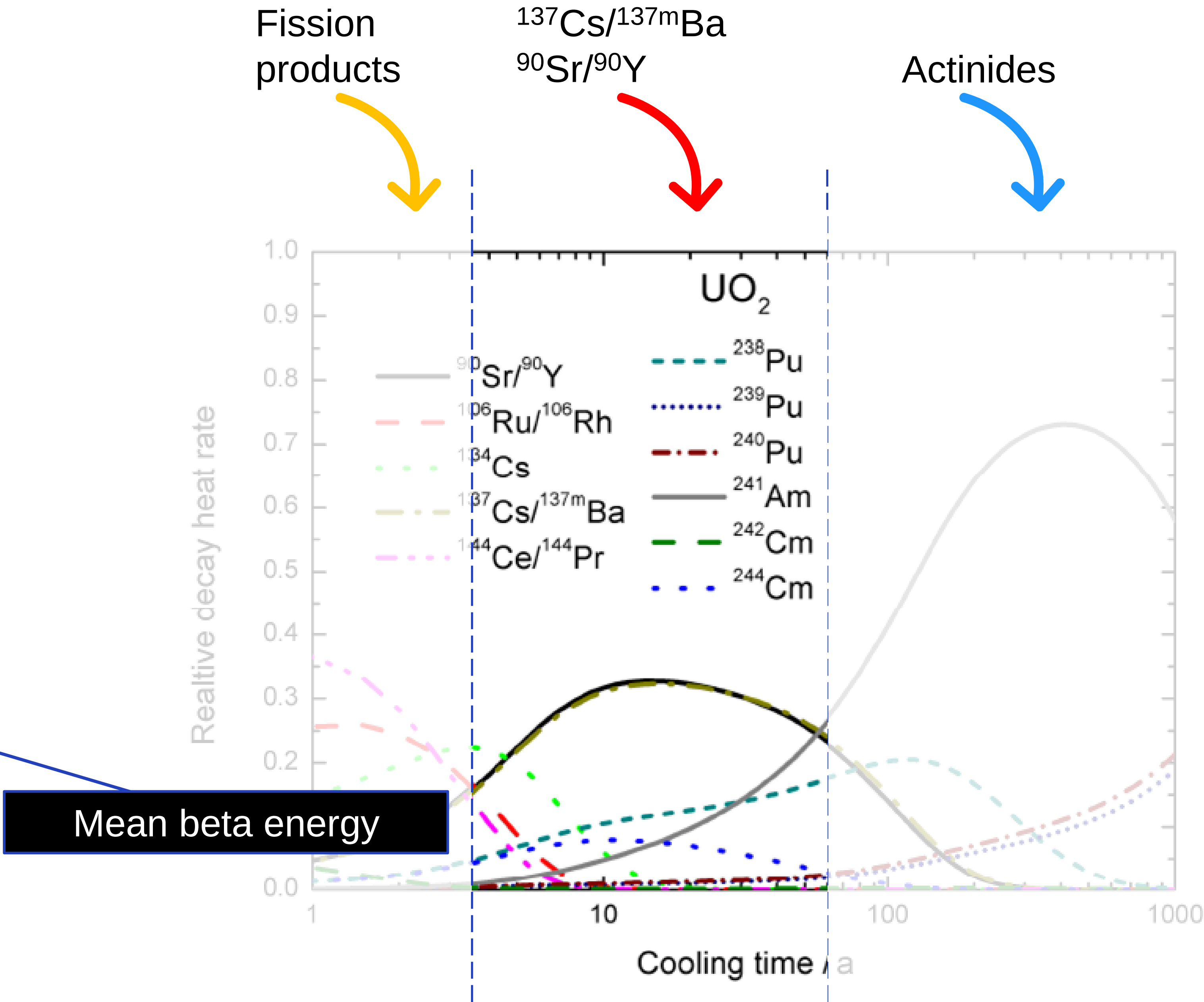


Major contributors

$$H(t) = \sum_i \lambda_i E_{d,i} N_i(t)$$

Recoverable energy for decay chains





Nuclide inventory (depletion codes)

Fission
- (n,f) xs
- Independent fission yields

Transmutation
- (n,γ) xs
- (n,p) xs
- (n,α) xs
- …

Radioactive decay
- Decay constants
- Branching ratios

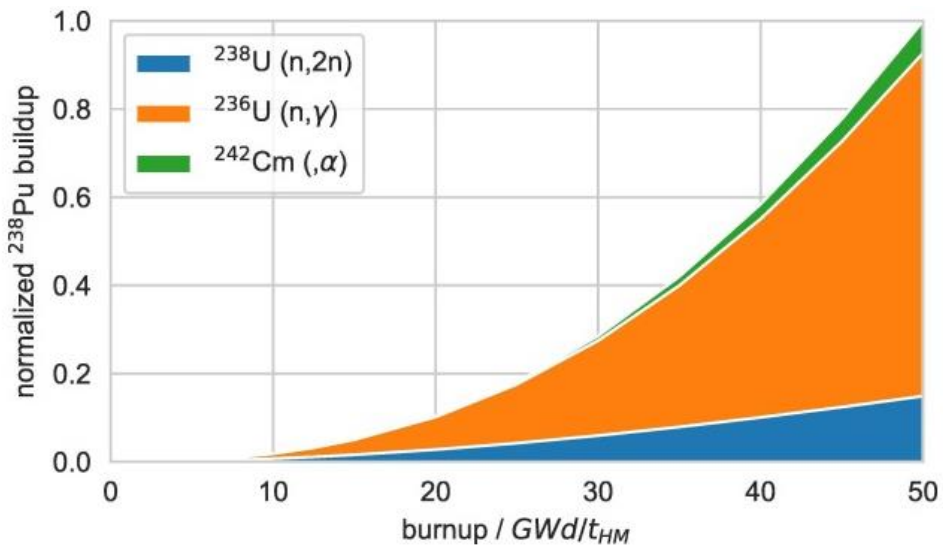
- Balance between production and loss (**only nuclear processes**)

$$\frac{dN_i(t)}{dt} = \text{PRODUCTION} - \text{LOSS}$$

1000+ decay / transmutation chains

- Extensive use of nuclear data (**specific for each nuclide**)

^{238}Pu buildup



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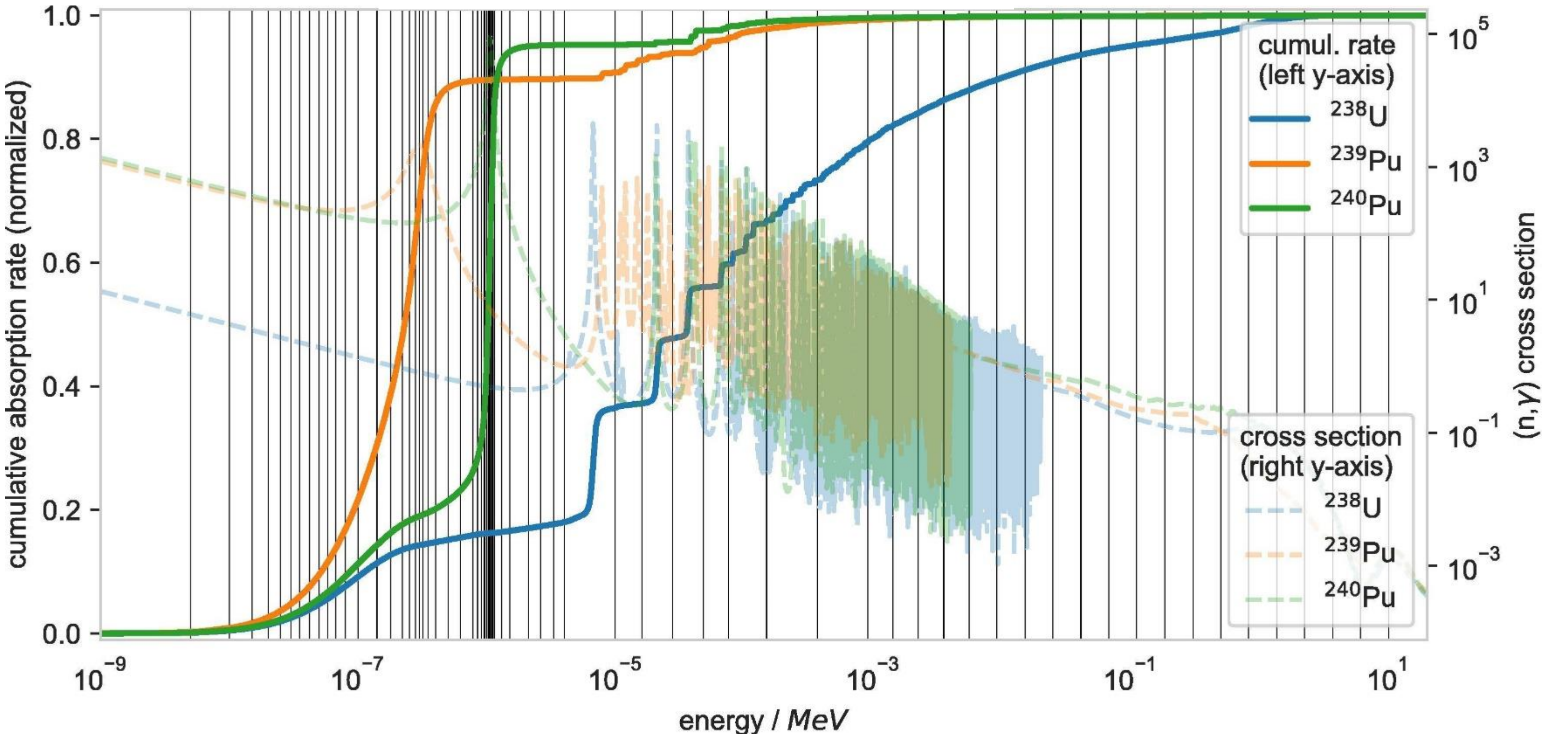
- …

Radioactive decay
- Decay constants
- Branching ratios

- Spectrum-averaged one-group reaction rates
  - ENDF-6 files **processing** (NJOY, …)
  - Criticality calculations for spectrum

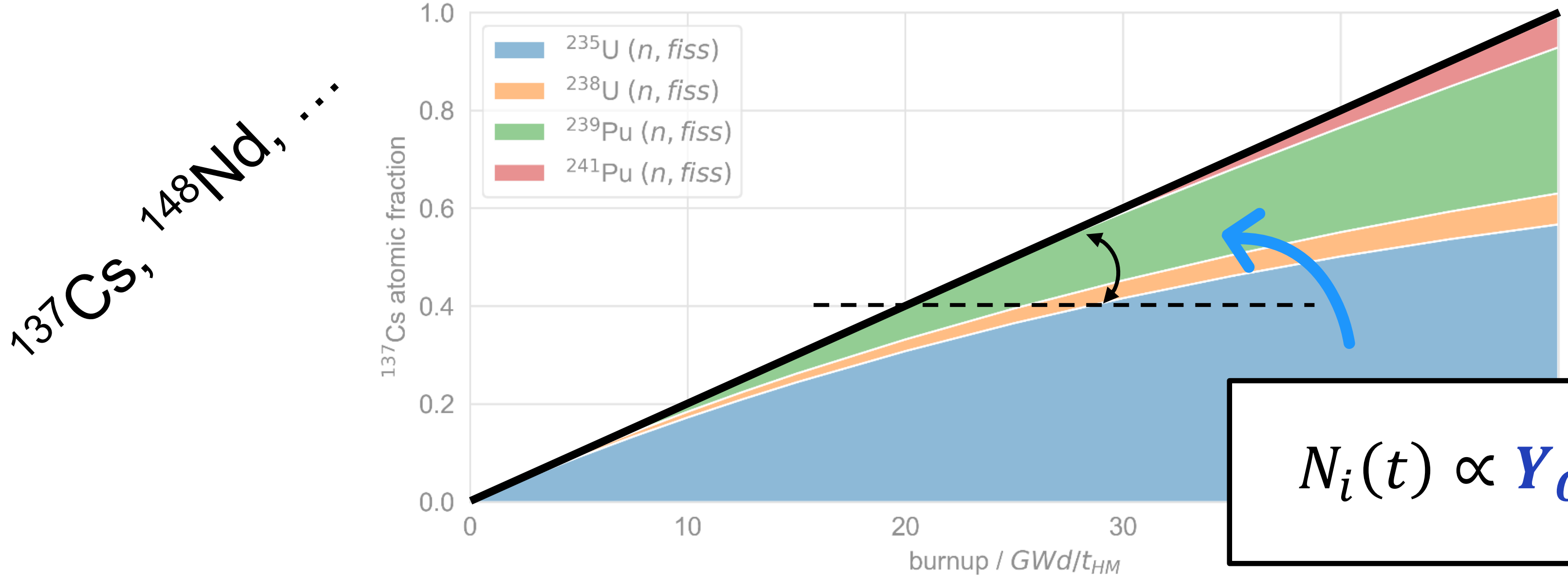
$$RR = \int dE\, \sigma(E)\, \varphi(E)$$



Nuclide inventory (analytical derivation)

Burnup indicator: a measurable quantity used to assess the extent to which nuclear fuel has been consumed in a reactor

Burnup: a measure of how much energy has been extracted from nuclear fuel



$$N_i(t) \propto Y_{C,i} \times \frac{BU}{E_{fiss}}$$

Nuclear data

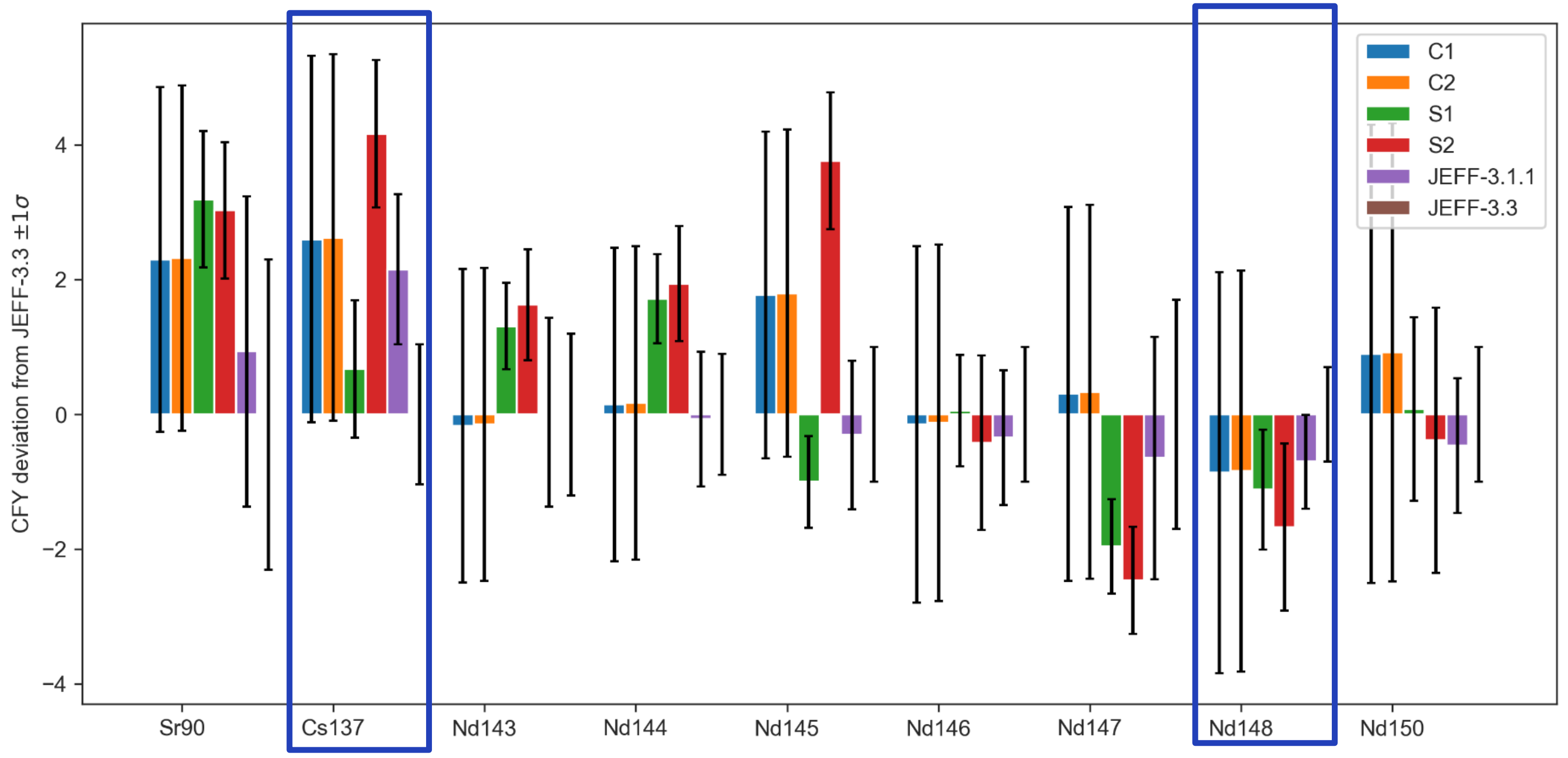
- Cumulative fission yields
- Recoverable fission energy

Nuclide inventory

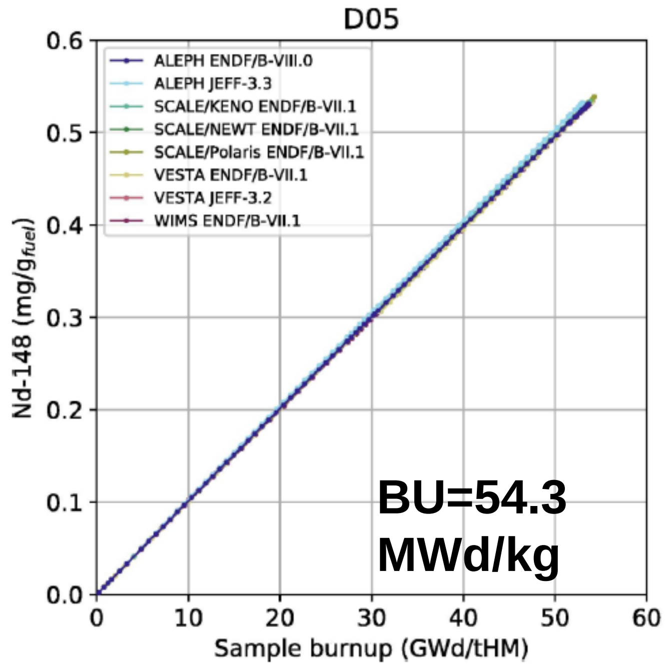
$$N_i(t) \propto Y_{C,i} \times \frac{BU}{E_{fiss}}$$

Issue with recoverable energy in REGAL sample

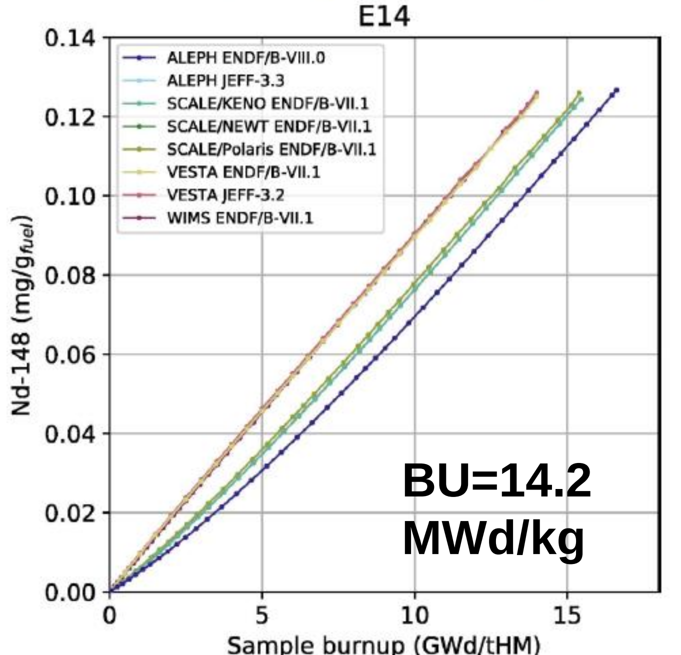
Re-evaluation of CFYs with covariance data (JEFF-4.0)



UO$_2$ fuel sample

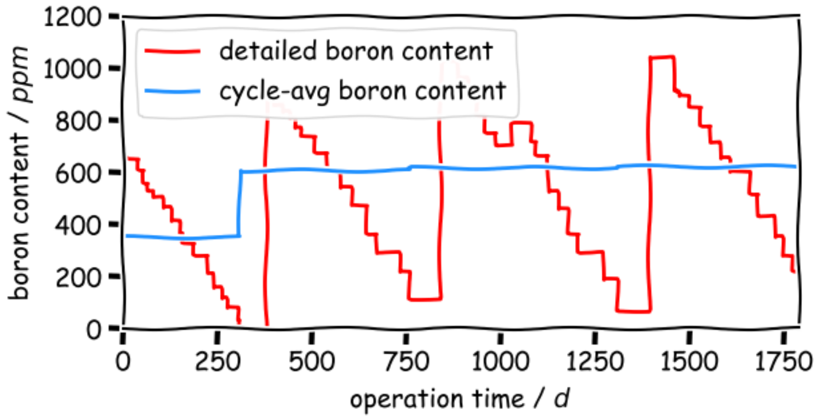


UO$_2$-Gd$_2$O$_3$ fuel sample



Verification and validation

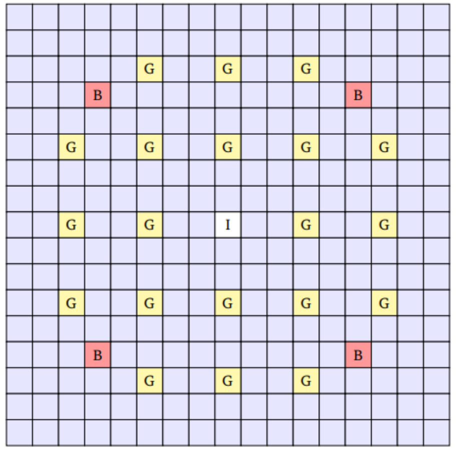
C/E comparison

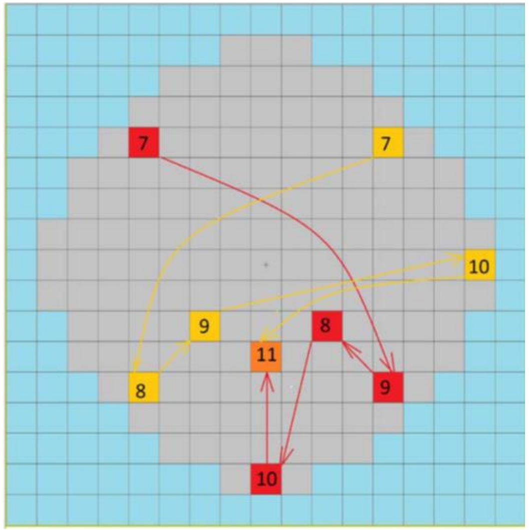


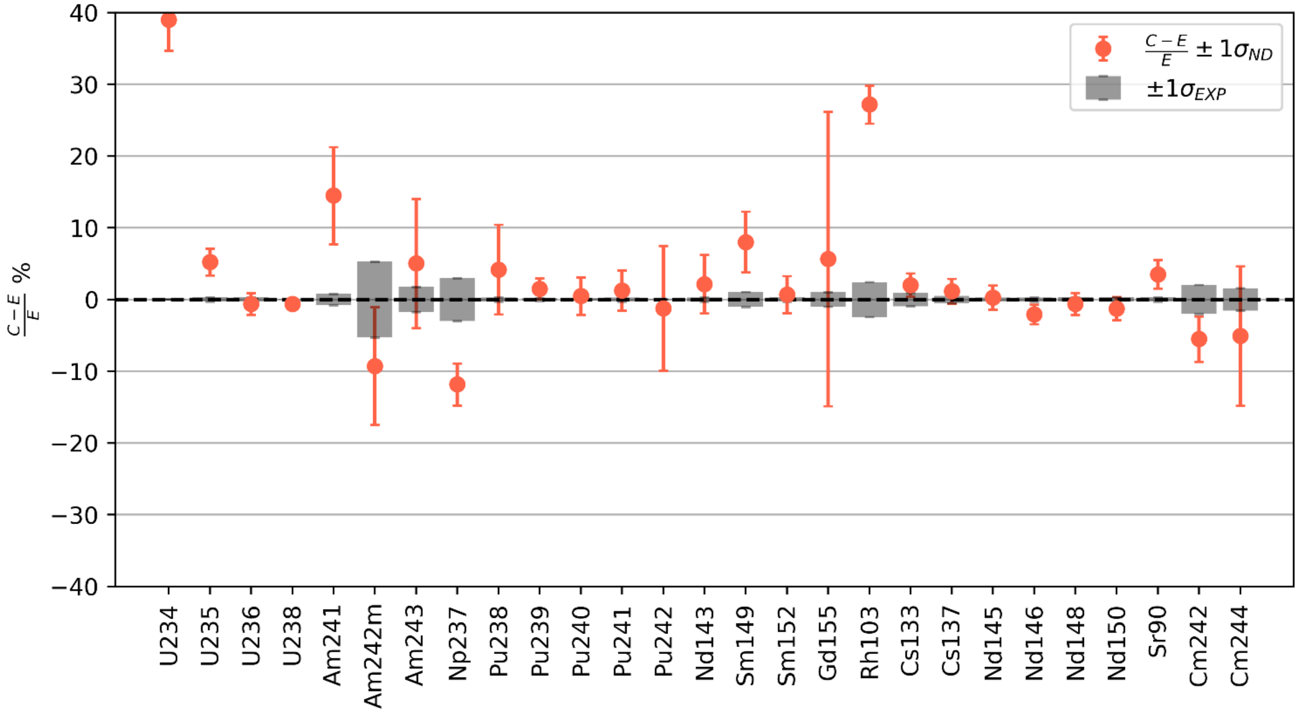
In burnup problems, nuclear data do not always justify discrepancies

Modelling approximations

UQ adds confidence to M&S







Verification and validation

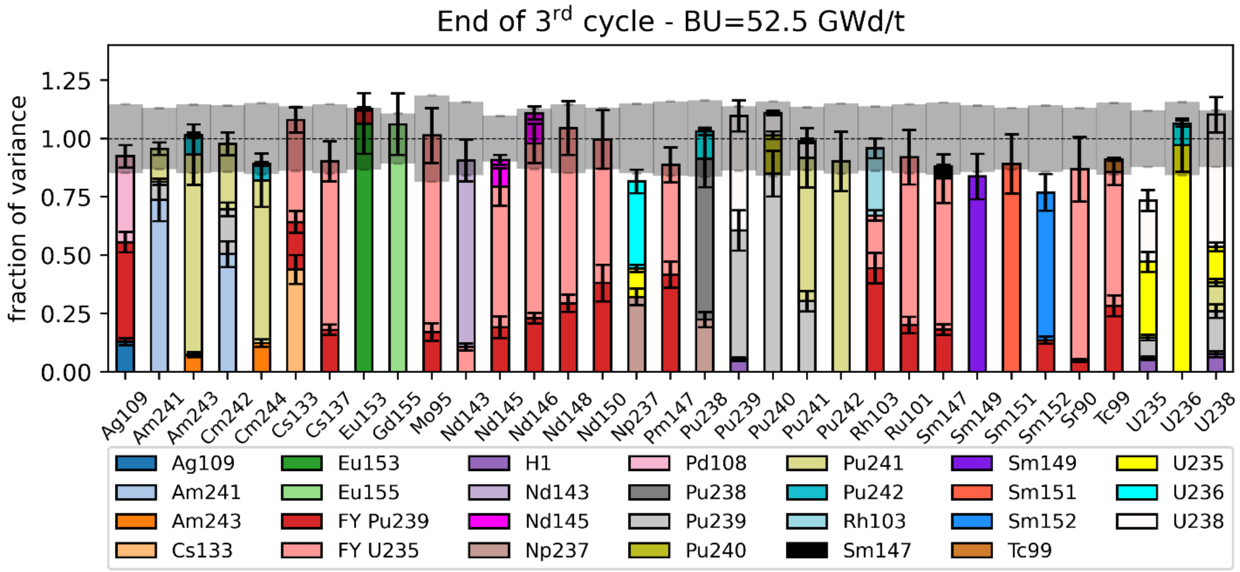
C/E comparison

In burnup problems, nuclear data do not always justify discrepancies

UQ adds confidence to M&S

Feedback from variance analysis

Specific efforts for each source term



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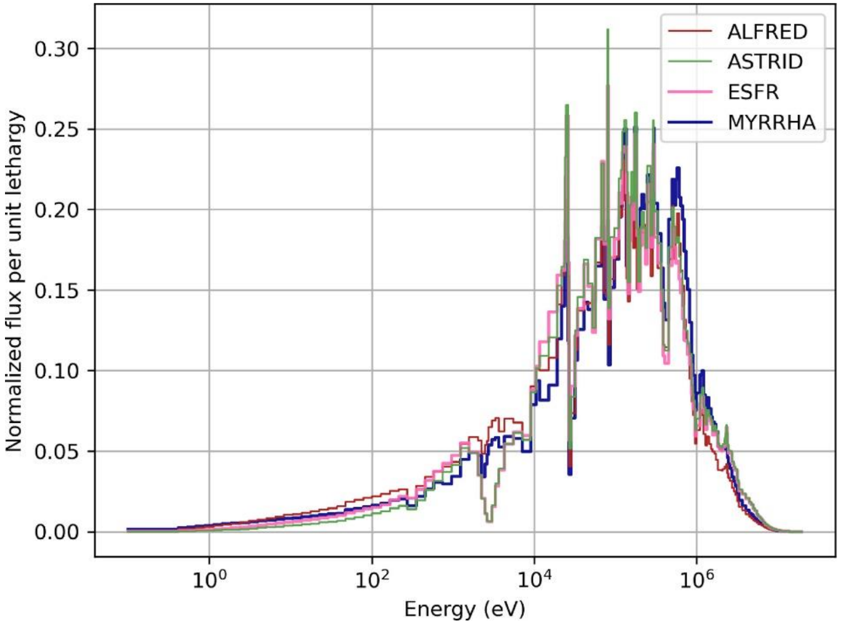
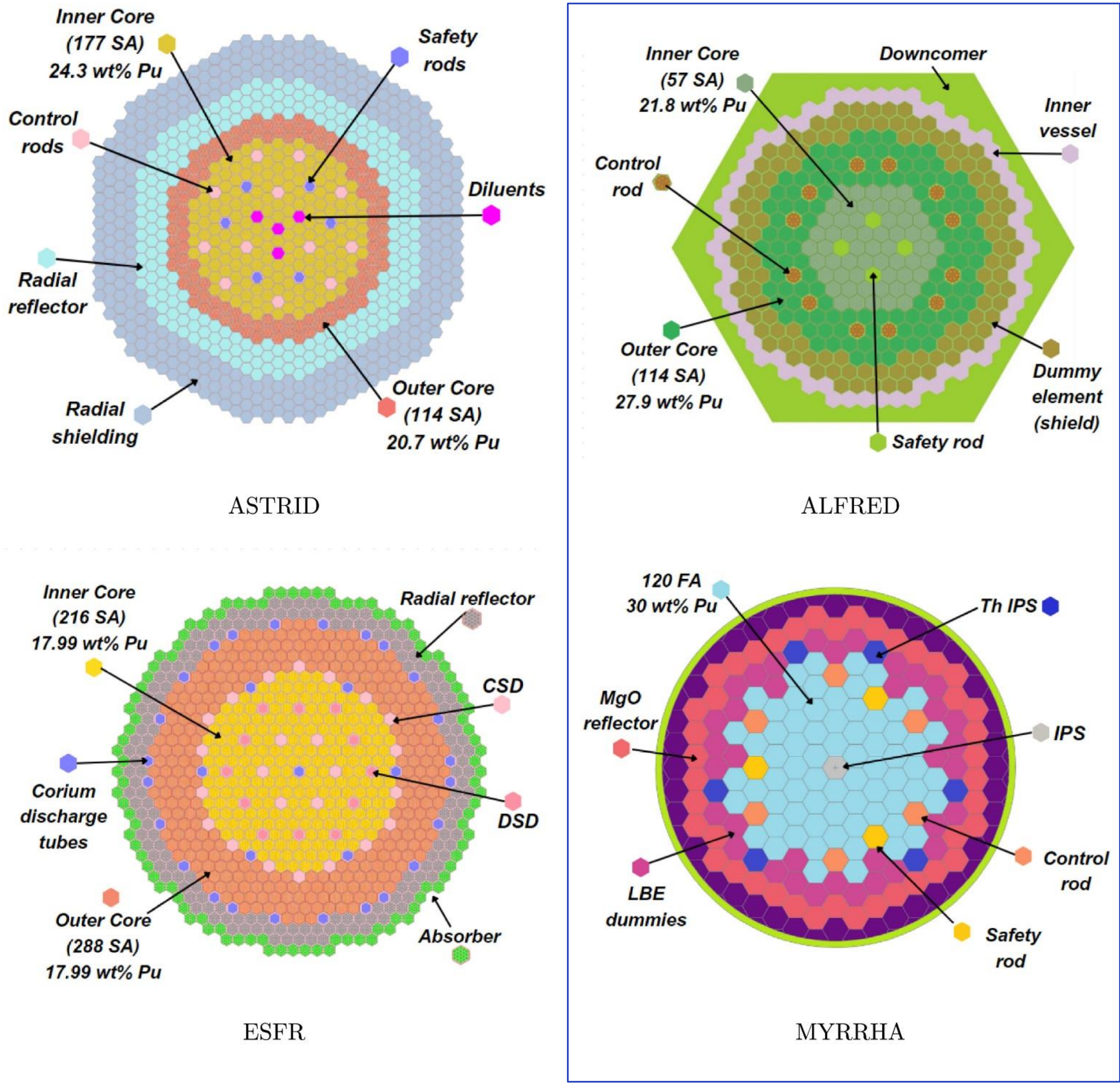
ND requirements for Gen IV systems

Fast spectrum

Different materials





Acronyms: SA: subassemblies, FA: fuel assemblies, CSD: control and shutdown devices, DSD: diverse shutdown device, IPS: in-pile-section, Th IPS: in-pile-section for radioisotope production (thermal islands), LBE: lead-bismuth eutectic,

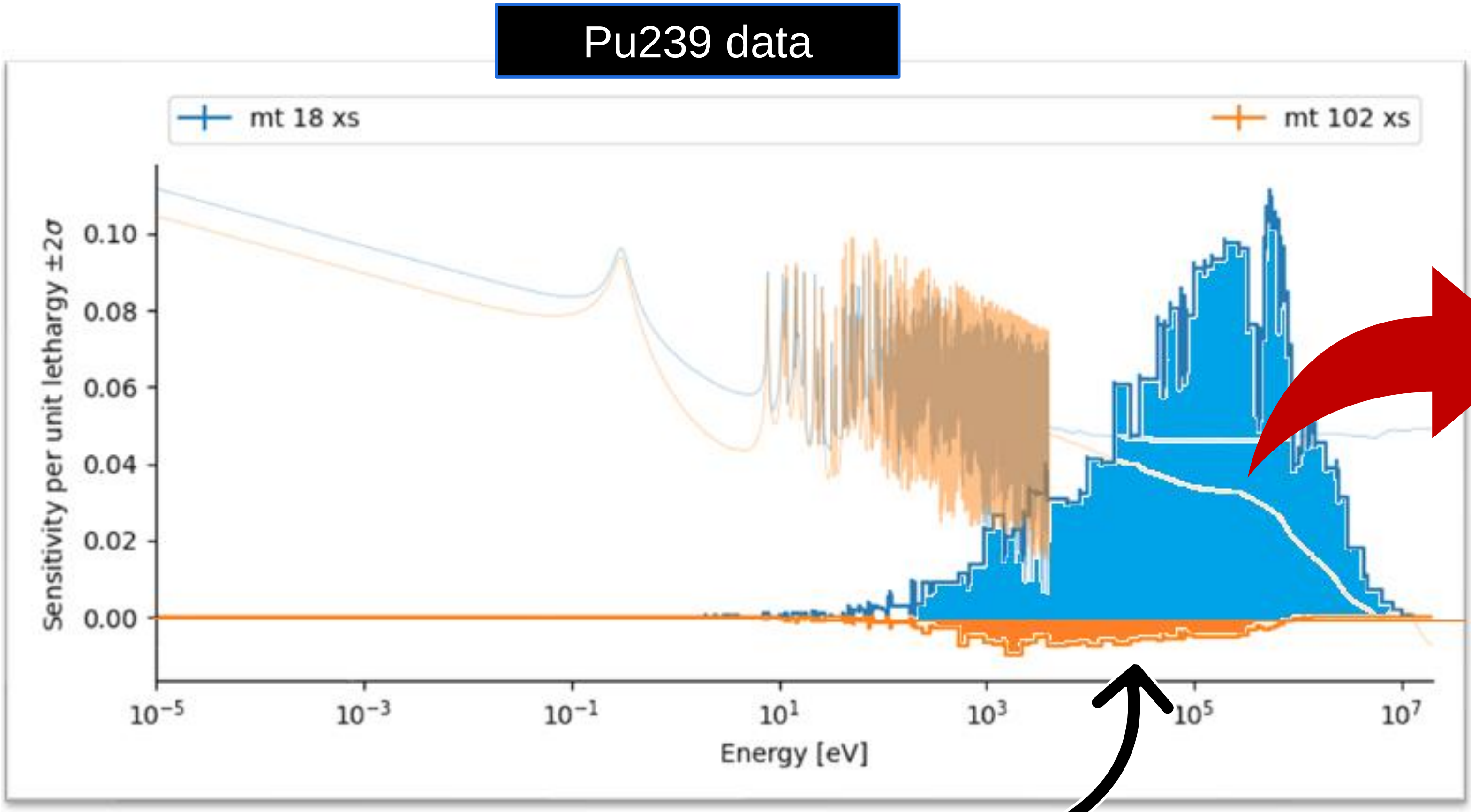
SANDA

SANDA
Supplying Accurate Nuclear Data for energy and non-energy Applications

HORIZON2020

Sensitivity analysis

Calculate first-order derivatives and obtain a linear surrogate model



Sensitivity to fast energy range

NUCL	XS	ISC
Pu239	nubar prompt	6.89E-01
Pu239	mt 18 xs	4.88E-01
U238	mt 102 xs	-1.67E-01
Pu241	nubar prompt	1.03E-01
U238	nubar prompt	8.70E-02
Pu240	nubar prompt	7.45E-02
Pu241	mt 18 xs	7.42E-02
U238	mt 18 xs	5.16E-02
Pu240	mt 18 xs	5.00E-02
Pu239	mt 102 xs	-4.83E-02
U238	mt 4 xs	-4.02E-02
O16	mt 2 xs	-4.00E-02
Pu240	mt 102 xs	-2.51E-02
U238	mt 2 xs	2.38E-02
Pu238	nubar prompt	1.79E-02
Pu242	nubar prompt	1.53E-02
Pb208	mt 2 xs	1.44E-02
Pb207	mt 2 xs	1.32E-02

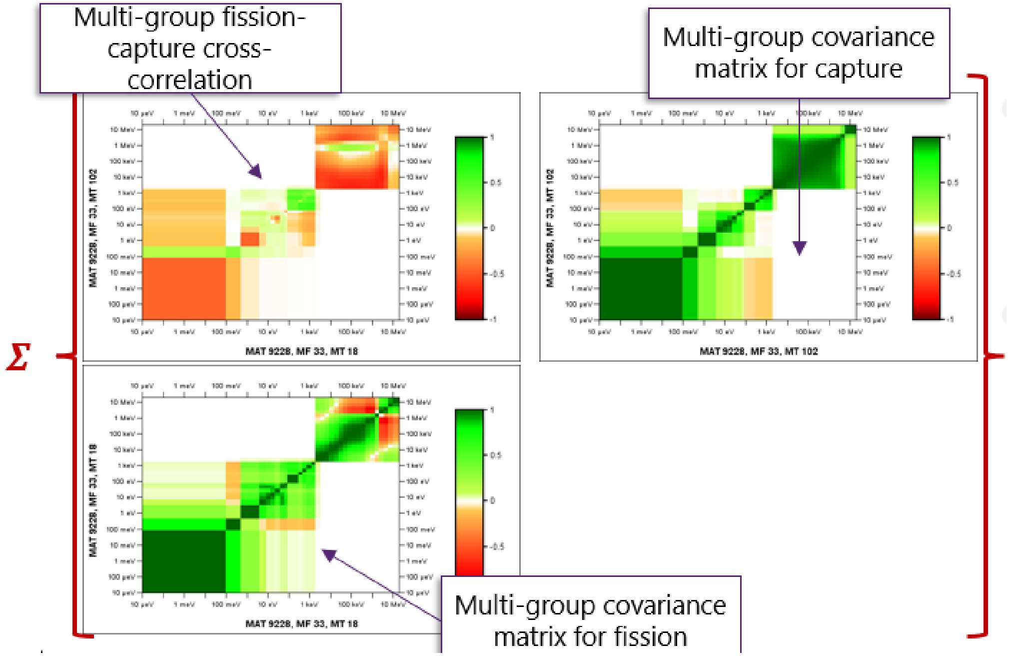
Uncertainty quantification

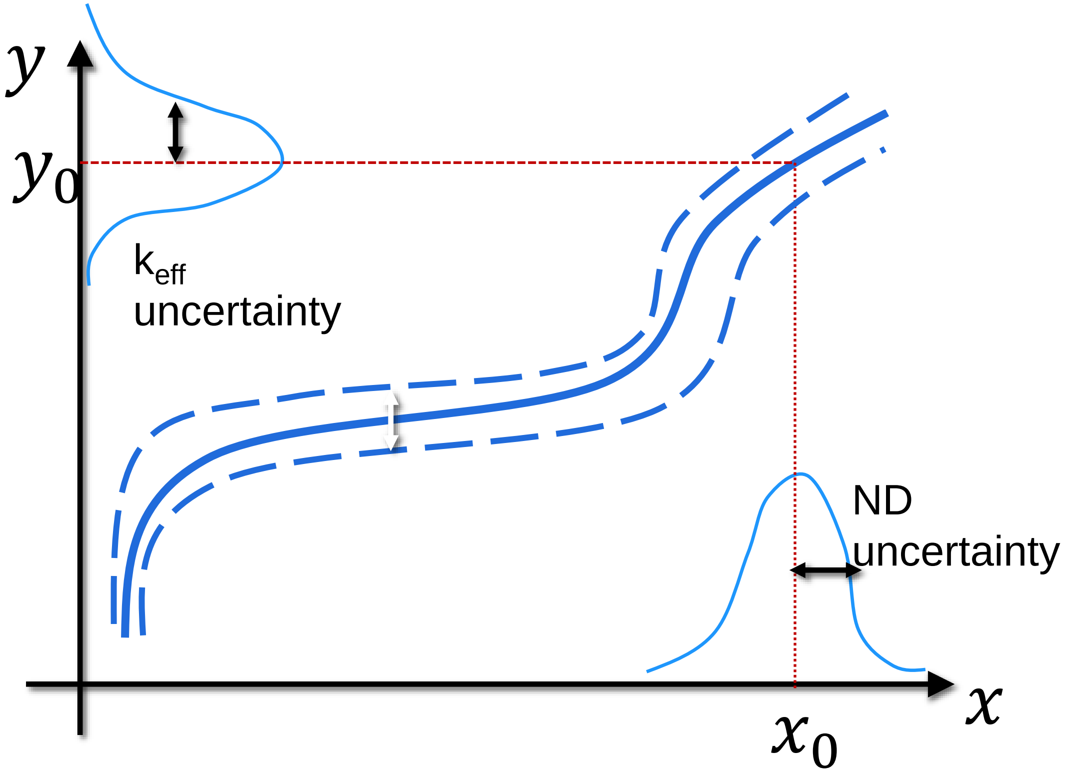
Nuclear data uncertainty propagation

Mapping input uncertainty into output

MG covariance data from ENDF-6 file

Cover all sources of uncertainties





Premise for criticality safety

The disagreement between experimental results and high-fidelity M&S tools is caused primarily by uncertainty in nuclear data

Total ND uncertainty: δk_{eff}~1000 pcm

Target accuracy :$\delta k_{eff} < 500$ pcm

Uncertainty quantification

k_{eff} uncertainty of nuclear data origin is ~700-1000pcm

Nuclide	pcm
Pu239	571
U238	440
Pu240	358
Pu241	153
Pb206	139
Fe56	91
O16	88
Pu238	87
Pb208	82
Ni58	55
Pb207	53

General interest of ND community

- ^{239}Pu: (n,γ) both in resonance and fast energy region, (n,f) fast, χ and $\bar{\upsilon}$ fast
- ^{238}U: (n,n') fast, (n,γ) resonance and fast, (n,n) resonance and fast
- ^{56}Fe: (n,γ) resonance and fast
- ^{235}U: $\bar{\upsilon}$, (n,f), (n,γ) resonance and fast

Specific to SCK CEN projects

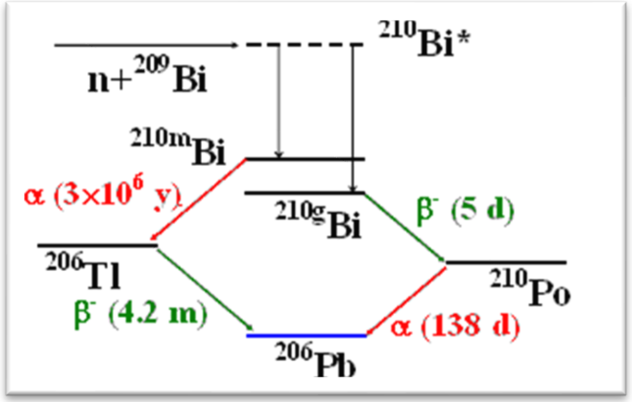
- ^{209}Bi (n,γ) and (n,n') resonance and fast
- ^{208}Pb (n,n) and (n,n') resonance and fast
- ^{241}Pu (n,f) resonance and fast
- ^{242}Pu (n,f) fast
- ^{240}Pu: $\bar{\upsilon}$ fast
- ^{238}Pu: (n,f) both resonance and fast

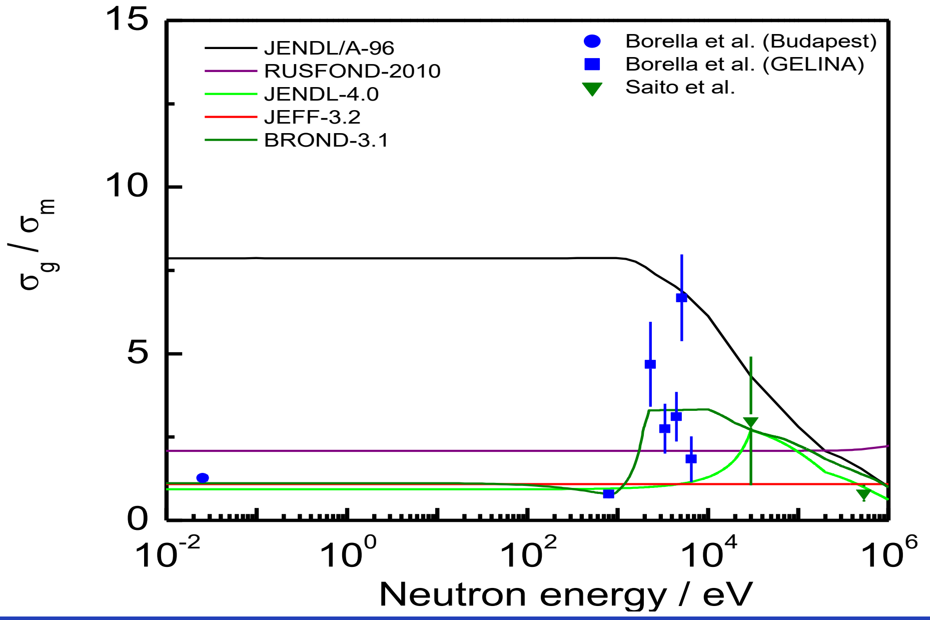
Radiotoxicity and decay heat of LBE

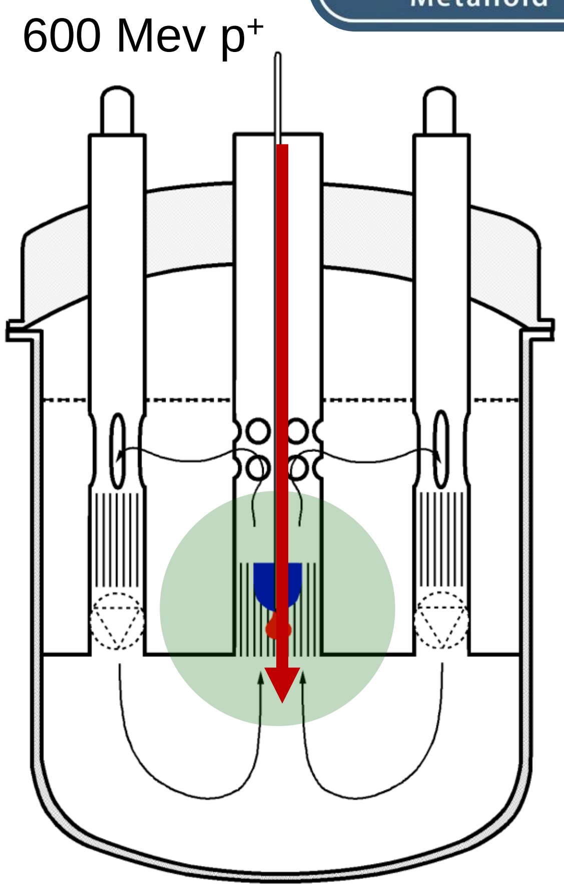
^{210}Po in MYRRHA

Activation yield for $^{209}Bi(n,\gamma)^{210g}Bi$

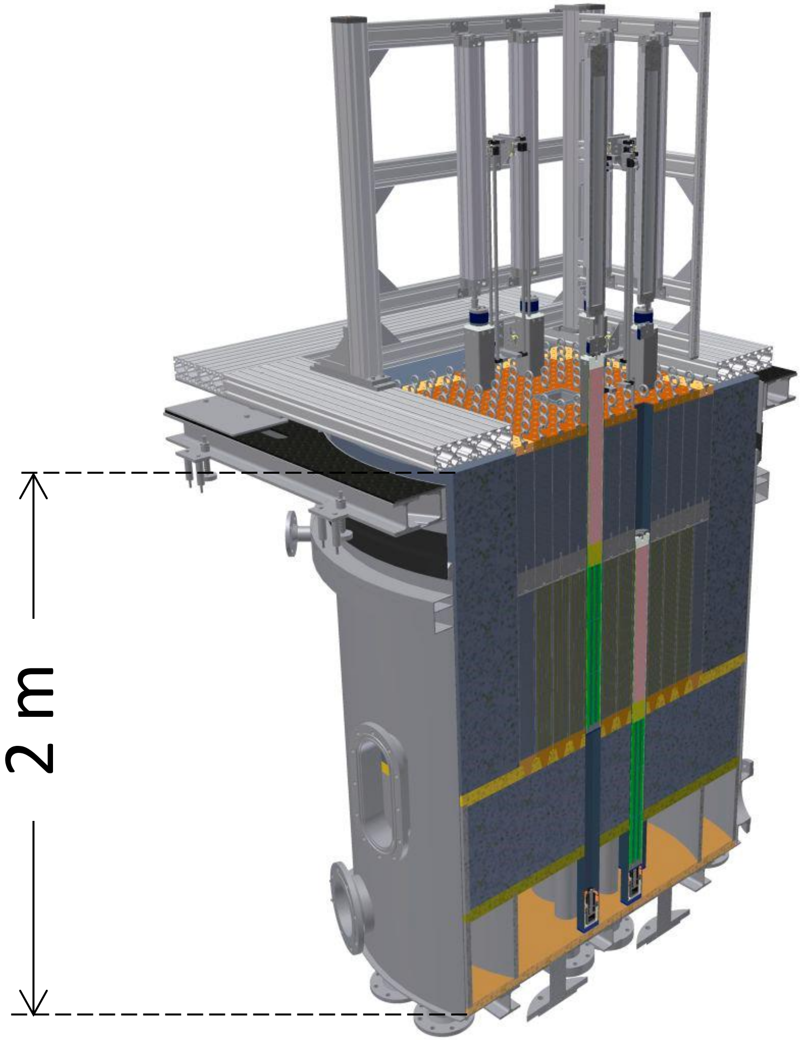
New entry added to the NEA HPRL in 2017

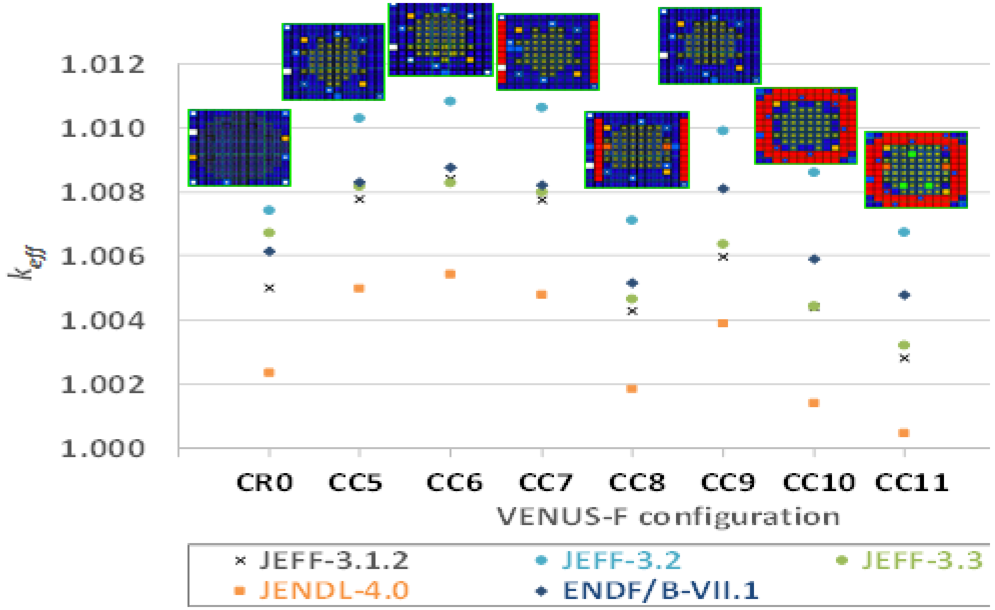






Nuclear Data Validation: VENUS-F

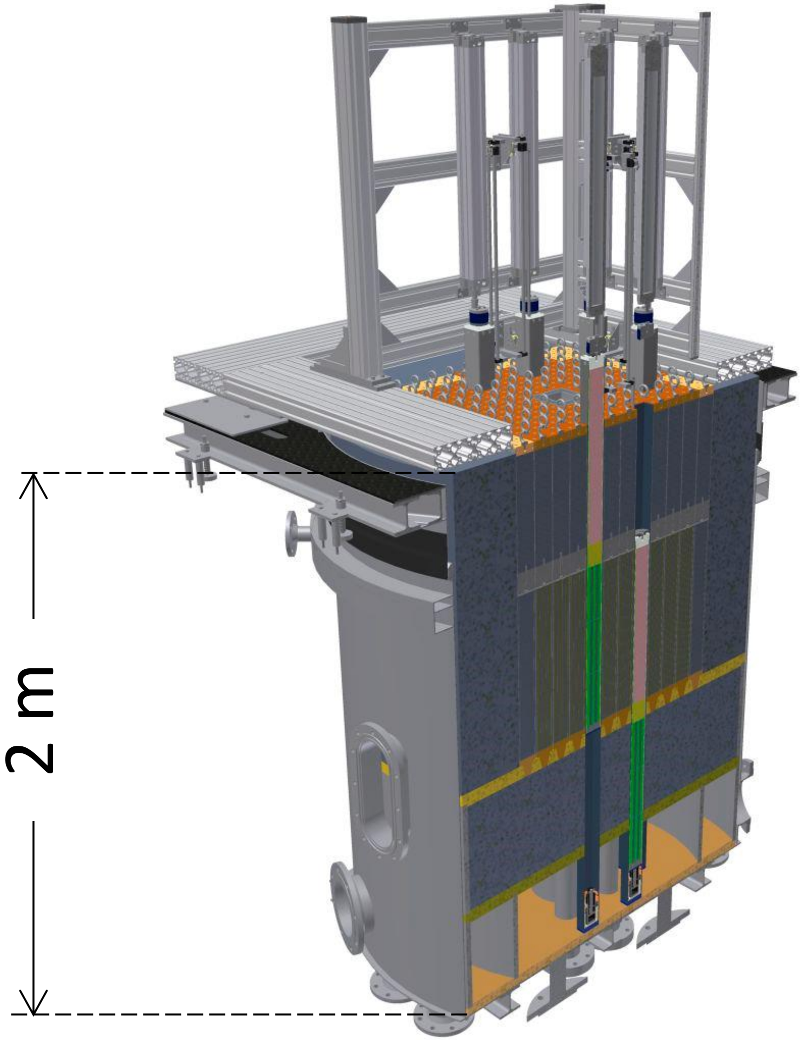




Core	#FAs	FA composition	Reflector
CR0	97	9 U+16 Pb	Pb
CC5	41	13 U+8 Pb+4 Al_2O_3	Pb
CC6	41	13 U+8 Pb+4 Al_2O_3	Pb
CC7	41	13 U+8 Pb+4 Al_2O_3	Pb+C
CC8	47	13 U+8 Pb+4 Al_2O_3	Pb+C
CC9	41	13 U+8 Bi+4 Al_2O_3	Pb
CC10	41	13 U+Pb+8 Bi+4 Al_2O_3	Pb+C
CC10b	47	13 U+Pb+8 Bi+4 Al_2O_3	Pb+C
CC11	50	13 U+Pb+8 Bi+4 Al_2O_3	Pb+C

- Kinetic parameters
- CR worth
- Spectral indices
- Axial and radial traverses
- Pb-Bi void
- Fuel Doppler

Nuclear Data Validation: VENUS-F



Serves licensing and design tasks:

Validation of online sub-criticality monitoring of an ADS

Validation of nuclear data and neutronics codes

Experimental characterization of fast critical and subcritical cores representative for MYRRHA


Robust data assimilation for LFR nuclear data improvement


Neutron Data Benchmarking at the VENUS-F zero power reactor for MYRRHA


Neutronic experiments at VENUS-F in support of lead-cooled small modular reactor deployment

Example: EC PULSAR project

Analysis of the production capabilities of ^{238}Pu in different irradiation conditions @BR2

Requirements

- At least 85% of the Pu produced must be ^{238}Pu
- Less than 2 ppm of ^{236}Pu

$$^{237}Np + n \xrightarrow{(n,\gamma)} {}^{238}Np \xrightarrow{\beta^-(2.117\ d)} {}^{238}Pu$$

$$^{238}Np + n \xrightarrow{(n,f)} fission\ products + 2\ n$$

$$^{237}Np + n \xrightarrow{(n,f)} fission\ products + 2\ n$$

$$^{238}Np + n \xrightarrow{(n,\gamma)} {}^{239}Np \xrightarrow{\beta^-(2.355\ d)} {}^{239}Pu$$

$$^{237}Np + n \xrightarrow{(n,2n)} {}^{236}Np + 2\ n$$

$$^{236}Np \xrightarrow{\beta^-(22.5\ h)} {}^{236}Pu$$