ALEPH2 code for spent fuel characterization

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SCK•CEN
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SNF observables

- Main studied observables:
  - Decay heat rate H
  - Neutron emission rate S_n
  - γ-ray emission rate S_γ
- difficult to be directly measured e.g.
  - Decay heat by calorimetry: accurate measurement but long measurement times
  - n. emission: difficult to separate SF and (n,α), impossible between different nuclides
  - γ-ray emission: measurements affected by self-absoption in fuel and in other materials
  - Reactivity: depends on configuration of interim storage or terminal disposal facility

Determined/estimated by theoretical calculations

Input: geometry and material data, operational history, nuclear data

ALEPH-2 code

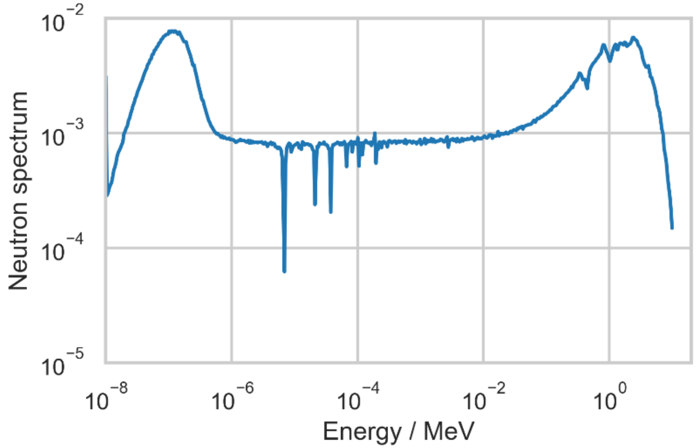
- Coupled neutron transport – fuel depletion calculation

Particle transport equation

- Given nuclide vector
- Snapshot of the particle spectrum

Bateman (transmutation) equation

- Assumed constant spectrum
- Flux normalization
- Isotopic density evolution



Update nuclide vector

ALEPH-2 code

- Coupled neutron transport – fuel depletion calculation

Particle transport equation

- Given nuclide vector
- Snapshot of the particle spectrum

↓

Bateman (transmutation) equation

- Assumed constant spectrum
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MCNP®

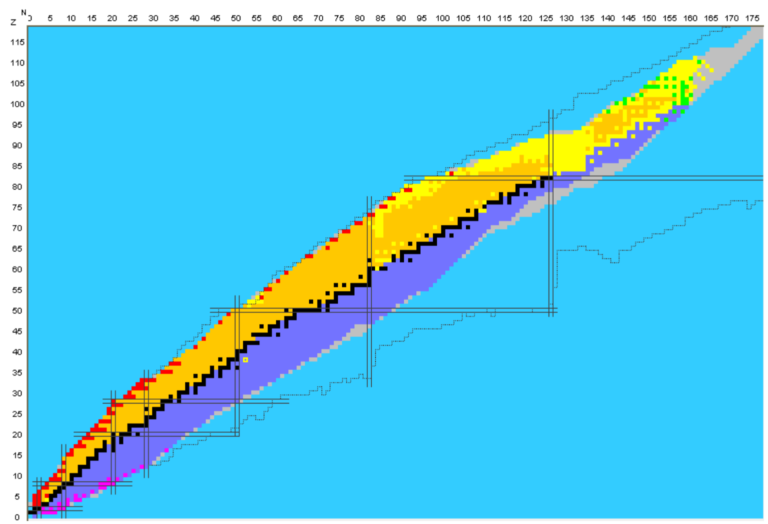
- Simple 1D to complex 3D
- Multi-particle physics
- Detailed energy-angle treatment
- Parallelization and commercial PC based cluster computing

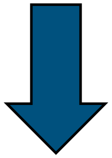
~~ORIGEN® (ALEPH-1)~~

RADAU-5
Runge-kutta solver

Depletion solver

- Consistent use of nuclear data for transport and depletion
- More than 4000 isotopes for which decay data are provided
- Cross sections available for 22 temperatures up to 1 GeV
  - ENDF/B-VIII.0
  - JEFF-3.3
  - TENDL
  - JENDL
  - GEFY





- ALEPH-DLG to process any nuclear data library in standard format

ALEPH-2 outputs

- Nuclide vector after irradiation / decay
- Derived quantities (observables of interest)
  - Decay heat
  - Neutron emission (spontaneous fission + (α, n))
  - Activities of individual nuclides
  - Prompt and delayed gamma / neutron heating
  - Nuclide radiotoxicities
  - Residual gamma doses

Fuel shuffling: example (Vandellós-II benchmark)

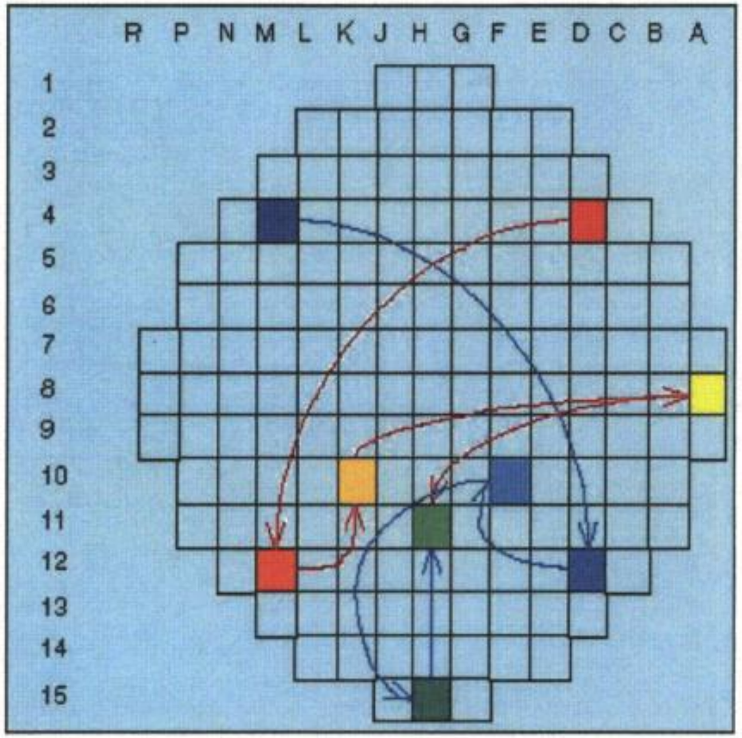
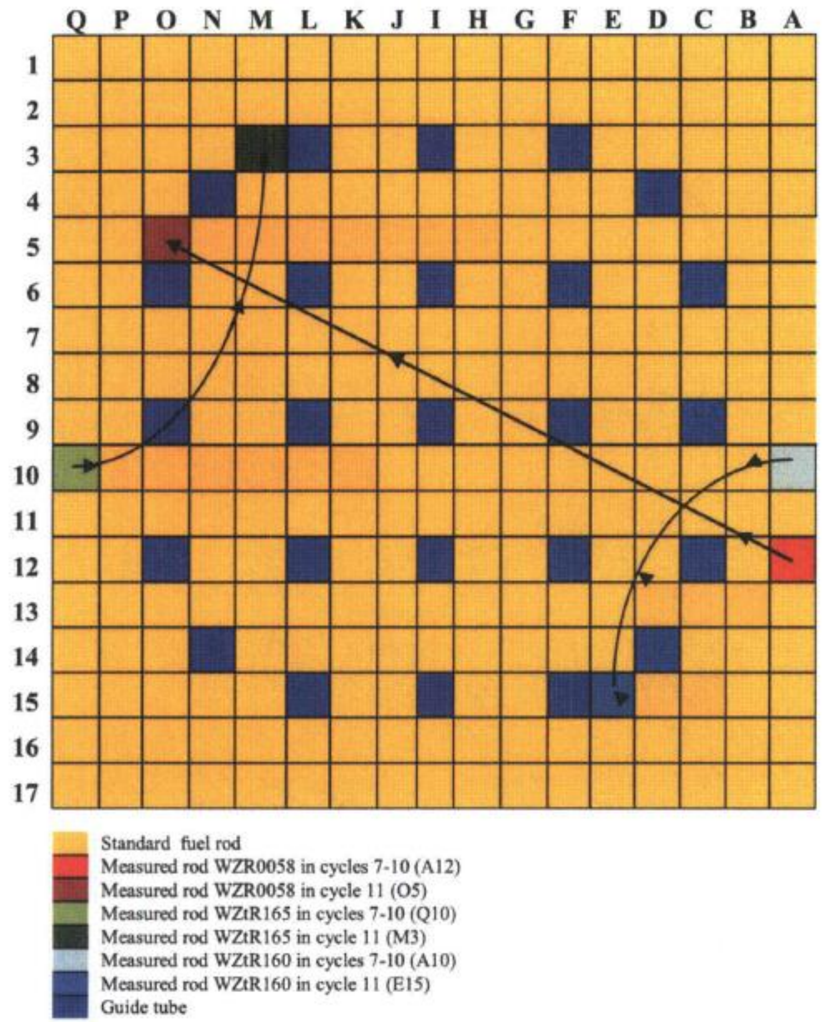


Figure 4.2. Vandellós II core layout.



Assembly layout for Vandellós II samples.

Analyses with ALEPH-2

- EURAD Subtask 2.1 - test case for code comparison and sensitivity analysis
  - 2D PWR 17×17, reflective boundary conditions. Zircaloy-4, 4% enriched UO_2 fuel, 4 × 300 d fuel cycles, cooling periods 30 d. Fuel radius 4.095 mm, clad inner/outer radii 4.18/4.75 mm, rod pitch 12.6 mm
  - **Codes:** Serpent (v2.1.29), **ALEPH-2**, SCALE/Polaris, DRAGON4
  - Sensitivity analysis:
    - Nuclear data
    - Modelling approximations
    - Operation history
    - Fuel composition
- SKB-50 campaign + (blind test SKB)
- JOYO decay heat

Code comparison

Output: nuclide vector and derived quantities (observables of interest)

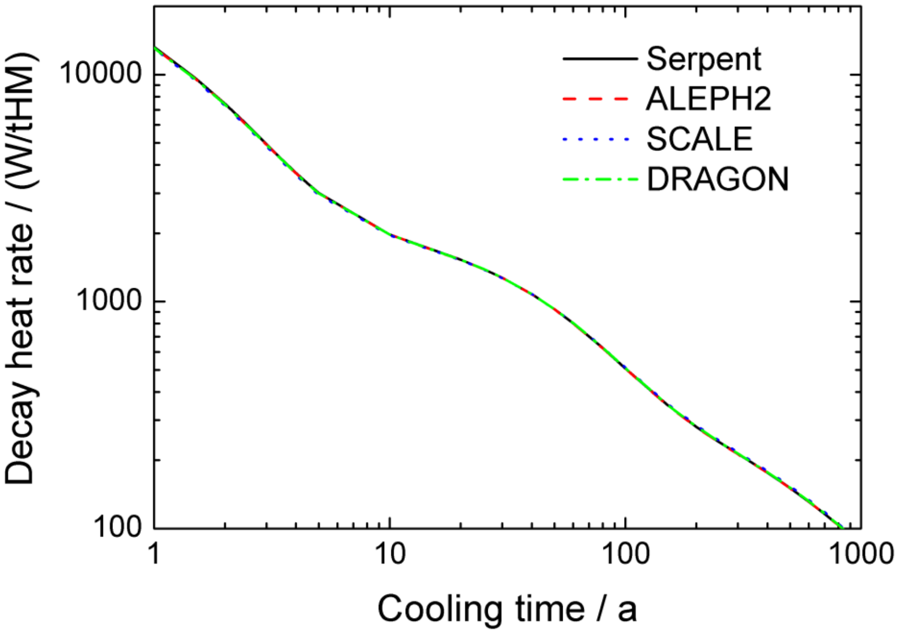
Code **Nuclide**	**Serpent** c_0 /(g/tHM)	**ALEPH2** c /(g/tHM)	$\Delta c/c_0$	**SCALE** c /(g/tHM)	$\Delta c/c_0$	**Dragon** c /(g/tHM)	$\Delta c/c_0$
^{90}Sr	678.56(2)	678.86	0.04%	675.43	-0.46%	679.08	0.08%
^{134}Cs	43.86(2)	43.68	-0.43%	41.11	-6.28%	43.64	-0.51%
^{137}Cs	1638.0(0)	1640.2	0.13%	1643.2	0.32%	1639.8	0.11%
^{235}U	7109.9(14)	7064.5	-0.64%	7283.3	2.44%	7119.6	0.14%
^{238}Pu	426.44(18)	426.55	0.03%	429.22	0.65%	434.35	1.85%
^{239}Pu	6747.4(18)	6786.5	0.58%	6947.2	2.96%	6825.4	1.16%
^{240}Pu	3065.2(13)	3044.1	-0.69%	2976.3	-2.90%	3056.1	-0.30%
^{241}Pu	1556.7(6)	1561.8	0.33%	1608.5	3.33%	1570.8	0.91%
^{242}Pu	970.92(30)	967.77	-0.32%	990.42	2.01%	963.26	-0.79%
^{241}Am	499.66(17)	499.79	0.03%	516.77	3.43%	503.06	0.68%
^{244}Cm	109.38(8)	108.80	-0.52%	102.37	-6.41%	106.86	-2.32%

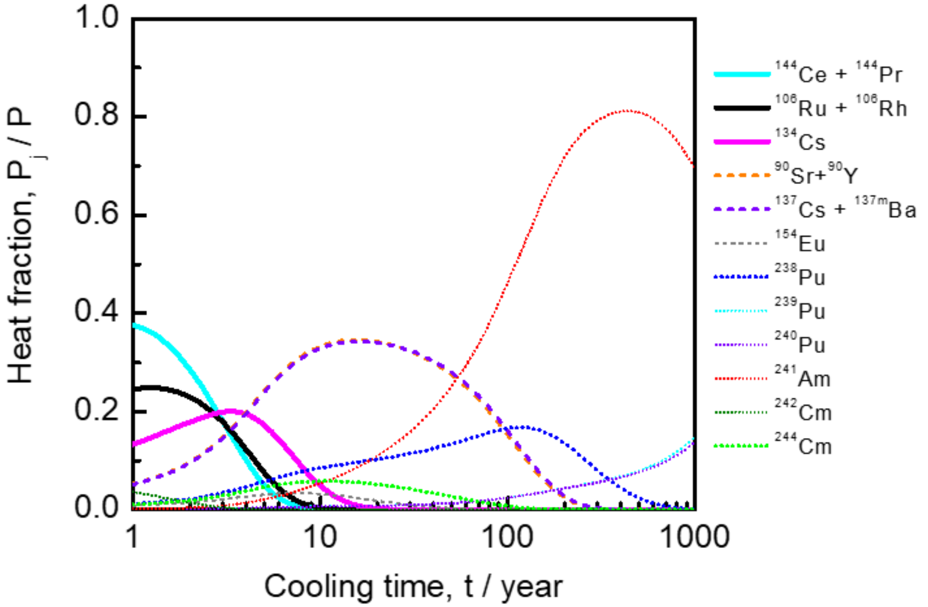
Code comparison: decay heat rate

- Decay heat rate: $H(t) = \sum_j H_j(t)$

$$H_j(t) = N_j(t)\lambda_j E_{rd,j}$$

λ - decay constant
E_{rd} - recoverable energy per decay
N - number density





$1\ a \le t_c \le 10\ a$

- **^{144}Ce / ^{144}Pr**
- **^{106}Ru / ^{106}Rh**
- **^{134}Cs**
- ^{90}Sr / ^{90}Y & ^{137}Cs / ^{137m}Ba

$10\ a \le t_c \le 100\ a$

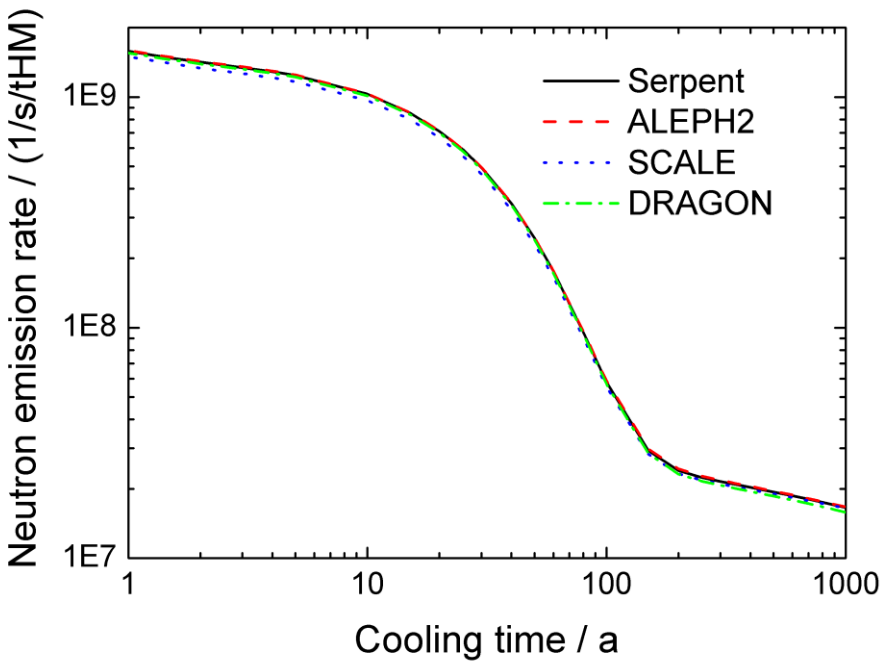
- **^{90}Sr / ^{90}Y & ^{137}Cs / ^{137m}Ba**
- ^{238}Pu
- ^{241}Am
- ^{244}Cm

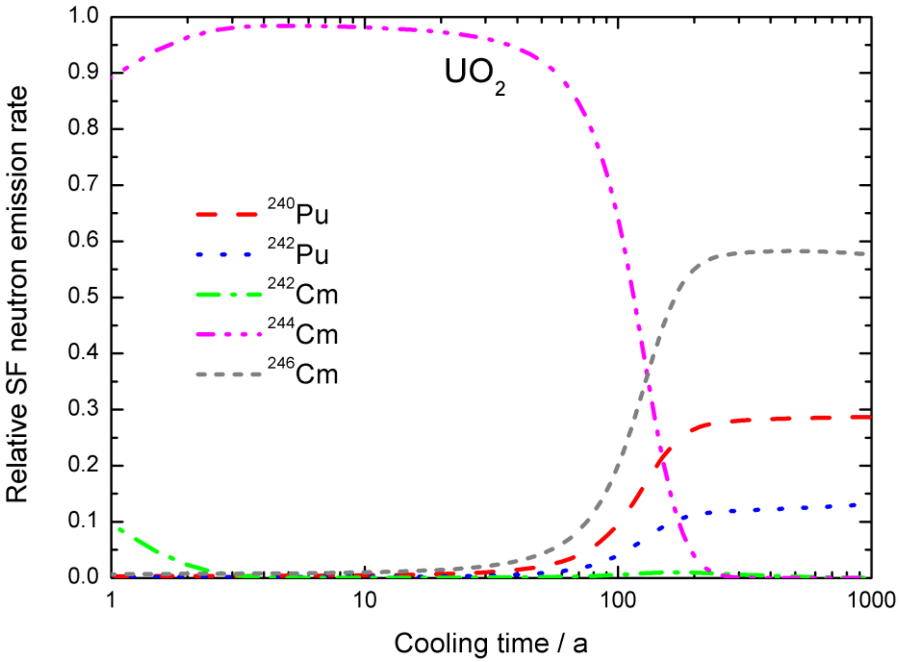
$100\ a \le t_c$

- **^{241}Am**
- ^{238}Pu
- $^{239,241}Pu$

Code comparison: neutron emission rate

- Neutron emission rate: $S_n(t) = \sum_j S_{n,j}(t) = \sum_j N_j(t)(s_{SF,j} + s_{\alpha,j})$
  - spontaneous fission rate per nucleus: $s_{SF,j} = \nu_j \lambda_{SF,j}$
  - (α,n) reaction rate per nucleus: $s_{\alpha,j} = \lambda_{\alpha,j} \sum_{l,k} P_j(E_{\alpha k}) Y_l(E_{\alpha k})$



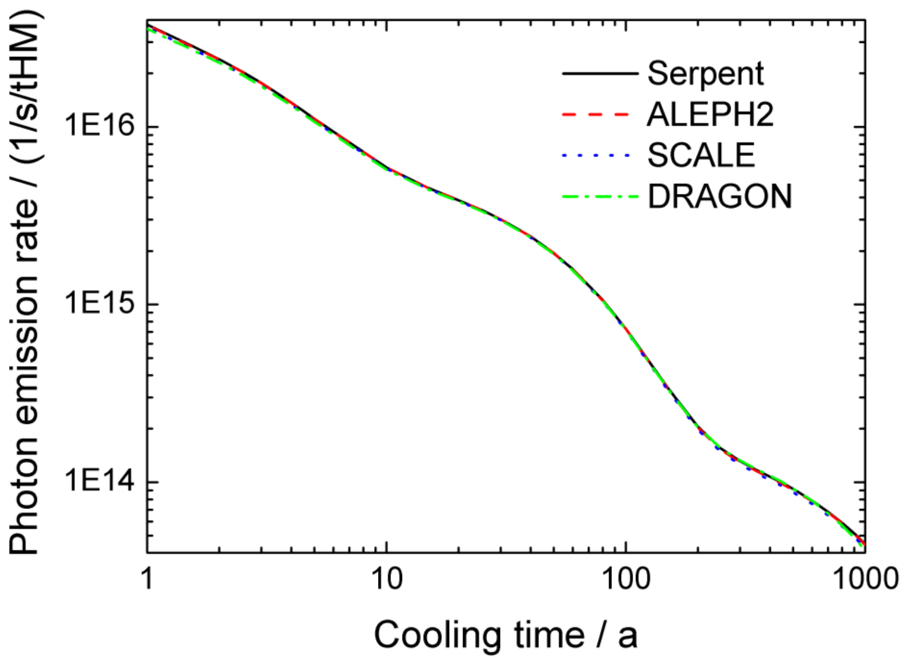


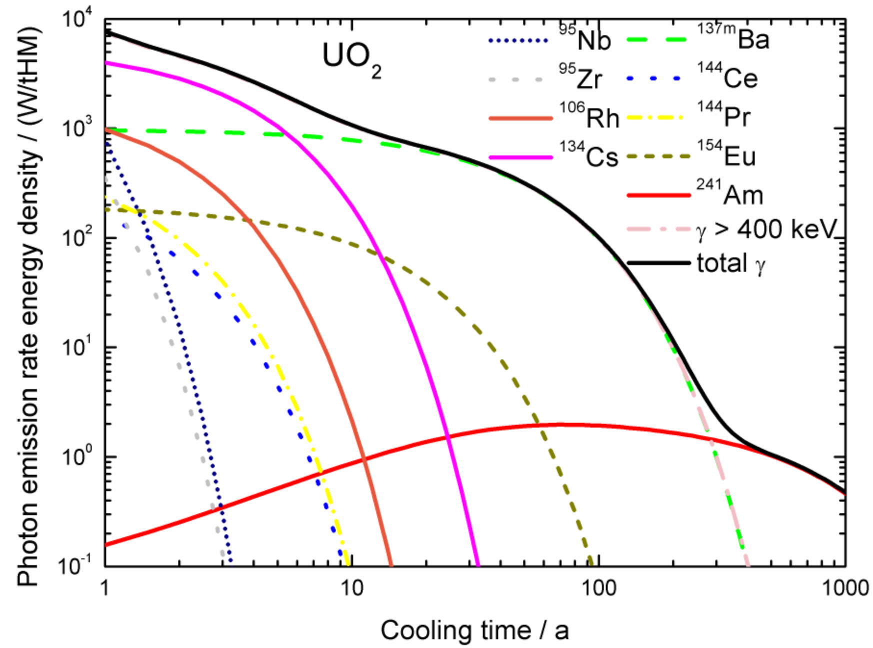
- **Contribution from SF dominating!**

Code comparison: gamma emission rate

- Gamma emission rate: $S_\gamma(t) = \sum_j S_{\gamma,j}(t) = \sum_j N_j(t)\lambda_j P_{\gamma j}$

$P_{\gamma j}$ - γ-ray emission probability per decay





1 a ≤ *t* ≤ 10 a

- **^{134}Cs**
- ^{137}Cs / **^{137m}Ba**
- ^{106}Ru / **^{106}Rh**

10 a ≤ *t* ≤ 300 a

- ^{137}Cs / **^{137m}Ba**
- **^{154}Eu**
- ^{241}Am

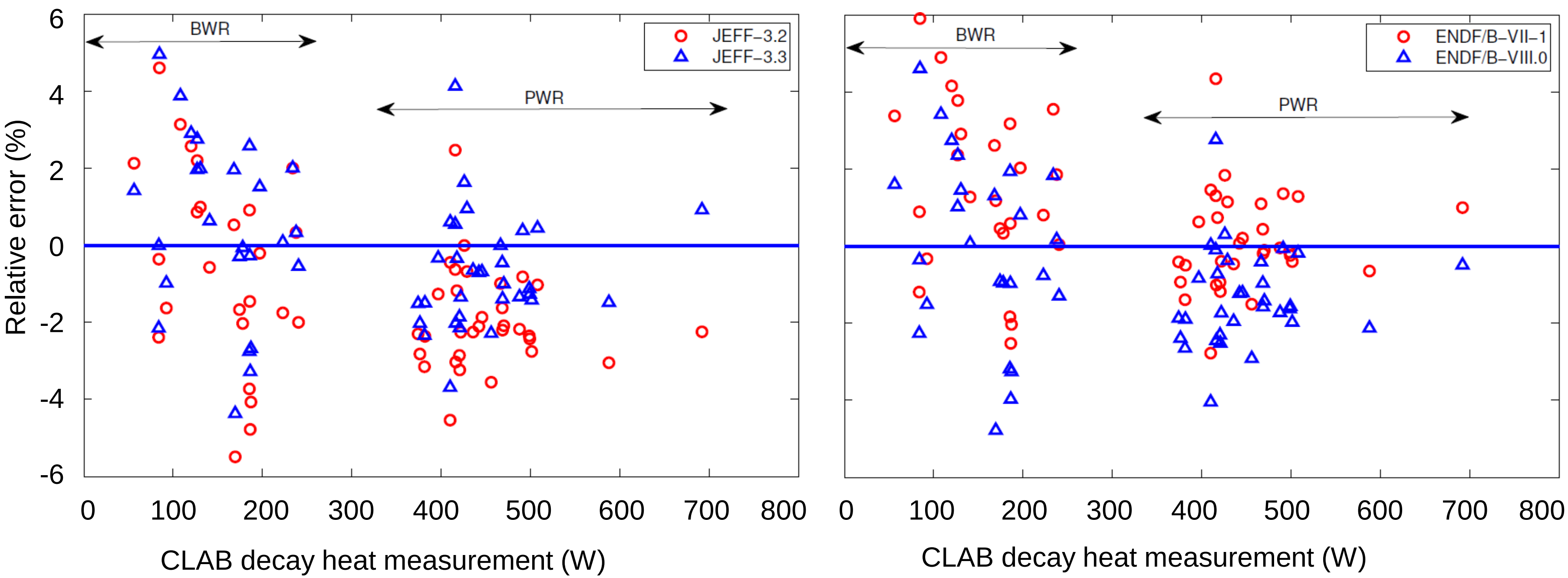
300 a ≤ *t*

- **^{241}Am**
- ^{137}Cs / ^{137m}Ba

Validation of ALEPH-2 for decay heat predictions

- SKB 50 measurement program
  - 50 BWR and 34 PWR assemblies were selected for measurement from the Clab inventory

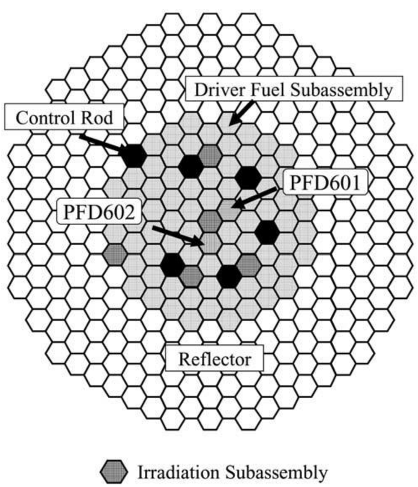
- SKB blind test benchmark

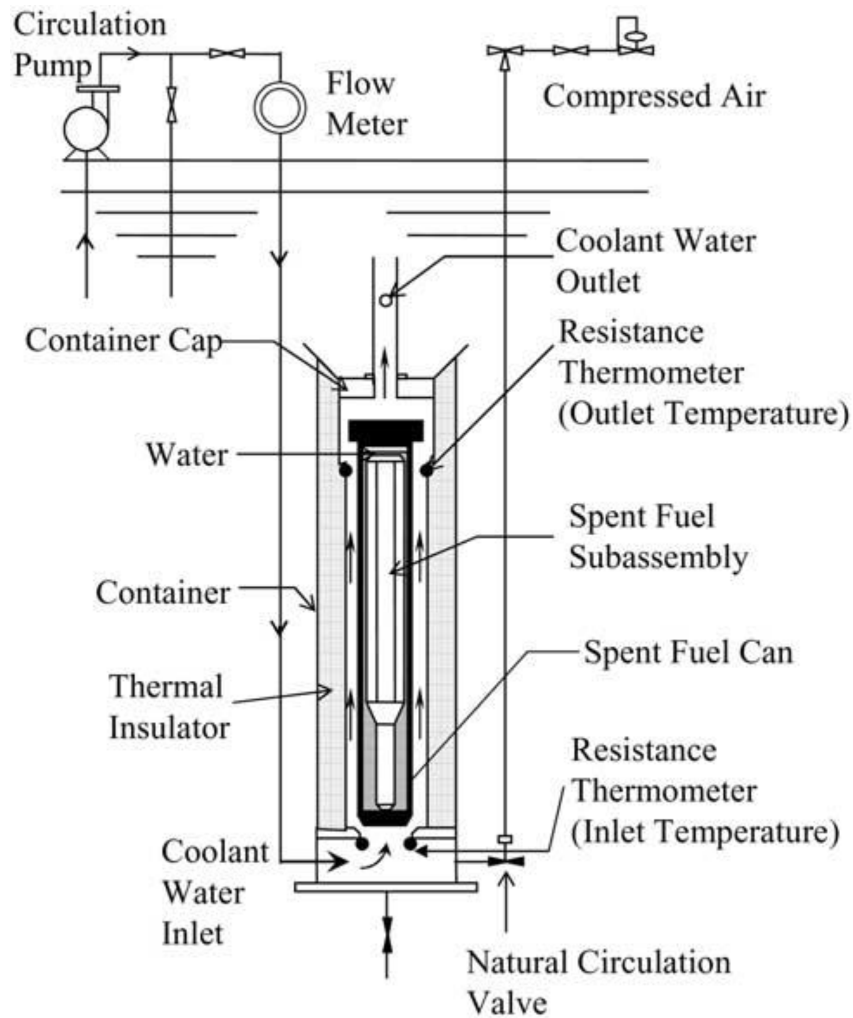


JOYO: calorimetric measurement

- Subassembly PFD601 from JOYO Mk-II
- Irradiation for 369 EFPD between 1997 until 2000

BU	66 GWd/tHM
CT	40 – 385 days
IE	29.3 wt% Pu



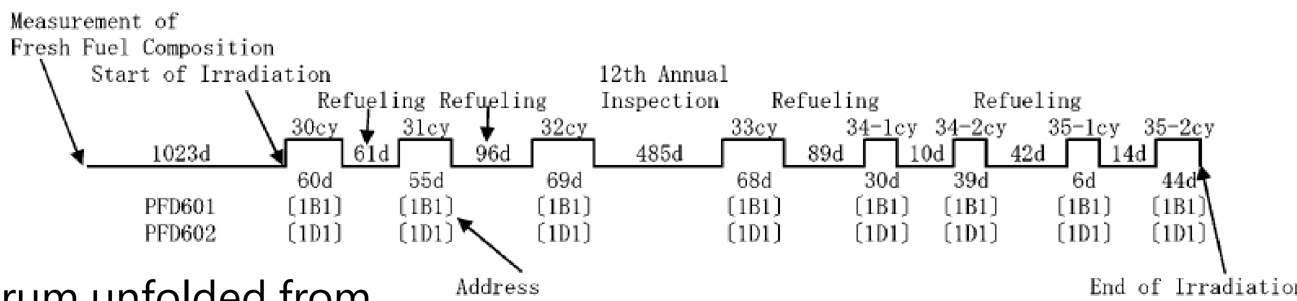


Decay heat measurement system diagram

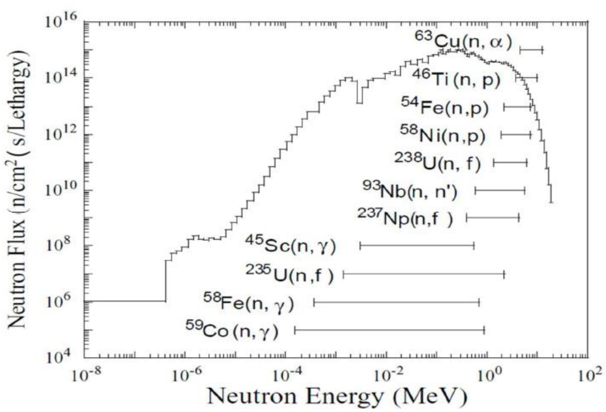
Source: [TBD]

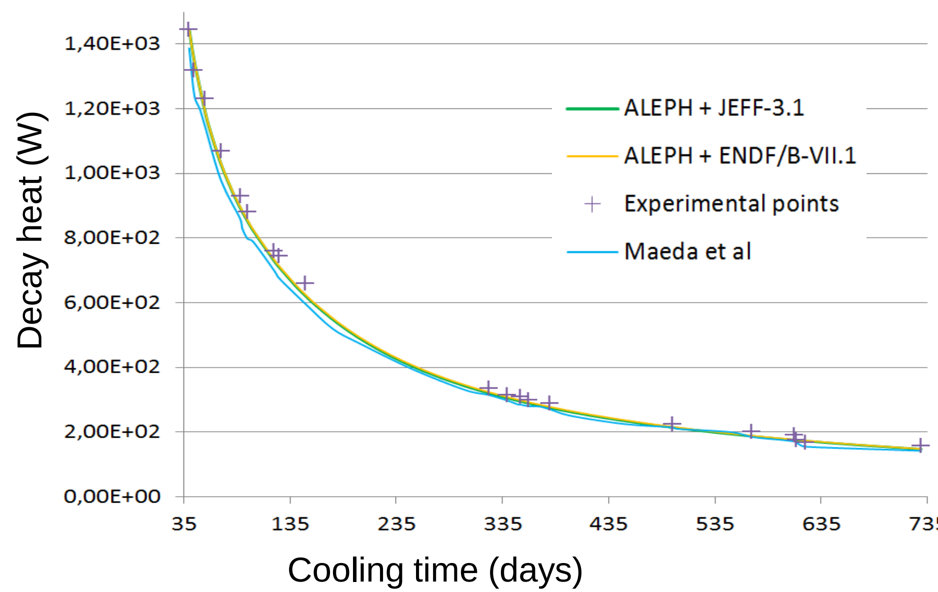
Decay heat for fast reactors

- Irradiation with constant flux



- Neutron spectrum unfolded from dosimetry measurements

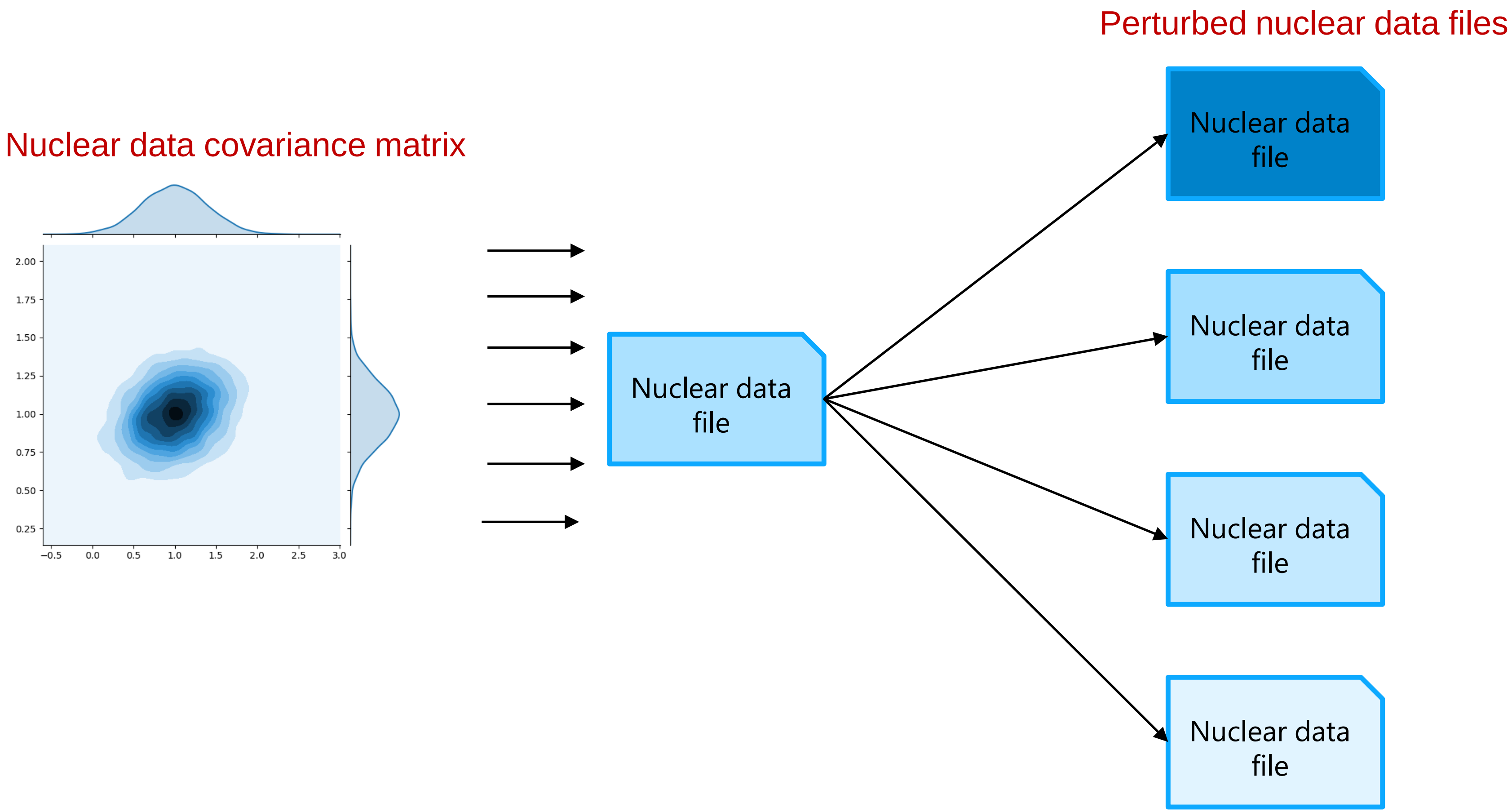




- Decay heat normalized to first exp. point

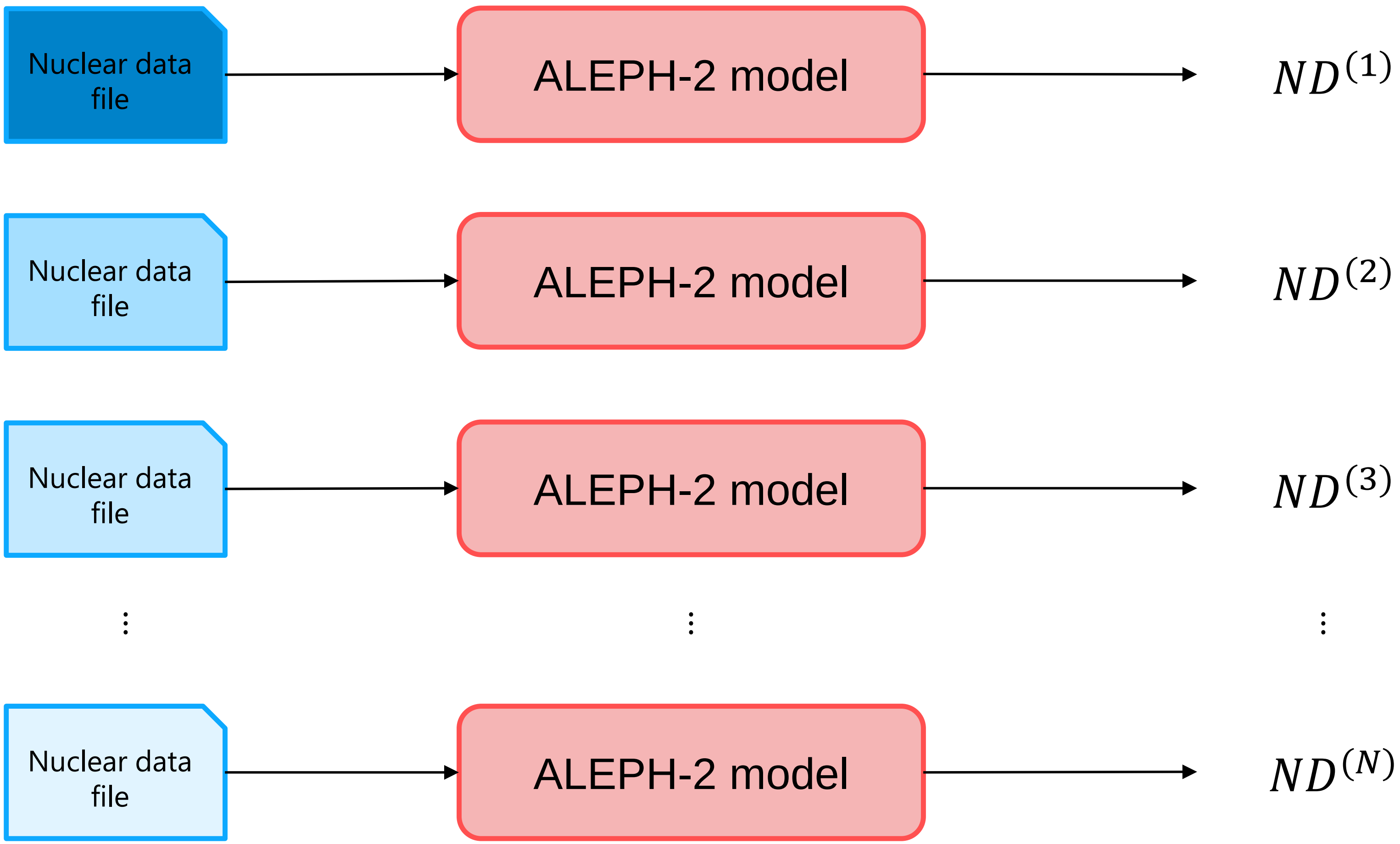
Uncertainty quantification - SANDY

- Nuclear data covariance propagation – SANDY code



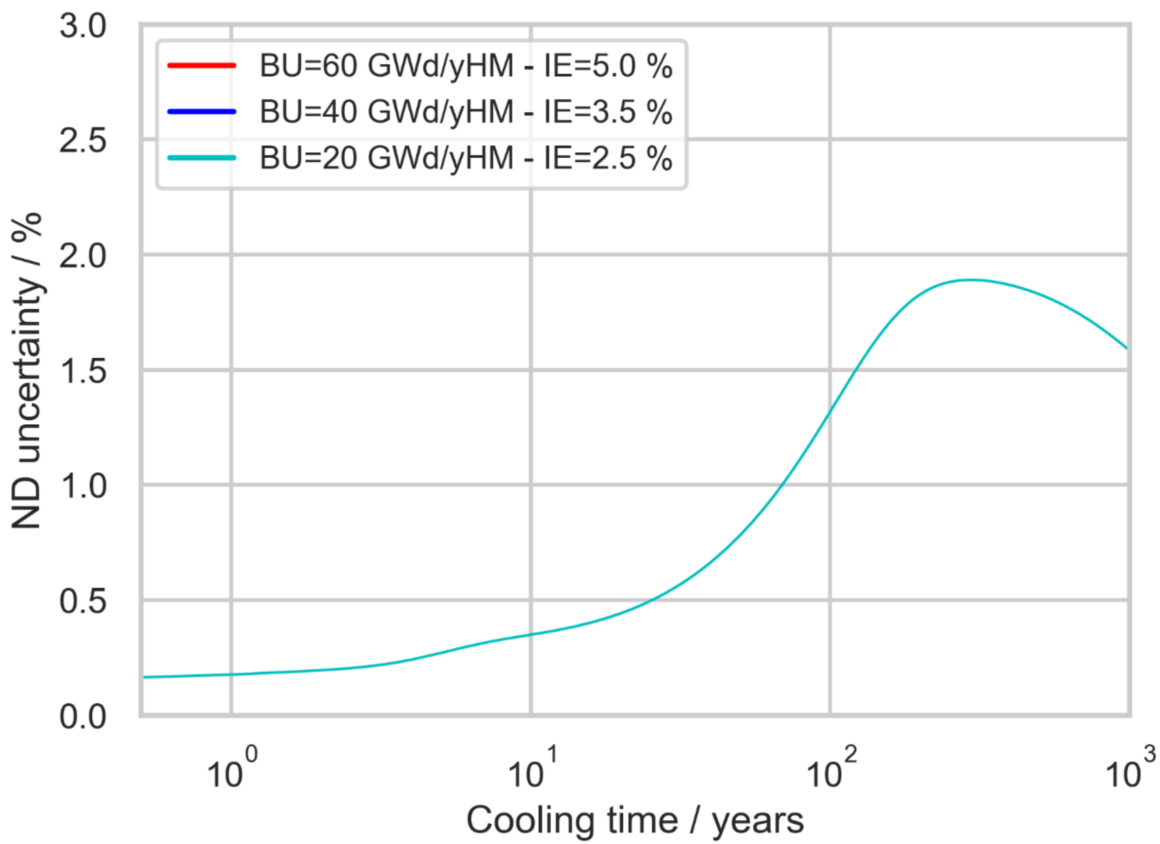
Uncertainty quantification

- Nuclear data covariance propagation – SANDY code



Decay heat uncertainty for PWR fuel

- Uncertainty variation with burnup and initial enrichment



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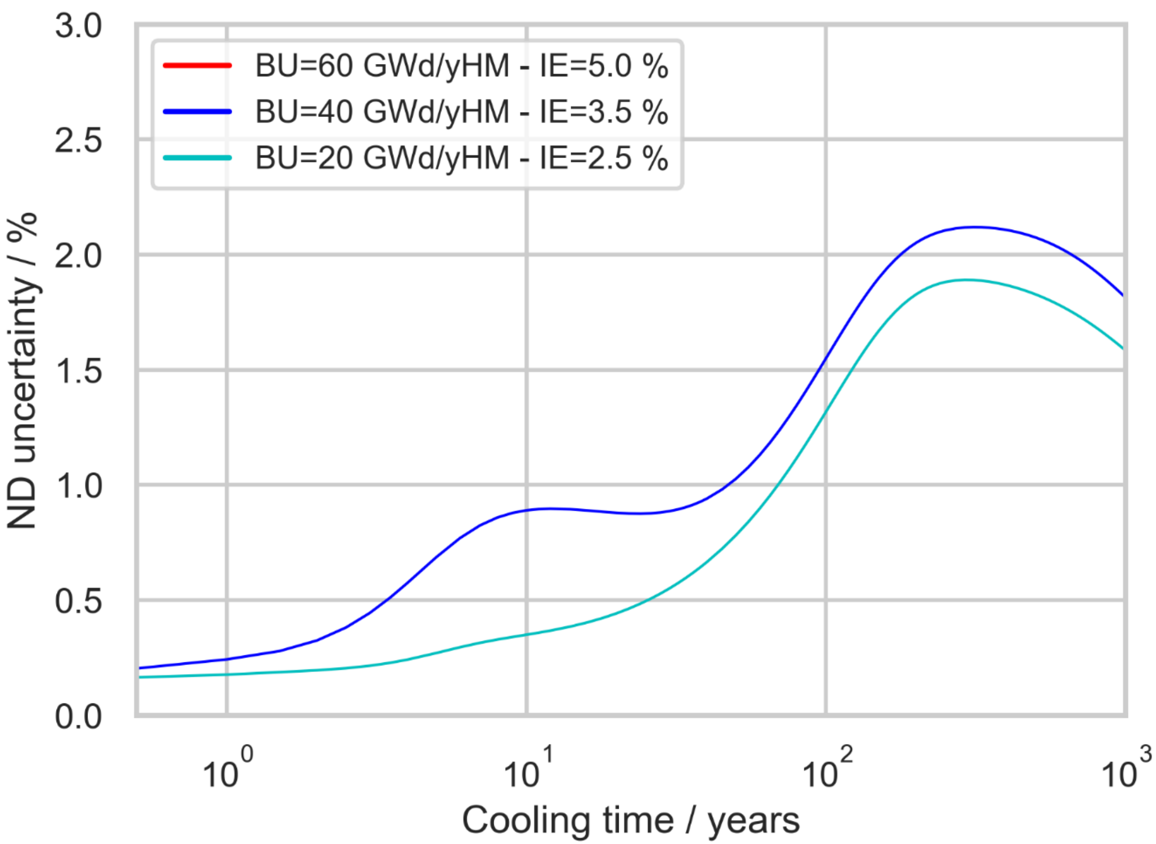

Decay heat uncertainty for PWR fuel

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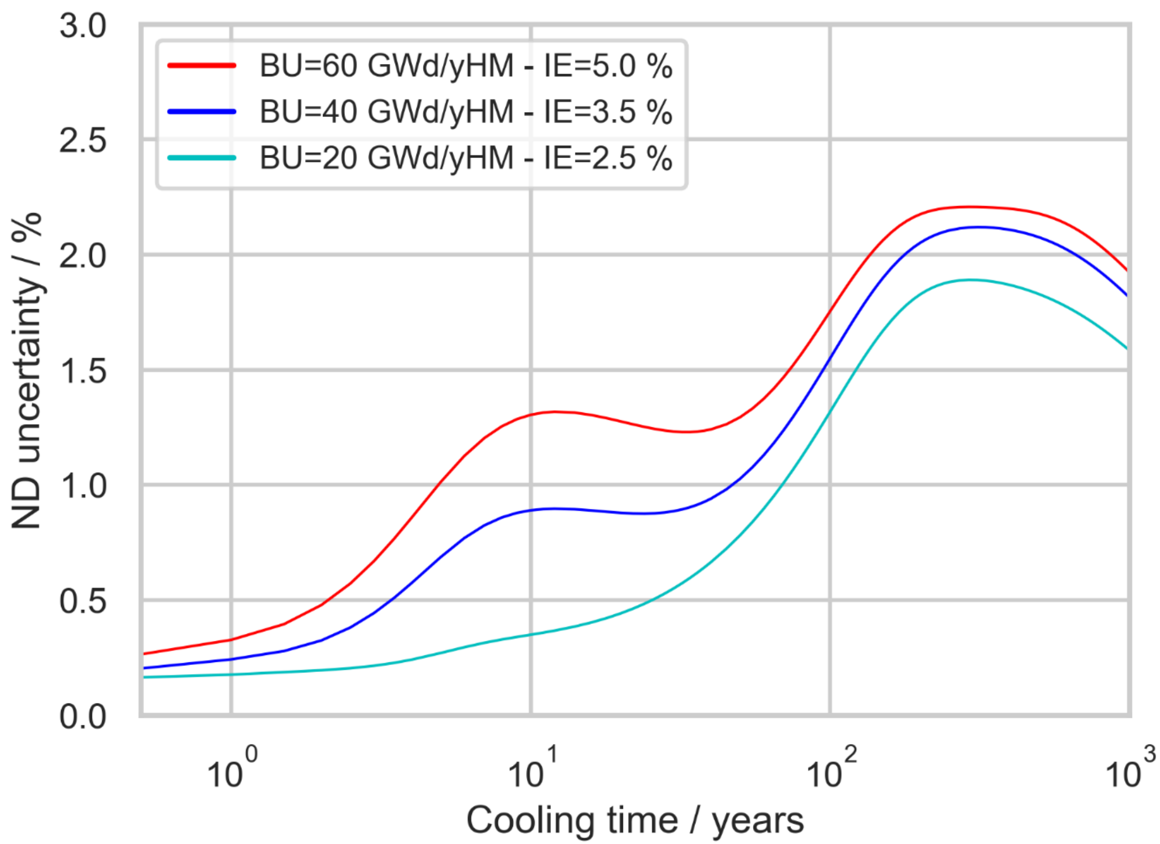
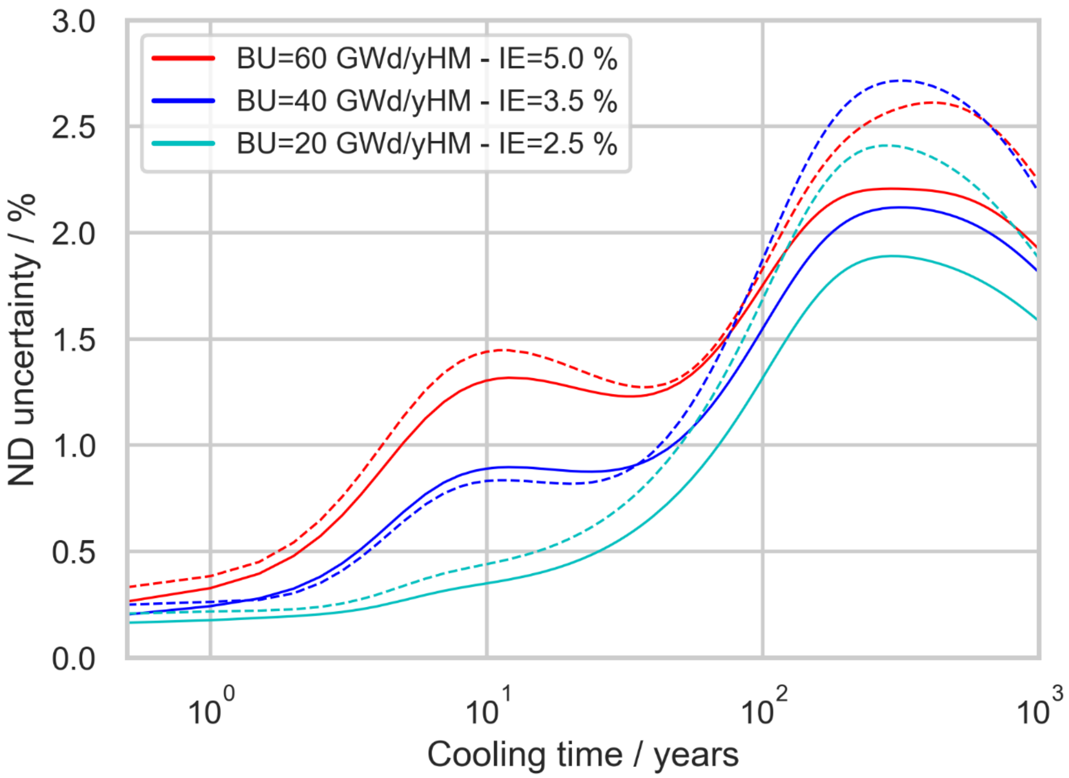


Decay heat uncertainty for PWR fuel

- Impact of different nuclear data libraries
  - Solid line: JEFF-3.3
  - Dashed line: JENDL-4.0



Conclusions

- ALEPH-2 to predict SNF isotopic inventory and related quantities
- SCK•CEN participation to EURAD 2.1 with ALEPH-2
- Sensitivity analyses using ALEPH-2 modelling features
- Uncertainty quantification using SANDY
- Continuous R&D to update the code
  - API for input / outputs → easy data post-processing
  - Compatibility with other transport solvers (Serpent)
  - Advanced analyses – python3.6, pandas, hdf5