KÄRÄHDE

Käytetyn polttoaineen karakterisaatio ja lähdetermi

Spent Fuel Characterization and Source Term

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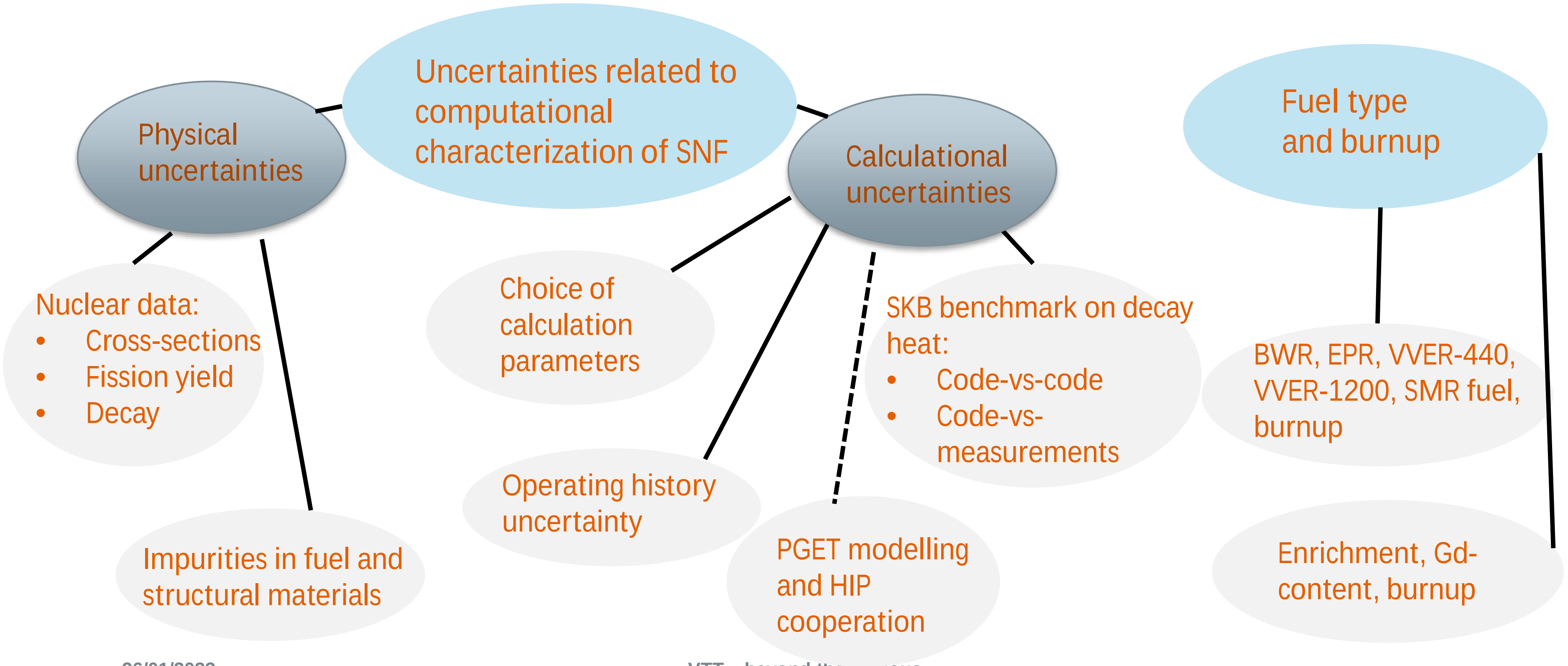
Motivation

- Knowledge of spent fuel (SNF) properties is important for safe handling and final disposal
  - Decay heat and reactivity → volume of repository space
  - Nuclide inventories → radiation protection, dose estimates
- Computational determination of decay heat involves several uncertainty sources
- SNF properties are also dependent on fuel type, enrichment and burnup
- At VTT, these uncertainties have been studied using the Monte Carlo reactor physics code Serpent 2 [1]

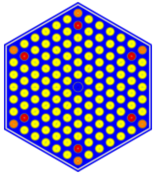
[1] Leppänen, J., et al. (2015) "The Serpent Monte Carlo code: Status, development and applications in 2013." Ann. Nucl. Energy, 82 (2015) 142-150.

KÄRÄHDE topics

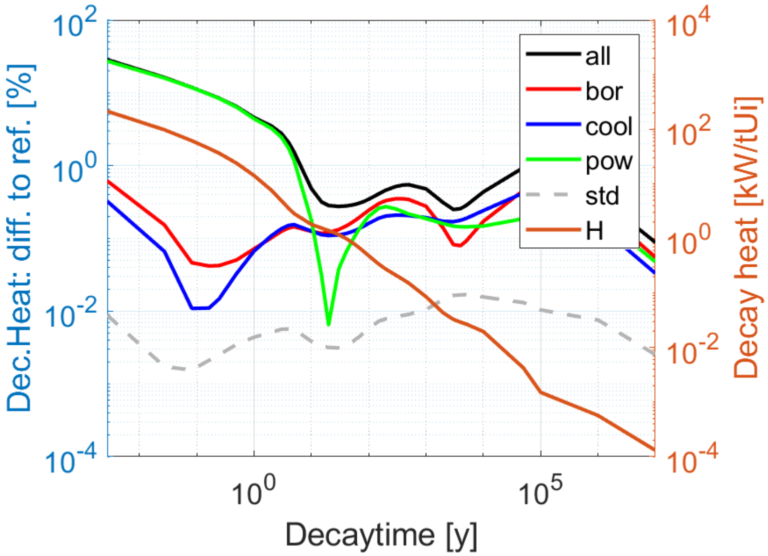


Computational choices, fuel types

Simplifications in operating history

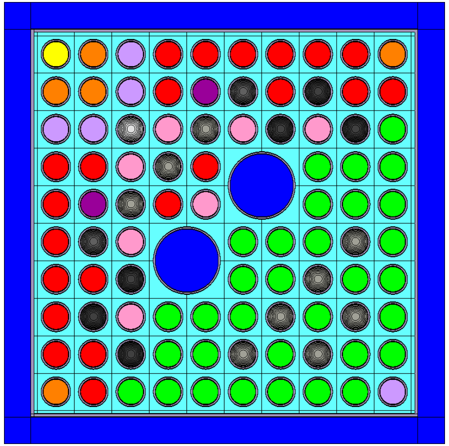


- Boron concentration, assembly power and coolant temperature and density were averaged over three cycles.
- Averaging assembly power overestimates activity, decay heat and photon emission rate 64 – 78 % right after irradiation.
- After 10 years the effect is < 1 %
- Effect on spontaneous fission rate and the studied nuclides (C-14, Cl-36, Mo-93, Ag-108m, I-129, U-233, U-235, Pu-239, Pu-241) is mostly below 1.5 %

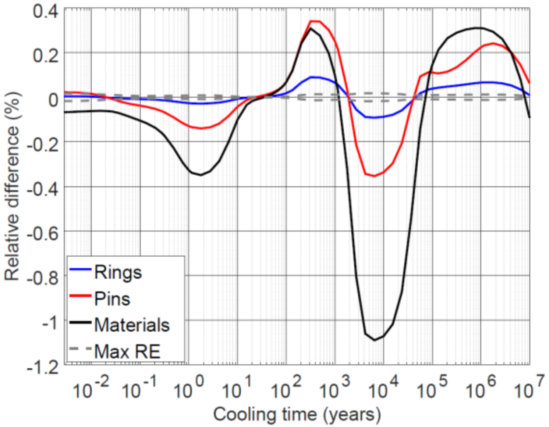


Choice of calculation parameters 1/2

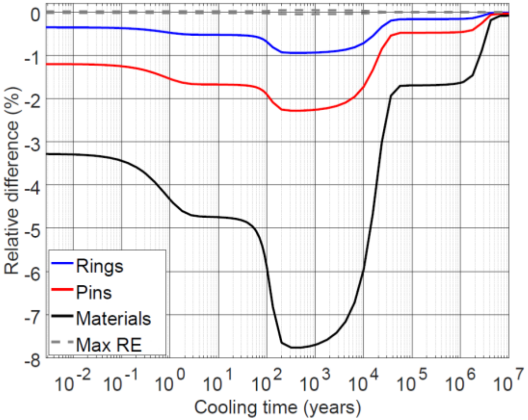
- A burnup calculation involves the choice of several input parameters.
- A BWR GE14 fuel assembly with 40 % void was applied in a 2D burnup calculation up to 60 MWd/kgU
- Studied calculation parameters:
  - Depletion zone division
  - Depletion step length
  - Doppler-broadening rejection correction (DBRC)
  - Unresolved resonance probability table sampling
  - Energy-dependent branching ratios



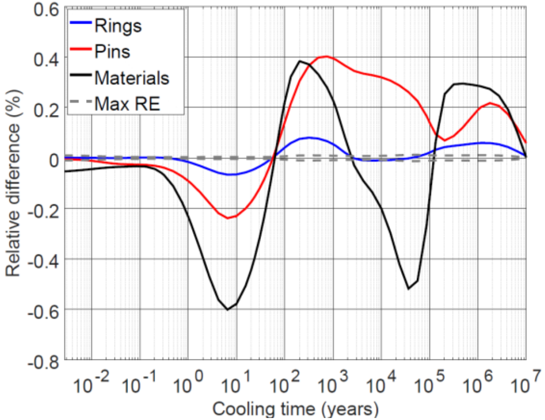
Uncertainties due to choice of calculation parameters (depletion zone division) 2/2



Photon emission rate



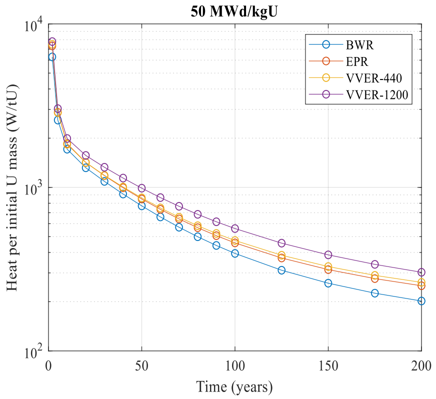
Spontaneous fission rate

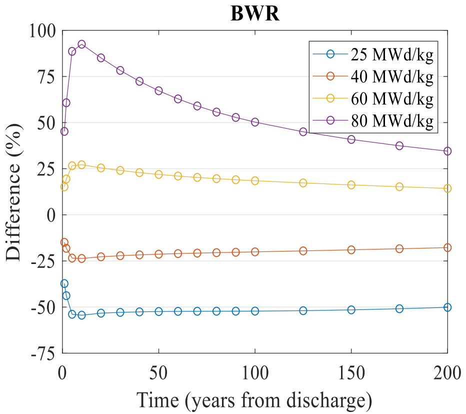


Decay heat

- Neglecting DBRC
  - non-negligible effect on some heavier nuclides
  - Maximum effect on DH and PE ~0.5 %

Impact of fuel type and burnup on decay heat





- Difference to 50 MWd/kgU

Top decay heat contributors 5 y (top) and 100 y (below) after irradiation

BWR	%	EPR	%	VVER-440	%	VVER-1200	%
Y90	27.7	Cs134	27.2	Cs134	27.9	Cs134	25.4
Ba137m	27.2	Ba137m	24.5	Y90	25.2	Y90	24.2
Cs134	24.9	Y90	23.2	Ba137m	25.1	Ba137m	23.2
Cm244	10.2	Cm244	13.7	Rh106	11.4	Pu238	16.9
Rh106	10.0	Rh106	11.4	Cm244	10.3	Rh106	10.4

Nuclides	% (BWR)	% (EPR)	% (VVER-440)	% (VVER-1200)
Am241	40.0	44.8	46.4	39.1
Pu238	22.8	23.6	22.6	34.8
Ba137m	16.3	14.1	13.6	11.4
Y90	15.0	12.1	12.4	10.7
Pu240	5.9	5.4	5.0	4.0

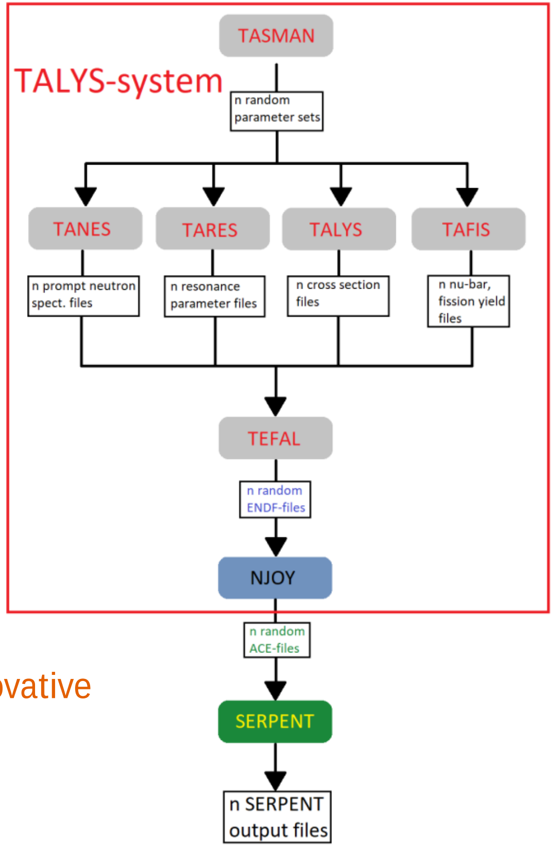
International: SKB benchmark and NEA guidance report

- SKB benchmark: characterization (e.g. decay heat) of five irradiated PWR assemblies.
- Comparison to the results of other participants and measurements.
  - Good agreement between codes, discrepancy vs. measured data
- VTT participated using Serpent 2.
- Decay heat subgroup initiated under NEA WPNCS in 2022, VTT's contribution to state-of-the-art report (under construction)
  - Benchmark calculation expected in the near future

Nuclear data uncertainty propagation

Total Monte Carlo - Key Idea

- Create hundreds of randomized nuclear data files for many nuclides
  - New nuclear data is produced from nuclear models and experimental data: No need to resort to covariance data.
  - The data is produced with TALYS and a few satellite programs = T6 [2]
- Assign a random combination of the random data files for a Serpent run
  - Repeat hundreds of times and compile uncertainty in the output with an appropriate statistic



[2] A.J. Koning et al. (2019) “TENDL: Complete Nuclear Data Library for innovative Nuclear Science and Technology”. In: Nuclear Data Sheets 155, 1-55.

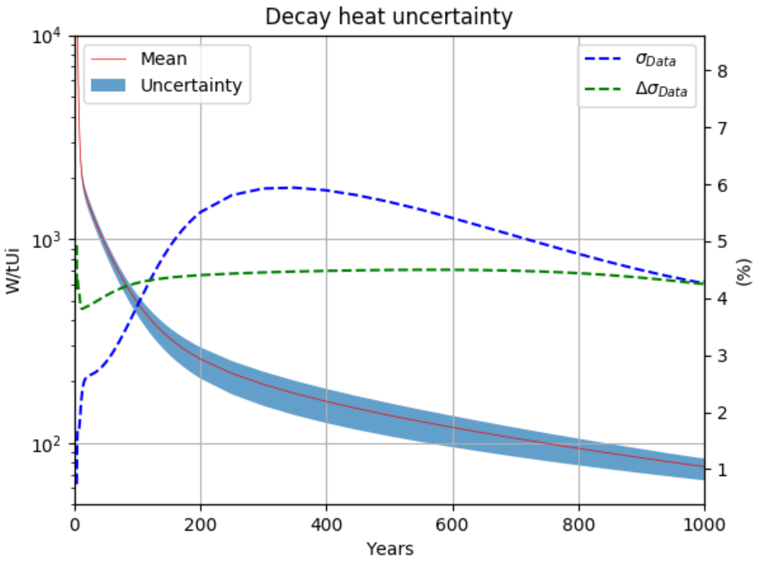
TMC environment at VTT

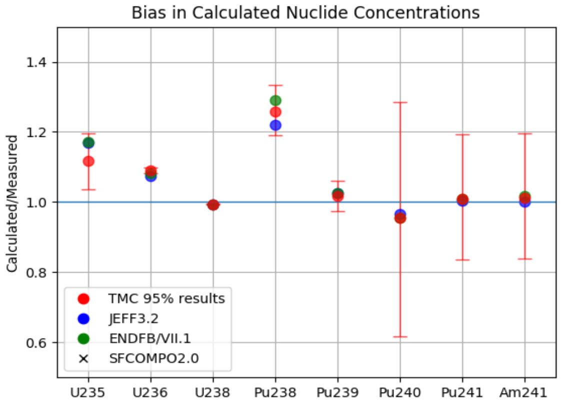
- 500 files for 88 nuclides have been produced for 0 K, 300 K, 600K, 900 K and 1200 K temperatures
- Random fission yield files have been included
  - Adopted from TENDL – website
- Scripts for file processing, TALYS/Serpent environment initialization, data visualization etc. have been set up.
- It is now straightforward to propagate data uncertainties through Serpent, although computationally expensive.

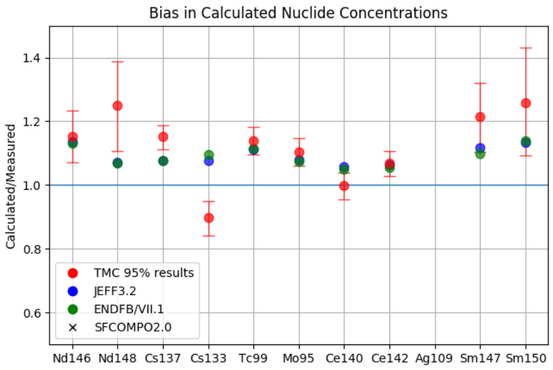
Total Monte Carlo with Serpent

VTT

Demonstration with SFCOMPO burnup credit benchmark, VVER-440 assembly, burnup ~45 MWd/kgU







Also in KÄRÄHDE

- Impurities in fuel and structures
  - Literature review, Serpent calculations based on its observations => 2 special assignments
- In addition to Total Monte Carlo, decay data uncertainty sampling implemented to Serpent
- PGET (passive gamma emission tomography) studies with Serpent for safeguard purposes: detector modelling and new variance reduction method development (2 special assignments)

Key take aways

- Approximations in power density should be avoided, when dealing with ”fresh” SNF (cooling time < 10 y).
- Pin-wise depletion zone division should be used in burnup calculations and Gd pins should be further divided in radial rings.
- DBRC should not be neglected. Use on U isotopes and ^{239}Pu and ^{240}Pu is mainly sufficient.
- Significant sources of uncertainty for BWR assembly calculations
  - Nuclear data
  - Burnup
  - (Void fraction and moderator density)
- Using recycled uranium significantly increases decay heat from SNF

Future work

- Additional C/E burnup calculation from SFCOMPO or other available sources
- Computationally less expensive alternatives to Total Monte Carlo
- Expanding from 2D assembly calculations to 3D full core
  - Serpent – Ants sequence (Kraken computational framework [3])
  - Particularly useful in SMR SNF characterization due to larger neutron leakage fraction
- Participation in activities of NEA subgroup on decay heat

[3] Leppänen, J., et al. (2022) "Current Status and On-Going Development of VTT's Kraken Core Physics Computational Framework" Energies, 15, 876, https://doi.org/10.3390/en15030876.

Selected publications

- International Journal publications
  1. Tuominen R., Valtavirta V. (2022), “The Effect of Serpent 2 Calculation Parameters on Evaluated Spent Nuclear Fuel Source Term”, Journal of Nuclear Engineering and Radiation Science, 8(4), [044503], https://doi.org/10.1115/1.4051445. .
  2. Häkkinen S. (2022), “Impact of Approximations in Operating History Data on Spent Fuel Properties with Serpent 2”, Journal of Nuclear Engineering and Radiation Science, 8(4), 041901. [NERS-21-1015]. https://doi.org/10.1115/1.4051444.
  3. Jansson P., et.al. (2022), ” Blind Benchmark Exercise for Spent Nuclear Fuel Decay Heat”, Nuclear Science and Engineering, 196, pp.1125-1145, https://doi.org/10.1080/00295639.2022.2053489.
  4. Rochman D., et.al., ”On the estimation of nuclide inventory and decay heat: a review from the EURAD Eurpean project”, Frontiers in Energy Research. (submitted in 2022).

- Conference articles
  1. Rintala A., ”Evaluating the Effect of Decay and Fission Yield Data Uncertainty on Spent Nuclear Fuel Source Term Using Serpent 2”, In Proc. 28th International Conference Nuclear Energy for New Europe, Paper No. 602, Portorož, Slovenia, 2019.
  2. Juutilainen P., Häkkinen S., “Impact of Fuel Type and Discharge Burnup on Source Term”, In Proc. 28th International Conference Nuclear Energy for New Europe, Paper No. 906, Portorož, Slovenia, 2019.
  3. Rintala A., ” Evaluating the Effect of Decay and Fission Yield Data Uncertainty on BWR Spent Nuclear Fuel Source Term”, In Proc. 29th International Conference Nuclear Energy for New Europe, Paper No. 1506, Portorož, Slovenia, 2020.
  4. Tuominen R., Valtavirta V., “The Effect of Serpent 2 Calculation Parameters on Evaluated Spent Nuclear Fuel Source Term”, In Proc. 29th International Conference Nuclear Energy for New Europe, Paper No. 1503, Portorož, Slovenia, 2020.
  5. Häkkinen S., “Impact of Approximations in Operating History Data on Spent Fuel Properties with Serpent 2”, In Proc. 29th International Conference Nuclear Energy for New Europe, Paper No. 1505, Portorož, Slovenia, 2020.

- Research reports
  1. Rintala A., “Evaluating the effect of decay and fission yield data uncertainty on spent nuclear fuel source term using Serpent 2 – continued study“, VTT Research Report, VTT-R-00209-20, 2020.
  2. Rintala A., “Separate effect of decay and fission yield data uncertainty on spent nuclear fuel source term“, VTT Research Report, VTT-R-00106-21, 2021.
  3. Juutilainen P., “Effect of burnable absorber rods and U-235 enrichment on EPR UO2 fuel assembly source term with Serpent 2”, VTT-R-00242-21, 2021.
  4. Häkkinen S., “Gundremmingen-A assembly B23 sample I2680 depletion calculation with Serpent 2”, VTT Research Report, VTT-R-00631-21, 2021.
  5. Häkkinen S., “Sensitivity and uncertainty analysis of Gundremmingen-A assembly B23 sample I2680 depletion calculation with Serpent 2”, VTT Research Report, VTT-R-00632-21, 2021.

- Thesis
  1. Vaara L., “Nuclear Data Uncertainty Propagation in Total Monte-Carlo Method”, M.Sc. Thesis, Aalto University, 2022.
  2. Vaara L., ”Impurity-generated impact on the characteristics of spent nuclear fuel”, Special Assignment, Aalto University, 2020.

beyond
the obvious

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