KÄRÄHDE
Spent Fuel Characterization and Source Term

Silja Häkkinen, Antti Rintala, Pauli Juutilainen, Lauri Vaara, Topias Kähkönen, Riku Tuominen, Jaakko Leppänen
KYT Interim Seminar 18.-19.3.2021

VTT – beyond the obvious
KÄRÄHDE motivation

- Spent Nuclear Fuel (SNF) properties are needed for safe handling and final disposal of SNF.
  - Decay heat and reactivity → volume of repository space
  - Nuclide inventories → radiation protection, dose estimates
- Computational characterization of SNF involves numerous uncertainty sources.
- SNF properties are also dependent on fuel type, enrichment and burnup.
KÄRÄHDE goals

- Understand how different uncertainties related to the computational characterization of SNF effect the source term and write instructions on how to characterize SNF with Serpent 2 [1].
- Understand how different fuel types (BWR, EPR, VVER-440, VVER-1200, SMR), enrichments and burnups effect the source term.
  - Source term = decay heat, nuclide inventory, etc. essential properties of spent nuclear fuel

KÄRÄHDE work 2019 - 2020

Physical uncertainties
- Nuclear data: fission yield and decay data
- Impurities in fuel and structural materials

Uncertainties related to computational characterization of SNF
- Choice of calculation parameters
- PGET modelling and HIP cooperation

Calculational uncertainties
- SKB benchmark and NEA report: decay heat
- Operating history uncertainty

Fuel type and burnup
- BWR, EPR, VVER-440, VVER-1200 fuel, burnup
- Enrichment, Gd-content, burnup

Physical uncertainties
- Nuclear data: fission yield and decay data
- Impurities in fuel and structural materials

Uncertainties related to computational characterization of SNF
- Choice of calculation parameters
- PGET modelling and HIP cooperation

Calculational uncertainties
- SKB benchmark and NEA report: decay heat
- Operating history uncertainty

Fuel type and burnup
- BWR, EPR, VVER-440, VVER-1200 fuel, burnup
- Enrichment, Gd-content, burnup
# Main results: effects on decay heat

<table>
<thead>
<tr>
<th>Subject</th>
<th>Main component</th>
<th>Effect [%]</th>
<th>Time after irradiation [y]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear data</td>
<td>Fission yield</td>
<td>3-5</td>
<td>1, 15</td>
</tr>
<tr>
<td>Impurities*</td>
<td>Co-60</td>
<td>4.5</td>
<td>5</td>
</tr>
<tr>
<td>Parameter choice</td>
<td>Depletion zone division</td>
<td>0.6</td>
<td>7</td>
</tr>
<tr>
<td>Averaging operating history</td>
<td>Assembly power</td>
<td>78</td>
<td>0</td>
</tr>
<tr>
<td>Burnup</td>
<td>Change 10 MWd/kgU</td>
<td>~15-25</td>
<td>0-200</td>
</tr>
<tr>
<td>Fuel type</td>
<td>BWR / VVER-1200</td>
<td>~-30 / -50</td>
<td>50 / 200</td>
</tr>
</tbody>
</table>

* Highly conservative values for impurities. Co-59 = 75 ppm (fuel), 20 ppm (Zry-4)
# Main results: effects on nuclide concentrations

<table>
<thead>
<tr>
<th>Subject</th>
<th>Main component</th>
<th>Effect [%]</th>
<th>Nuclides</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear data</td>
<td>Fission yield</td>
<td>42 / 1.6 / 5</td>
<td>Ag-108m / C-14 / I-129</td>
</tr>
<tr>
<td>Averaging operating history</td>
<td>Bor, cool / bor, cool / power / - / -</td>
<td>2.5 / 1.5 / 1.5 / 1.4 / 0.3</td>
<td>Pu-241 / Pu-239 / U-233 / Ag-108m / C-14</td>
</tr>
<tr>
<td>Fuel type</td>
<td>BWR, VVER-440 / EPR, VVER-1200</td>
<td>~130 (0.07 vs 0.03 g/tU)</td>
<td>C-14</td>
</tr>
</tbody>
</table>
Publications

- **Conference articles**

- **Research reports**

- **Thesis**
Supplementary material
Nuclear data: fission yield and decay data

- Fission yield data mainly responsible for uncertainties in activity, decay heat, photon emission rate and studied nuclide concentrations (C-14, Cl-36, Mo-93, Ag-108m, I-129, Pu-239)
- Decay data uncertainties have an effect on spontaneous fission yield
- Largest uncertainties for photon emission rate, 6-9 % at around 30 y after irradiation depending on burnup
- Maximum uncertainties for decay heat 3-5 % at 1 or 15 y after irradiation depending on burnup
- In a BWR, maximum uncertainties were slightly larger for lower void fraction except for spontaneous fission rate
Choice of calculation parameters

- Studied calculation parameters:
  - Depletion zone division
  - Depletion step length
  - Doppler-broadening rejection correction (DBRC)
  - Unresolved resonance probability table sampling
  - Energy-dependent branching ratios

- Maximum effects (depletion zone division)
  - Decay heat 0.6 % at 7 y
  - Photon emission rate 1.1 % at ~7000 y
  - Spontaneous fission rate 8 % at ~400 y
Impurities in fuel and structural materials

- Conservative impurity concentrations: 0.7 wt-% of fuel and 0.3 wt-% of Zircaloy cladding based on maximum values found in literature
- Impurities have a significant effect on neutron absorption in Zircaloy cladding
- Max increase in cladding activity > 800 % ~30 y after irradiation
- Max increase in fuel activity 2.5 % ~70 000 y after irradiation

Cl = 20 ppm
Co = 20 ppm
Cu = 50 ppm
Mo = 50 ppm
N = 80 ppm
Ni = 80 ppm
Th = 10 ppm

Activity from impurities in Zry-4 cladding
Uncertainties 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 %

9.4.2021 VTT – beyond the obvious
SKB benchmark and NEA report: decay heat

- SKB benchmark
  - characterization (e.g. decay heat) of five irradiated PWR assemblies.
  - Comparison to the results of other participants and measurements.
  - VTT participates using Serpent 2.
  - Calculations finished. Journal article under preparation.

- NEA report
  - Participation in the writing of NEA guidance report on decay heat calculations
PGET modelling and HIP cooperation

- HIP and STUK co-operation: RADAR
  - RADAR includes the development of image reconstruction methods for PGET (Passive Gamma Emission Tomography)
  - PGET is used to scan SNF assemblies to determine that no rods have been removed.
- First Serpent model of PGET constructed in a thesis financed by Aalto University and instructed at VTT
- Work continued in KÄRÄHDE and SAFIR project RACSA: special assignment ongoing.
Fuel type and burnup

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

<table>
<thead>
<tr>
<th>Nuclides</th>
<th>% (BWR)</th>
<th>% (EPR)</th>
<th>% (VVER-440)</th>
<th>% (VVER-1200)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Am241</td>
<td>40.0</td>
<td>44.8</td>
<td>46.4</td>
<td>39.1</td>
</tr>
<tr>
<td>Pu238</td>
<td>22.8</td>
<td>23.6</td>
<td>22.6</td>
<td>34.8</td>
</tr>
<tr>
<td>Ba137m</td>
<td>16.3</td>
<td>14.1</td>
<td>13.6</td>
<td>11.4</td>
</tr>
<tr>
<td>Y90</td>
<td>15.0</td>
<td>12.1</td>
<td>12.4</td>
<td>10.7</td>
</tr>
<tr>
<td>Pu240</td>
<td>5.9</td>
<td>5.4</td>
<td>5.0</td>
<td>4.0</td>
</tr>
</tbody>
</table>