

Decay Heat Validation

SCALE 6.3

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Learning goals

- **Summarize** decay heat validation for SCALE
 - Results shown here correspond to SCALE 6.3.2 with ENDF/B-VII.1 data
 - Quality assurance on code changes provides confidence that SCALE 6.3.x will yield similar performance with the same data library
- **Gain hands-on experience** on decay heat calculations for an available benchmark

Sources of decay heat validation data

- Hanford Engineering Development Laboratory assembly calorimeter measurements (1980)
 - Boil-off (steam) calorimeter design
 - 15×15 assemblies measured (4 assemblies)
- GE Morris Facility calorimeter measurements (1985)
 - Static mode calorimeter design (temperature increase)
 - 14×14 and 7×7 assemblies (75 assemblies)
- SKB Swedish Central Interim Spent Fuel Storage Facility (Clab) assembly calorimeter measurements (2005–2010)
 - GE calorimeter design
 - PWR – 15×15, 17×17 designs (34 assemblies)
 - BWR – 8×8, SVEA-64, SVEA-100 (31 assemblies)
- Fissile material irradiations (small samples, short decay times)

Validation based on full-assembly decay heat experiments



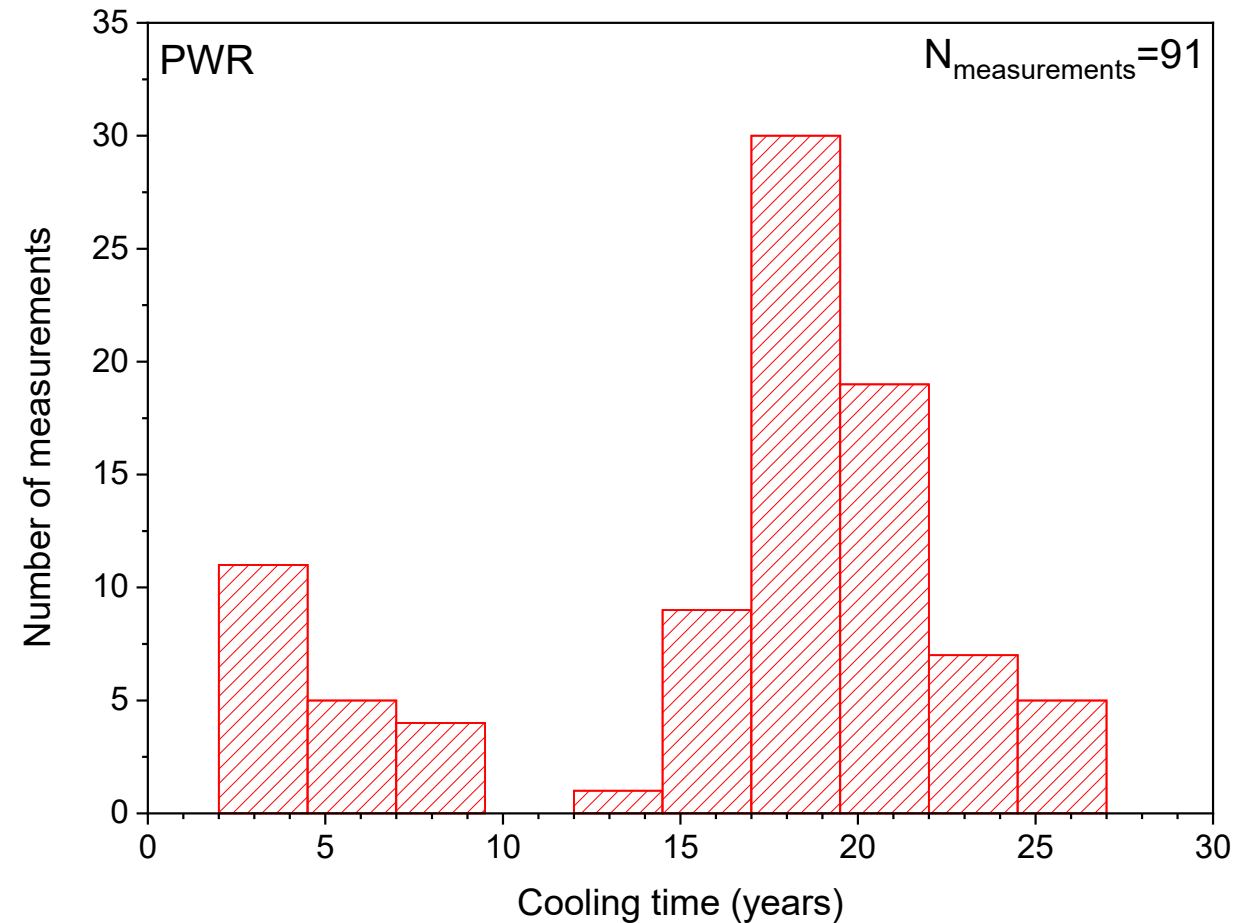
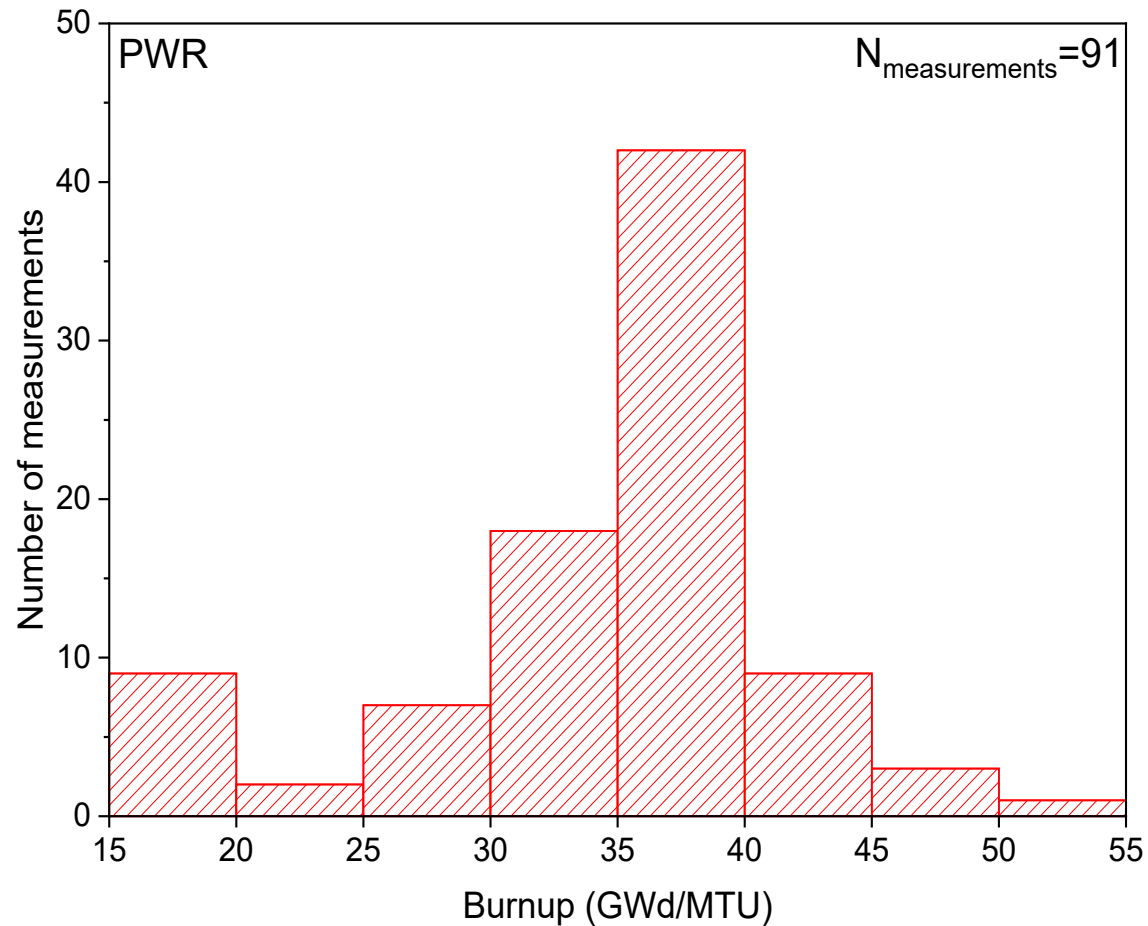
Summary of fuel assembly decay heat measurements

Reactor type	Reactor name	Assembly lattice	Burnup (GWd/MTU)	Cooling time (years)	Enrichment (wt % ²³⁵ U)	Measurement laboratory	No. of measured assemblies	No. of measurements	Exp. relative uncertainty* (%)
PWR	Point Beach 2	14×14	31.9–39.4	4.5	3.4	GE-Morris	6	6	4.7
	San Onofre 1	15×15	26.5–32.4	3.0–8.2	3.9–4.0	GE-Morris	8	8	4.7
	Turkey Point 3	14×14	18.4–28.4	2.4–5.7	2.6	GE-Morris	4	6	5.0–10.0
	Ringhals 2	15×15	34.0–51.0	15.9–26.7	3.1–3.3	Clab	18	33	2.3–3.0
	Ringhals 3	17×17	19.7–47.3	12.9–25.9	2.1–3.4	Clab	16	38	2.2–4.1
BWR	Cooper	7×7	11.7–28.0	2.3–7.2	1.1–2.5	GE-Morris	54	81	4.7
	Dresden 2	7×7	5.3	8.1	2.1	GE-Morris	1	1	4.7
	Monticello	7×7	9.2–21.0	9.7–11.2	2.3	GE-Morris	6	13	4.7
	Oskarshamn 2	8×8	14.5–24.5	20.3–26.7	2.2	Clab	5	5	4.2–7.5
	Ringhals 1	8×8	21.3–44.7	12.6–23.6	2.3 – 2.9	Clab	17	45	2.5–5.1

* Exp. Stands for Experimental.

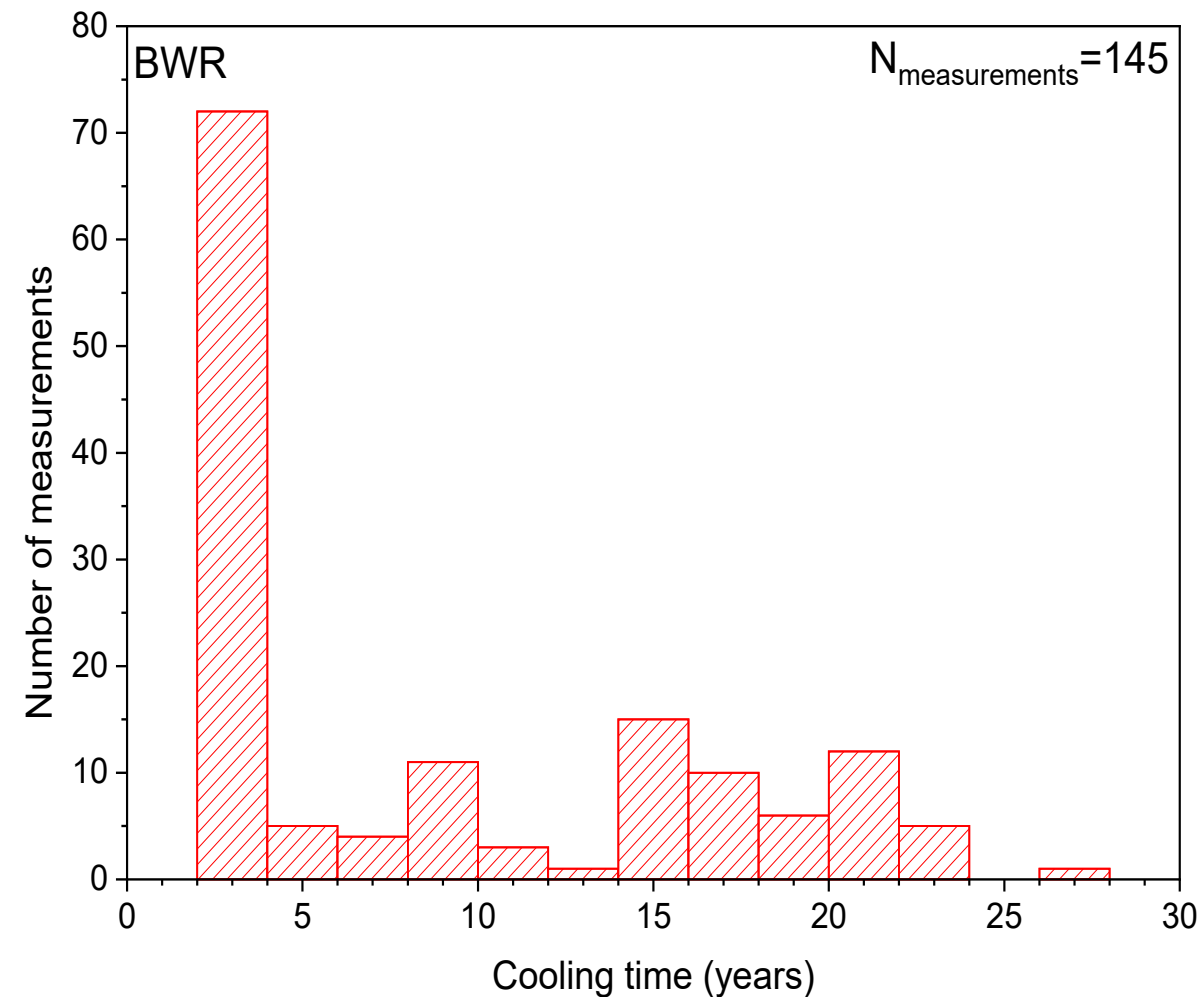
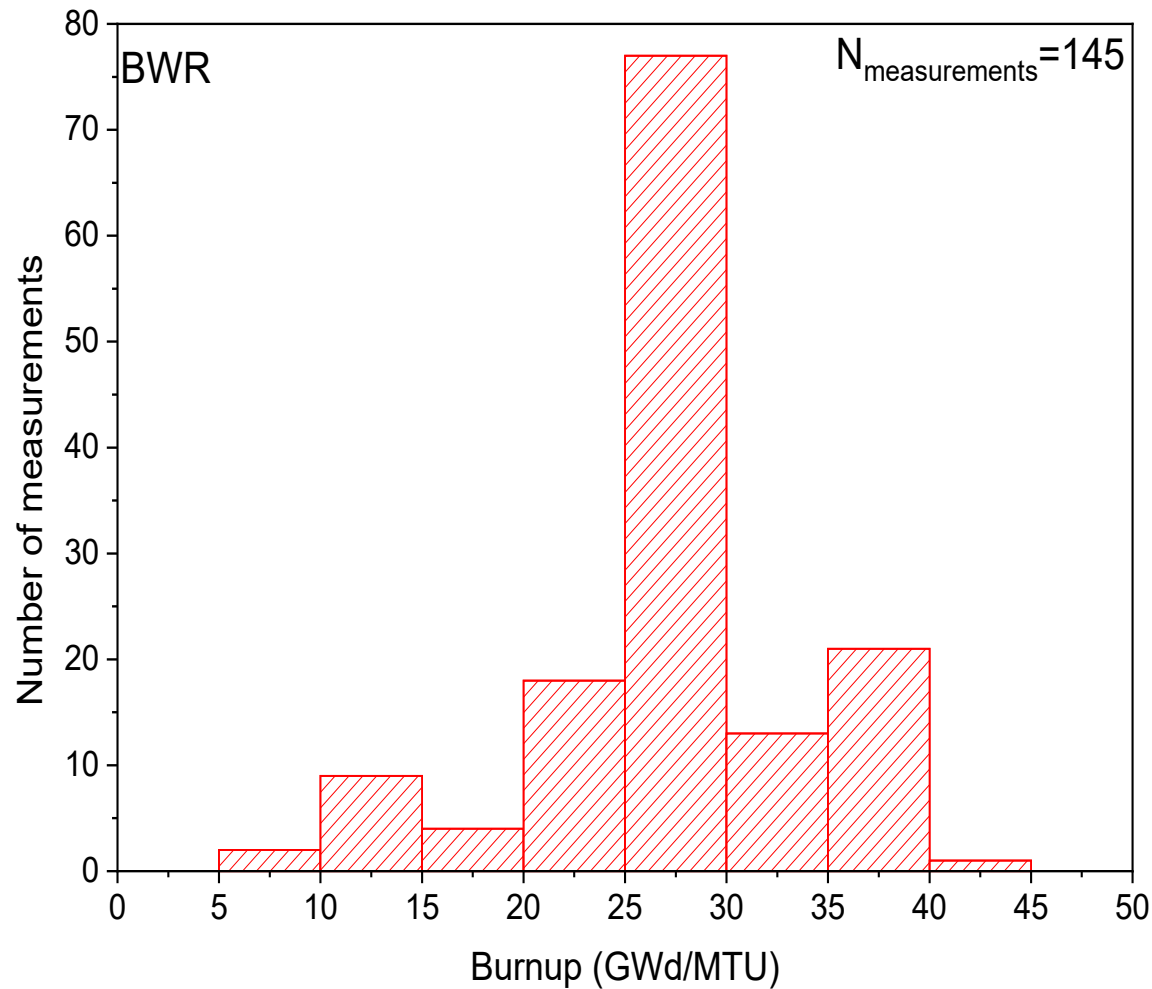
Experimental data: Decay heat for PWR fuel assemblies

burnup and cooling time space covered

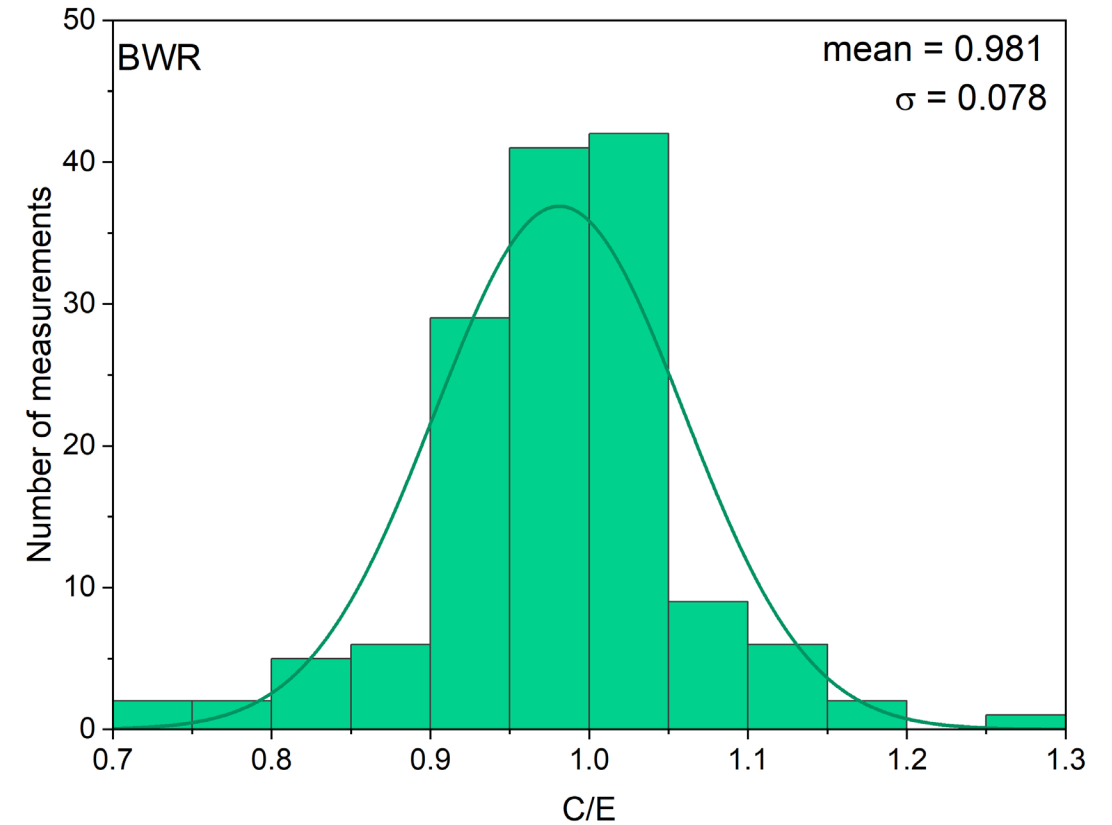
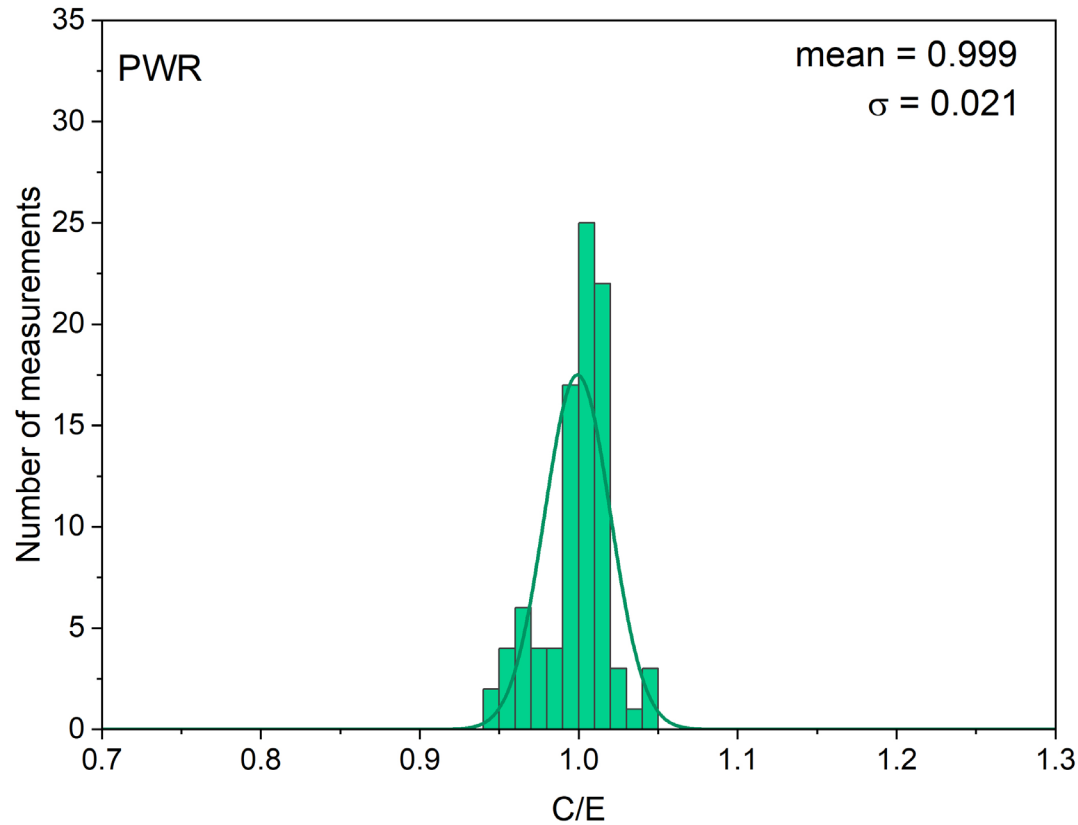


Experimental data: Decay heat for BWR fuel assemblies

burnup and cooling time space covered

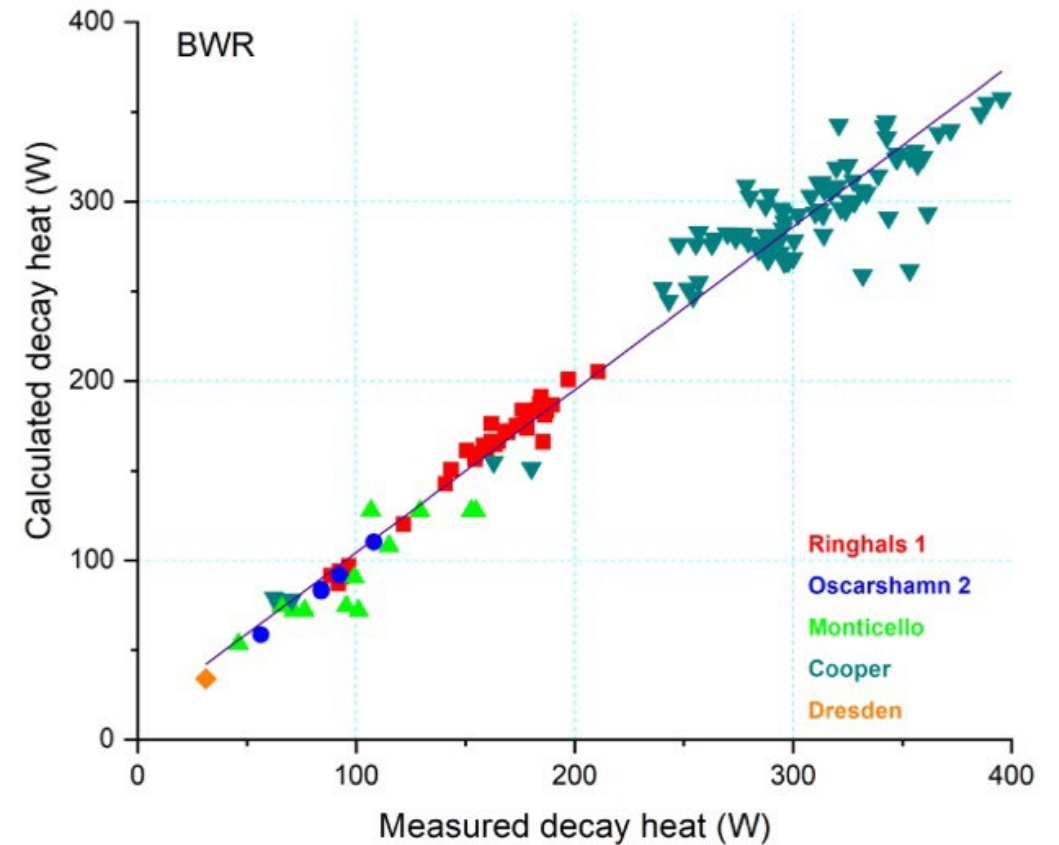
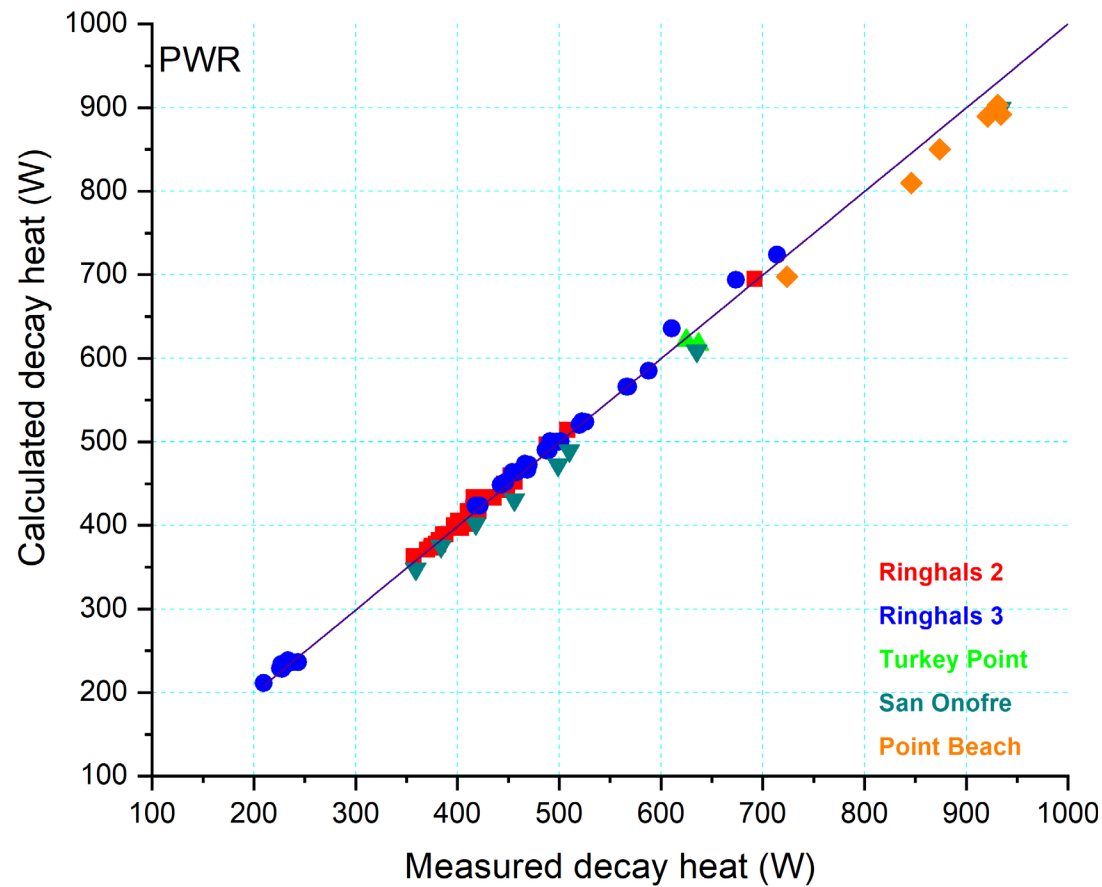


Histogram plots for decay heat calculation-experiment comparison

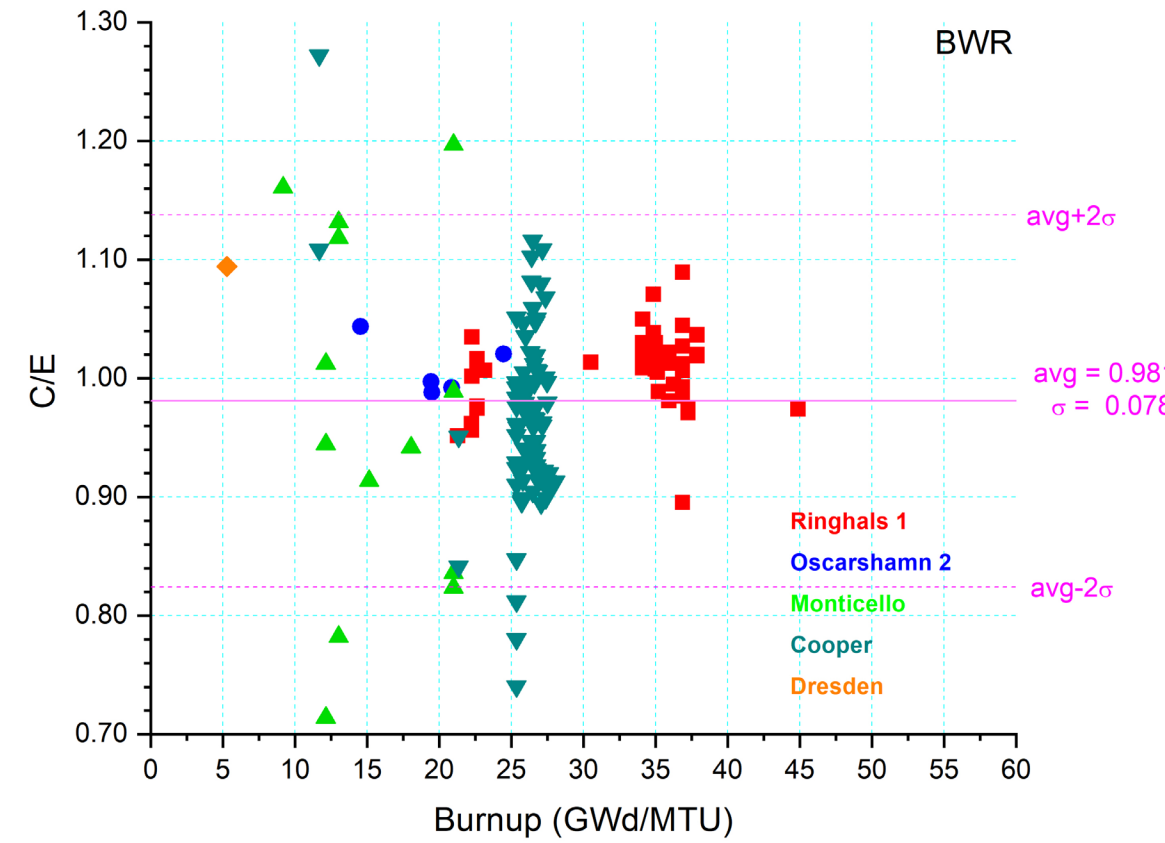
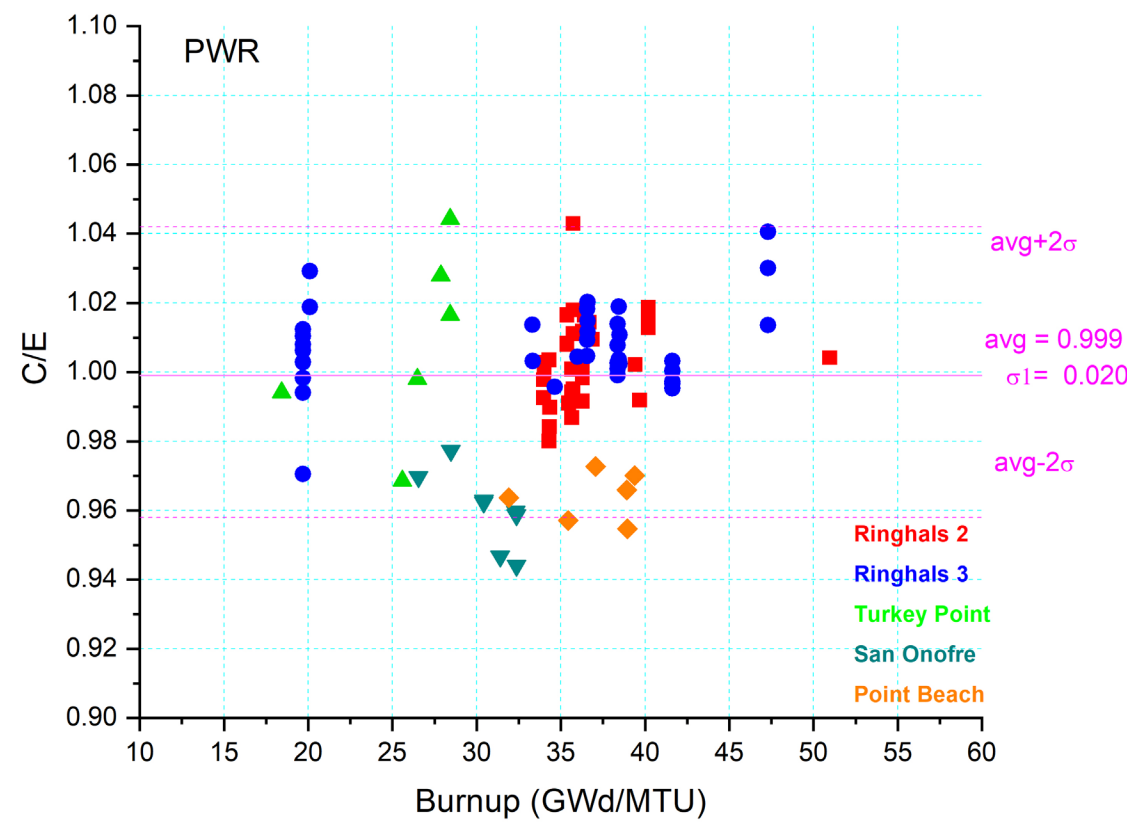


C = Calculation; E = Experiment

Comparison of calculated vs. measured assembly decay heat

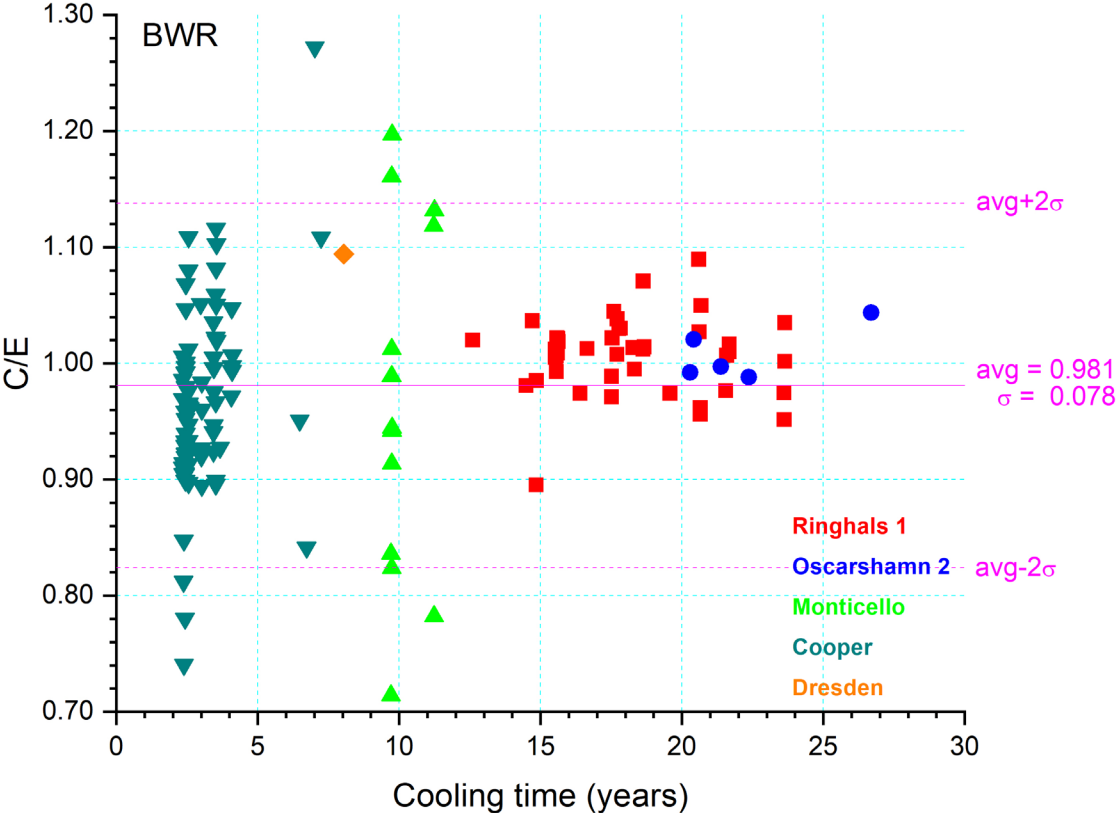
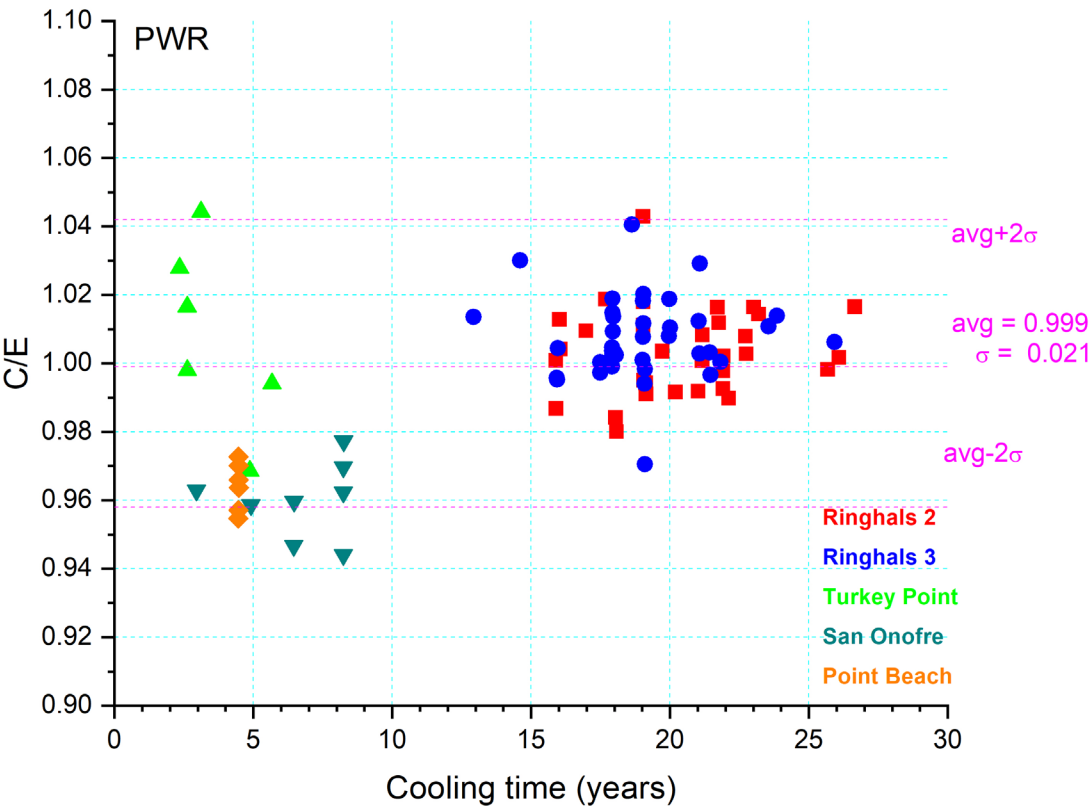


Decay heat calculation-experiment comparison as a function of burnup



No significant trend with burnup

Decay heat calculation-experiment comparison as function of cooling time



No significant trend with cooling time

Validation based on fissile material irradiation experiments



Summary of full-assembly decay heat results indicates good agreement between calculation and experiment

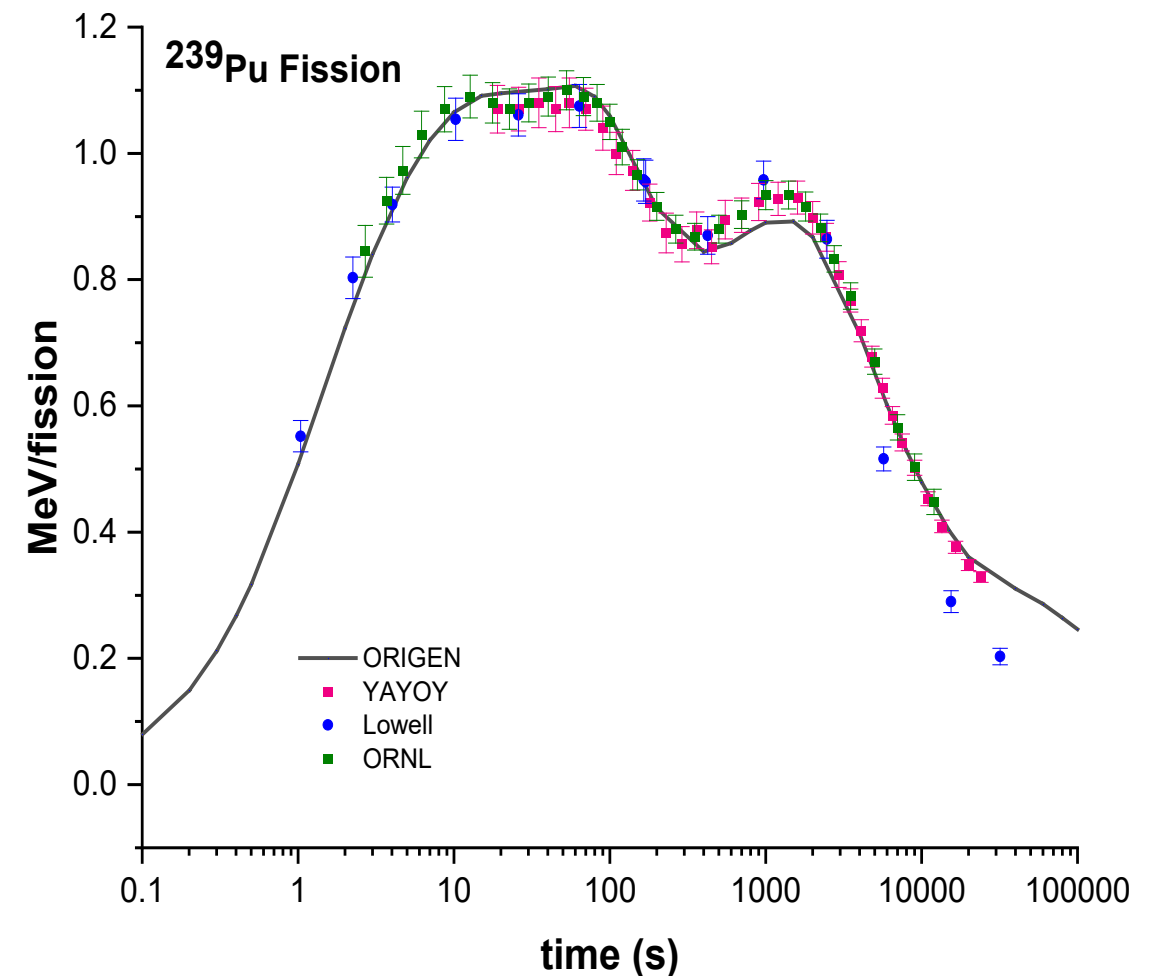
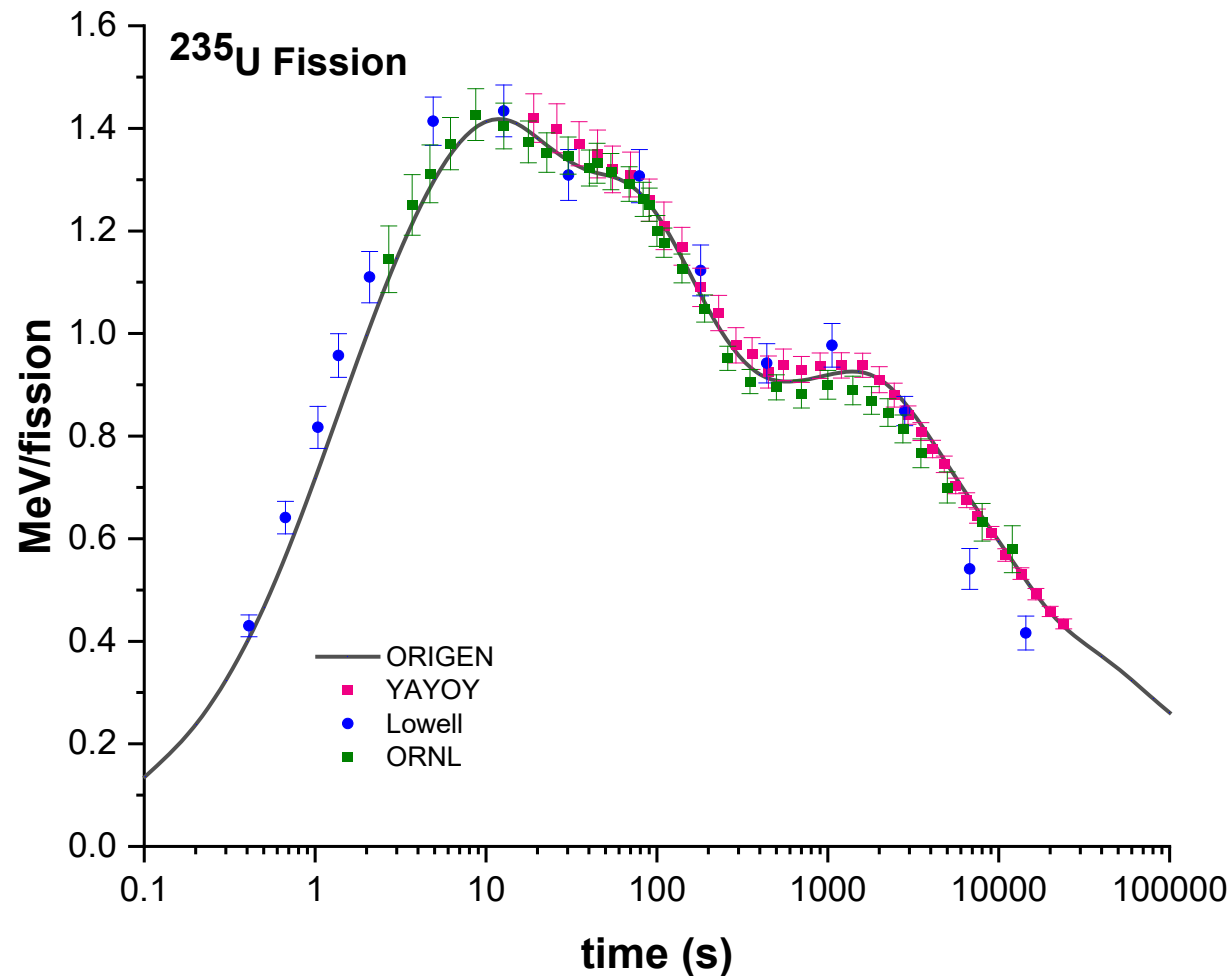
Reactor name	Reactor type	No. of meas.	Exp. uncert. (%)	Cooling time (years)	C/E		C-E (W)	
					mean	σ	mean	σ
Point Beach 2	PWR	6	4.7	4.5	0.964	0.007	-31.3	6.9
Ringhals 2	PWR	33	2.3–3.0	15.9–26.7	1.004	0.013	1.7	5.4
Ringhals 3	PWR	38	2.2–4.1	12.9–25.9	1.007	0.012	3.5	5.8
San Onofre 1	PWR	8	4.7	3.0–8.2	0.960	0.011	-21.1	8.8
Turkey Point 3	PWR	6	5.0–10.0	2.4–5.7	1.008	0.027	15.1	28.2
Cooper	BWR	81	4.7	2.3–7.2	0.966	0.078	-12.7	22.0
Dresden 2	BWR	1	4.7	8.1	1.094	na	3.0	na
Monticello	BWR	13	4.7	9.7–11.2	0.967	0.154	-5.9	15.7
Oskarshamn 2	BWR	5	4.2–7.5	20.3–26.7	1.008	0.023	0.6	1.7
Ringhals 1	BWR	45	2.5–5.1	12.6–23.6	1.007	0.033	1.2	5.2
PWR		91		2.4–26.7	0.999	0.021	-0.8	14.5
BWR		145		2.3–26.7	0.981	0.078	-7.2	18.4
PWR+BWR		236		2.3–26.7	0.988	0.063	-4.8	17.2

Validation data for decay heat, short decay time

- Small samples of fissile material were irradiated, and total energy release after fission was measured for
 - Thermal fission of ^{235}U , ^{239}Pu , and ^{241}Pu
 - Fast fission of ^{233}U and ^{238}U
- Data applicable to time scales up to $\sim 10^5$ s (28h) of interest for reactor accident analysis
- This type of data served in development of decay heat standards (e.g., NRC RG-3.54, ANS-5.1)
- Pulse fission experiments performed at
 - ORNL
 - University of Tokyo YAYOI fast reactor facility
 - Karlsruhe
 - Studsvik
 - University of Massachusetts, Lowell

Results: Fissile material irradiations

experiment–calculation comparison



Workshop: Decay heat benchmark for a PWR assembly



Workshop: Decay heat benchmark for a PWR assembly

Determine the effect of modeling assumptions (i.e., ORIGEN reactor library) on assembly decay heat for the PWR assembly F32 decay heat benchmark, using the following computational approaches:

- 1) Use ORIGAMI with the ORIGEN reactor library w15x15 available in SCALE
 - 2) Use ORIGAMI with custom library, generated using assembly-specific design data
- **Input data** (sources [NUREG/CR-6972](#) and [NUREG/CR-6971](#)):
 - Custom library for ORIGAMI and corresponding arpdata.txt content provided (see starters folder in provided material)
 - Benchmark specifications are shown on the following slides
 - Neglect light element loading in decay heat calculation

Benchmark assembly specifications

- Assembly lattice: 15×15 design
- Initial fuel enrichment: 3.197% ^{235}U
- Initial U contains 0.04% ^{234}U and 0.02% ^{236}U
- Assembly discharge burnup: 50.962 GWd/MTU
- Assembly U loading: 436.99 kg
- Assembly measured decay heat: 692.0 W
- Cooling time (from discharge to measurement date): 5860 days

Assembly irradiation history

Cycle #	Duration (days)	Down (days)	Assembly power (MW/MTU)
1	290	80	36.390
2	317	84	33.467
3	273	778	30.736
4	320	63	24.253
5	297	54	22.320
6	329		21.334

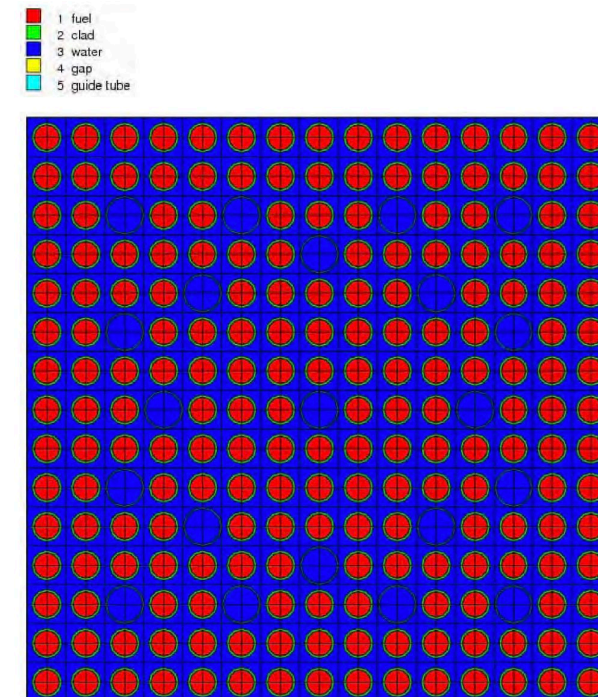
Benchmark assembly geometry and materials

used in the TRITON model to generate the custom ORIGEN reactor library

Table 4.32 Fuel assembly design data for PWR 15 × 15 assemblies

Parameter	Data	
Assembly and reactor data	Type 1	Type 2
Lattice geometry	15 × 15	15 × 15
Fuel rod active length (cm)	365.8	365.8
Assembly pitch (cm)	21.50	21.50
Coolant density (g/cm ³)	0.72	0.72
Coolant temperature (K)	552	552
Average soluble boron level (ppm)	650	650
Number of fuel rods	204	204
Number of guide tubes	20	20
Number of instrument tubes	1	1
Rod pitch (cm)	1.43	1.43
Spacers material	Inconel	Inconel/Zircaloy-4
Spacers total mass (g)	788	720/160
Fuel rod data		
Fuel material type	UO ₂	UO ₂
Effective fuel density (g/cm ³)	10.227	10.137
Effective fuel temperature (K)	900	900
Fuel pellet diameter (cm)	0.929	0.911
Fuel rod outside diameter (cm)	1.072	1.075
Clad material	Zircaloy-4	Zircaloy-4
Clad thickness (cm)	0.0618	0.0725
Average clad temperature (K)	573	573

Assembly geometry data (Type 2)



Desired results

- Assembly decay heat (W) as calculated with approaches 1 and 2 at following cooling times:
 - 5860 days (measurement date)
 - 1 year
 - 5 years
 - 10 years
 - 50 years
 - 100 years
- Calculated-to-measured (C/E) assembly decay heat ratio and C-E (W), when C is calculated using computational approaches 1 and 2
- Nuclides contributing >1% to the total decay heat and their % contribution, as calculated using computational approaches 1 and 2 at the following cooling times:
 - 5860 days (measurement date)
 - 5 years

Solution: Decay heat benchmark for PWR assembly



Input files: Custom ORIGEN reactor library

Irradiation simulation with ORIGAMI

```
=shell
cp ${INPDIR}/clab_kwu15_e2.lib ${TMPDIR}/
cp ${INPDIR}/clab_kwu15_e3.lib ${TMPDIR}/
cp ${INPDIR}/clab_kwu15_e4.lib ${TMPDIR}/
cp ${INPDIR}/arpdata.txt ${TMPDIR}/
end

=origami
title="PWR: 0D approximation"
options{ mtu=0.43699 ft71=all}
libs=[clab_kwu15x15]
fuelcomp{
  mix(1){ stdcomp(fuel){
    base=uo2 iso[ 92234=0.04 92235=3.197 92236=0.02 92238=96.743 ]
  }
}
}
hist[
cycle{ power=36.390 burn=290 nlib=4 down=80 }
cycle{ power=33.467 burn=317 nlib=4 down=84 }
cycle{ power=30.736 burn=273 nlib=4 down=778 }
cycle{ power=24.253 burn=320 nlib=4 down=63 }
cycle{ power=22.320 burn=297 nlib=4 down=54 }
cycle{ power=21.334 burn=329 nlib=4 down=0 }
]
end
```

Decay only simulation with ORIGEN

[illegible]

Results:

Calculation–measurement comparison at 16.04-yr cooling time

Standard ORIGIN reactor library

- C (W) = 715.6
- E (W) = 692
- C-E (W) = 23.6
- C/E-1 (%) = 3.4

Custom ORIGIN reactor library

- C (W) = 698.5
- E (W) = 692
- C-E (W) = 6.5
- C/E-1 (%) = 0.9

Results: Decay heat as function of cooling time

Cooling time (yr)	1	5	10	16.04	50	100
Standard lib (W)	4351	1201	846	716	392	212
Custom lib (W)	4297	1179	827	698	378	200
Difference (W)	54	22	19	18	14	12
Difference (%)	1.3	1.9	2.3	2.6	3.7	6.0

Results: Top contributors to decay heat at 5 and 16-yr cooling times

Standard ORIGEN reactor library

5-yr cooling time

Nuclide	% Decay heat
ba137m	18.3
y90	16.6
cs134	16.4
cm244	14.3
pu238	10.1
rh106	5.9
cs137	5.2
sr90	3.5
eu154	2.5
pr144	2.0
am241	1.9

16.04-yr cooling time

Nuclide	% Decay heat
ba137m	23.8
y90	21.4
cm244	15.8
pu238	15.5
am241	6.9
cs137	6.8
sr90	4.5
eu154	1.7
pu240	1.4

References on SCALE decay heat validation

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Publicly available documents can be accessed via OSTI. See <https://www.ornl.gov/scale/references> under Depletion and Decay.